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# Measuring air temperature in glazed ventilated façades in the presence of direct solar radiation

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## SUMMARY

A distinctive element of buildings with a double glazed façade is naturally or mechanically driven flow in a ventilated cavity. Accurate air temperature measurements in the cavity are crucial to evaluate the dynamic performance of the façade, to predict and control its behavior as a significant part of the complete ventilation system. Assessment of necessary cooling/heating loads and of the whole building energy performance will then depend on the accuracy of measured air temperature. The presence of direct solar radiation is an essential element for the façade operation, but it can heavily affect measurements of air temperature and may lead to errors of high magnitude using bare thermocouples and even adopting shielding devices. Two different research groups, from Aalborg University and Politecnico di Torino, tested separately various techniques to shield thermocouples from direct irradiance, in order to achieve an accurate and reliable way to measure the air temperature reducing the error caused by radiation. Experiments include bare thermocouple, naturally and mechanically ventilated shielded thermocouples, mechanically ventilated thermocouple with double shielding, silver coated thermocouples and screens. In both tests mechanically ventilated (single) shielding devices provide better results than naturally ventilated ones. A few of the best performing techniques were compared between two research groups and a comparison shows good agreement of the results.

## INTRODUCTION

Buildings with the double glazed façade (DGF) are frequently regarded as ones with the dynamic ventilation system which is normally designed as a part of complete building ventilation system. The dynamics of such ventilation system is expressed in the periodical changes of ventilation modes with the intention to follow rapid changes in weather conditions. The dynamics of the DGF system requires an efficient control in order to react to frequent variations in weather and finally to ensure comfort for the occupants [1]. The main classification of the DGF ventilation modes are given in [2].

In many cases the control strategies for ventilation systems of buildings with a double glazed façade involve continuous measurements of air temperature in the occupied zone and in the double façade cavity. Depending on the actual ventilation mode the overestimation of the cavity air temperature may cause discomfort in the occupied zone due to draught, moreover it can lead to weakening of the control strategy, expressed by too early or too late switch between DGF ventilation modes. This will result in poorer Indoor Enviromental Quality (IEQ) for the occupants and finally will lead to inferior building energy efficiency. Thus accurate air temperature measurements are crucial for prediction, evaluation and control of the dynamic performance of the façade, as a significant part of the complete ventilation system. The presence of direct solar radiation is an essential element for the façade operation, but it can heavily affect measurements of air temperature and may lead to errors of high magnitude using bare thermocouples and even adopting shielding devices.

Another distinctive element of the double glazed facades is application of shading devices in the cavity in order to prevent glare and penetration of solar heat gains into the occupied zone. Depending on type of shading in the ventilated cavity, the surface of the shading device is heated up to 65$^{o}$C. Location of the temperature sensor nearby the shading device may lead to serious measurement errors if the temperature sensor is unprotected.

In the field of meteorology the problem of accuracy in temperature measurements was recognized over 150 years ago [3], a screen, designed by Stevenson, is widely used now to measure air temperature in the field. Moreover, some meteorologists even suggest a standard methodology for dealing with this sort of errors. It is essential that the experts dealing with the issues of occupants' thermal comfort consider developing of similar guidance for measurements of air temperature under the shortwave or long-wave radiation loads.

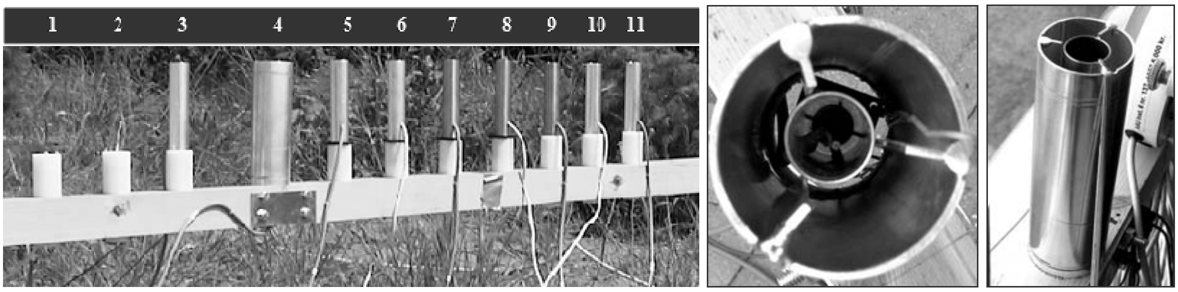
Two different research groups, from Aalborg University and Politecnico di Torino, tested separately various techniques to shield thermocouples from direct irradiance, in order to achieve an accurate and reliable way to measure the air temperature reducing the error caused by radiation. This paper describes the experimental setups for the undertaken investigation and the results obtained. A few of the best performing techniques were compared between the two research groups and a comparison shows good agreement of the results.

## METHODS

### Aalborg University Experimental setup

These particular experiments were undertaken in order to minimize the error in an air temperature measurement during the experimental investigation in the double glazed façade test facility 'Cube' at the Aalborg University. The experimental setup included 11 thermocouples, placed in a row 15 cm away from each other, as shown in Figure 1.

Thermocouples type K (Chromel /Alumel) with the junction of approximately 2.5 mm in the diameter were used in the experimental setup. Thermocouples were calibrated in three points: 10, 20 and 35$^{o}$C. The measurement results collected by a data logger HBM 334 measured at a frequency 0.2 Hz. Experimental results are reported as 10 minutes average values.




a) b) c)

Figure 1. a) Experimental setup. Test cases are numbered according to their position in the experimental setup. b) Test case 4 - Thermocouple coated with silver and shielded with two silver coated tubes (photo from above). c) Visualization of double shielding.

After completing preliminary tests of shielding strategies the test cases in the Table 1 and Figure 1-a, were chosen for the final experiments. The experimental setup includes bare thermocouples, thermocouples shielded differently from the direct solar access, shielded and ventilated thermocouples and differently shielded silver coated thermocouples.

Table 1. Test cases in the experimental setup.

*K* – thermocouple type K without silver coating
*KS* – thermocouple type K with silver coating
*T* – copper shielding tube
*TS* – copper shielding tube coated with silver (both inner and outer surfaces)
*2TS* – two copper shielding tubes coated with silver (both inner and outer surfaces)
*F* – ventilated with a mini fan
- – no ventilation or no shielding tube

| Test case | 1 | 2 | 3 | 4 | 5 | 6 | 7* | 8 | 9* | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Thermocouple | *K* | *KS* | *KS* | *KS* | *KS* | *K* | *KS* | *K* | *KS* | *K* | *KS* |
| Shielding tube | - | - | *TS* | *2TS* | *TS* | *TS* | *T* | *T* | *T* | *TS* | *TS* |
| Fan | - | - | - | *F* | *F* | *F* | *F* | *F* | - | - | - |

*- Results are not available due to measurement errors

If a thermocouple is shielded with a copper tube (K+T), it is most likely that the shielding tube becomes overheated due to the solar radiation and readings from the temperature sensor become affected by the strong radiative heat exchange. In the case (8) it is assumed that the fan increases convection at the surface of the tube, removes heated air from the cavity and finally reduces the effect of radiation heat flux. However, the radiative heat exchange between the sensor and the heated surface of the tube exists and still causes some errors. In order to fight the radiative heat flux, silver, the metal which has the most superior reflectivity of visible light rays, is considered for the test cases. Thus besides the traditional thermocouples and copper tubes, the test cases include silver coated thermocouple, silver coated shielding tubes and a combination of both (2,3,4,5,6,7,9,10,11).

In the experimental setup shown in Figure 1-a the mini fans are located at the bottom of a shielding tube and the air is sucked in the direction from the top to the bottom of the tubes. In a case of double shielding, Figure 1-b, one mini fan ventilates both of the cavities. Shielding tubes have the following dimensions: for the inner tube Ø25mm and length 100mm, tubes of the same dimensions were used in the other test cases. The outer tube in the test case 4: Ø60mm and length 130mm.

The experimental setup was placed outdoors, in the open flat country facing south. Due to necessity to run the fans connected to the electricity the experiments were run only at the day time.

**Politecnico di Torino Experimental setup**

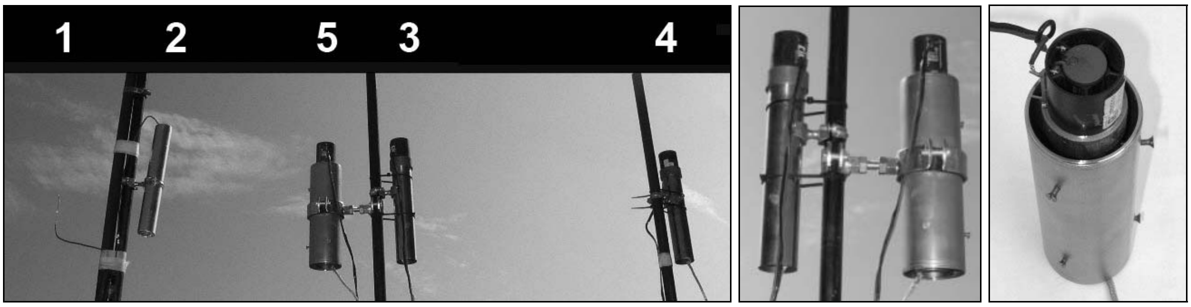
During the design of the experimental test facility TWINS (Testing Window INnovative Systems) [4], designed and built at the Department of Energy at the Politecnico di Torino, particular attention was payed to the choice of sensors to measure the temperature of the air flowing in the mechanically ventilated cavity.

5 different thermocouples were placed outdoors, under the solar radiation in a sunny day; the direct and diffuse irradiance was measured by a pyranometer placed on a vertical plane, facing the south. The thermocouples and the pyranometer were placed at about 1 meter above the floor level.

All the thermocouples were type J (Iron/Constantan), and the datalogger internal reference junction was used. The measurement chain was calibrated over three points at 0, 20 and 40°C, using a certified thermal resistence PT100 as reference.
A multimeter Keithley 2700 was used to collect data and the scan acquisition rate was 0.2 Hz.

Following are the 5 tested sensors (Figure 2):
1. Bare thermocouple
2. Shielded thermocouple
3. Shielded and ventilated thermocouple
4. Shielded and ventilated thermocouple with additional internal insulation
5. Double shielded and ventilated thermocouple

The bare thermocouple *(1)* was a 0.4 mm wire. The shielded thermocouple *(2)* used the same wire and junction as *(1)* and was shielded by means of an aluminium pipe, Ø26mm, thickness 1.4mm and length 175mm, with the outside surface covered by a reflecting aluminium tape. The shielded and ventilated thermocouple *(3)* was an armoured thermocouple, Ø4.0mm; it was shielded with a chromium-plated brass pipe, Ø30mm, thickness 1.0mm and length 150mm, ventilated by a DC axial centrifugal fan. The fan was located on the top of the pipe, the measured air velocity in the pipe was 3.8 m/s, the air flowed upwards. The shielded and ventilated thermocouple with additional insulation *(4)* was the same as *(3)* but the internal surface of the pipe was covered with a polyester fabric layer. The double shielded and ventilated thermocouple *(5)* was the same as *(3)* but with an external additional steel pipe, Ø40mm, thickness 2.0mm and length 150mm; only the internal pipe was ventilated.



a) b) c)

Figure 2. a) Experimental setup. b) Shielded ventilated thermocouple and double shielded ventilated thermocouple. c) View of the double shielded ventilated thermocouple.

Solution *(2)* is the simplest way to shield a thermocouple from solar radiation, but there's still the problem of the effect due to the pipe overheating. Ventilation of the air inside the pipe was chosen as the main strategy to reduce the influence of radiative effect by increasing the convective coefficient: this is the principle of solution *(3)*. In solutions *(4)* and *(5)* two different additional shielding layers were used to further reduce the radiative heat flow between the pipe and the sensor.

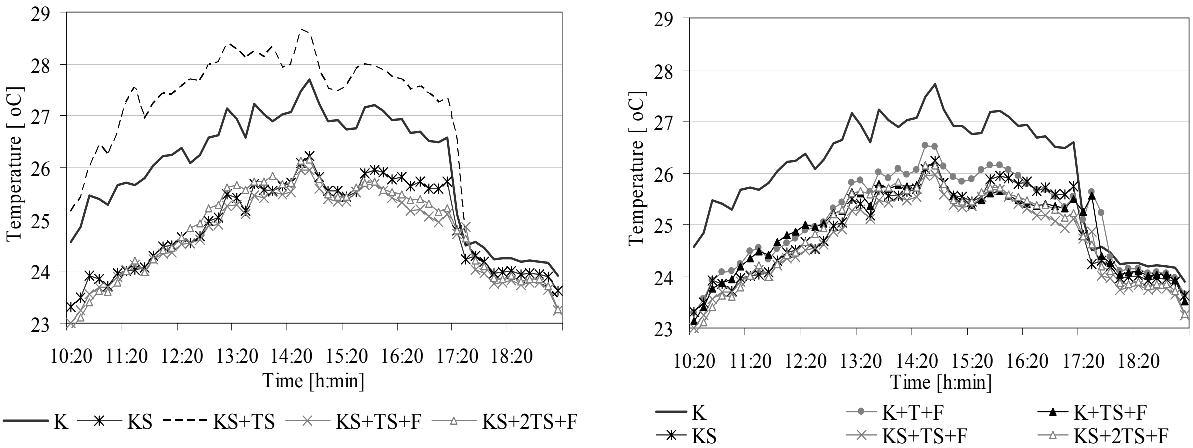
## RESULTS

### Experimental results from Aalborg University

In order to verify equal intensity of solar radiation to all sensors in the setup, two pyranometers were located at the left and at the right hand side of the temperature sensors. The results of the preliminary investigation show that in a day with the small or medium cloudiness the distribution of the solar radiation to the temperature sensors can be estimated as uniform, due to the comparably small size of the experimental setup. There are no experiments performed in the cloudy days with the dominating diffuse solar radiation.

In order to investigate the best suitable way to measure the air temperature, eleven cases were tested in the final experimental setup (Table 1). The challenging part of the experiments is the lack of knowledge about the true air temperature and that an evaluation of the results in absolute terms is not possible. As a result, the best approximation to the true air temperature is the measured air temperature in the test case which shows the minimal values in the presence of solar radiation. The same approach was used in [5] to investigate outdoor air temperature measurements. On the contrary in the clear night unprotected sensors have a tendency to show lower temperature due to night time long-wave radiation.

Experimental results show that there is a wide spread in the temperature readings between protected and unprotected sensors. In a day with a medium intensity of solar radiation the difference between minimum and maximum air temperature measured with differently protected thermocouples is 4 $^{o}$C (mean values are compared), but this temperature difference can increase up to 10 $^{o}$C for a day with a stronger direct solar radiation.




a) b)

Figure 3. a) Measured air temperature for the test cases 1, 2, 3, 4, 5. b) Measured air temperature for the test cases 1, 2, 4, 5, 6, 8.

Air temperature readings show three different levels in Figure 3-a. The figure includes stepwise increase in implemented shielding devices starting from a bare thermocouple. Improvement of the bare thermocouple with the silver coating gives a remarkable result, as the temperature readings decrease almost to the minimal values (mean value 24.86$^{o}$C). Moving forward shading a silver coated thermocouple with the silver coated tube (both inner and outer surfaces), the measured air temperature increases drastically due to the thermal mass of the tube, which gets heated and subsequently heats air in the tube, the radiative heat exchange in this case should be minimized due to silver coating of the thermocouple and tube. The situation is improved with increase of the convective coefficient by application of a mini fan (test case *KS+TS+F*) and the minimum measured air temperatures are distinctive for this test case (mean value 24.67$^{o}$C).

Additionally, one more enhancement was developed for protecting the temperature sensor: a double shielding of the temperature sensor with two silver coated tubes (*KS+2TS+F*) as explained earlier. Experimental results show that application of double shielding is not efficient (mean value 24.79°C), as it requires larger size of the external shield and thus the thermal mass is increased. Otherwise the reason for the inefficiency is the fan which in this case might not be strong enough to ensure the necessary flow motion through the two cavities (the external cavity between the shields and internal cavity in the internal shielding tube). Hence, the test case 4 requires further investigations.

One can find intricate dealing with silver due to its oxidation feature and cost. The results for uncoated thermocouples in comparison to the experimental results are discussed above. It is evident that avoiding silver coating will lead to higher readings than in the case with the coating, but the improvement is still very good when compared with application of bare thermocouple (Figure 3-b).

Table 2. Mean measured air temperature.

| Test case | 1 | 2 | 3 | 4 | 5 | 6 | 7* | 8 | 9* | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test case | *K* | *KS* | *KS TS* | *KS 2TS F* | *KS TS F* | *K TS F* | *KS T F* | *K T F* | *KS T* | *K TS* | *KS TS* |
| Mean measured temperature, [°C] | 26.02 | 24.86 | 26.87 | 24.79 | 24.67 | 24.94 | - | 25.12 | - | 28.43 | 27.06 |
| STD [°C] | 1.17 | 0.89 | 1.64 | 0.90 | 0.82 | 0.79 | - | 0.90 | - | 2.16 | 1.70 |

Min of mean measured temperature, 24.67°C
Max of mean measured temperature, 28.43°C
* Results are not available due to measurement errors

On the basis of the investigations the shielding type of test case 5 (*KS+TS+F*) was chosen as the most suitable for the accurate measurements of air temperature. The silver coated shielding tube and a mini fan (test case 5, *KS+TS+F*) and silver coated thermocouples (test case 2, *KS*) were applied for measurement and control of the air temperature in the DGF and also in the room adjacent to the DGF in the test facility at the Aalborg University. Readings from the sensors with the shielding technique from the test case 5 and test case 2 are compared in Figure 4, results are remarkable, as according to one sensor the air temperature kept by ventilation system was relatively constant (shielding approach of test case 5), while another temperature sensor (shielding approach of test case 2) shows a swing in the periods with the direct solar access to the sensors.

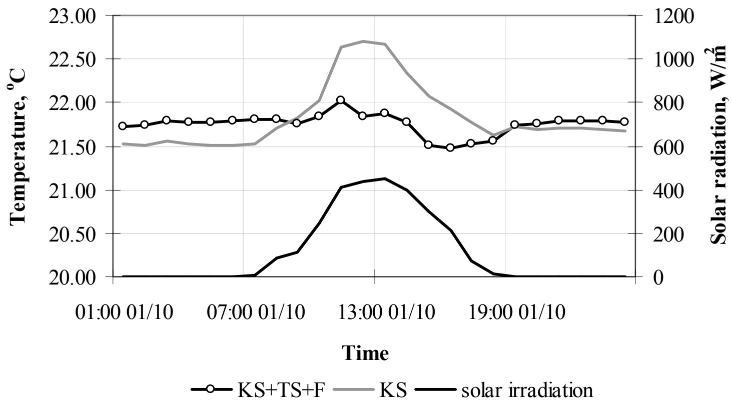



Figure 4. Results of application shielding technique from test case 2 and 5.

**Experimental results from Politecnico di Torino**
Experiments were performed in various days with different weather conditions. The day with the highest measured irradiance and with the clearest sky conditions was considered as the most representative and used for the analysis of data. The experiment lasted about 5 hours, from 13:05 to 18:05, and the measured global vertical irradiance is shown in Figure 5.

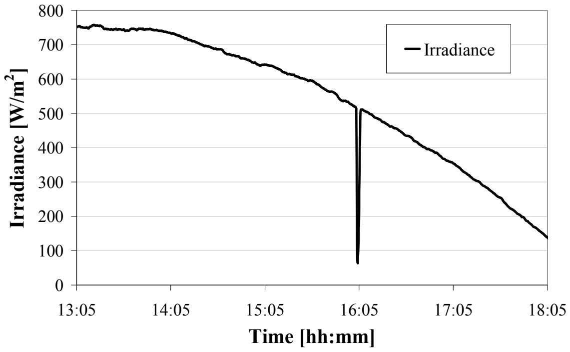
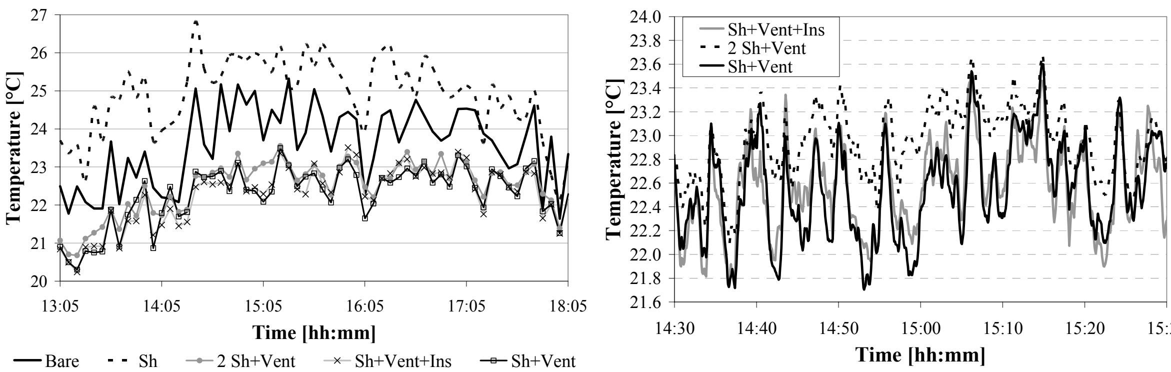



Figure 5. Global vertical irradiance measured during the experiment.

The reliability of each sensor was evaluated in terms of mean measured temperature value and of standard deviation. The thermocouple with the minimum mean temperature and the minimum standard deviation was considered the less affected by solar radiation, and thus the most reliable one. Temperature values measured by the 5 thermocouple and reported as 5 minutes average values, are shown in Figure 6-a. The bare thermocouple *(Bare)* shows higher temperatures (mean value 23.43°C) with big fluctuation. Shading the sensor with a simple pipe *(Sh)* doesn't improve its performance: even if the junction is not heated by direct solar radiation, convective and radiative fluxes due to the overheated pipe result in even higher temperature values (mean value 24.73°C) and fluctuations of amplitude comparable to the bare one. Remarkable improvements can be observed when ventilation (with relatively high air speed: 3.8 m/s) is used. All the three ventilated solutions present lower temperature values and fluctuations. Compared to the bare and to the simply shielded thermocouples, the three ventilated ones show almost the identical behavior.




a) b)

Figure 6. a) Measured air temperature for the 5 tested solutions, reported as 5 minutes average values. b) Measured air temperature for the ventilated thermocouples.

Adding an internal or an external layer to reduce the radiative flux doesn't seem to be beneficial (Figure 6-b). The solution with the internal fabric layer *(Sh+Vent+Ins)* shows temperatures very close to the simply ventilated one (same mean temperature: 22.21°C) with slightly higher fluctuations (STD is 0.77°C vs. 0.72°C). Hence, considering problems related to the fabric layer maintenance as well, the simply shielded and ventilated thermocouple

*(Sh+Vent)* is preferable. Finally, the double shielded and ventilated solution *(2 Sh+Vent)* is less efficient than the simply ventilated one. The double shielded sensor is slightly more stable (STD is 0.71°C vs. 0.72°C) but the mean temperature is higher: 22.43°C (compared to 22.21°C), as shown in Table 3. This is probably due to the additional thermal mass of the external shield and to the lack of ventilation in the cavity between the two shields.

Therefore, if a relatively high speed ventilation strategy is adopted, and thus if the convective coefficient between the thermocouple and ventilation air is high enough, then further reduction of long-wave radiation by means of addictional shielding layers doesn't lead to significant improvements.

Table 3. Mean measured air temperature and standard deviation.

| Test case | Bare | Sh | Sh+Vent | Sh+Vent+Ins | 2 Sh+Vent |
|---|---|---|---|---|---|
| Mean meas. Temperature [°C] | 23.43 | 24.73 | 22.21 | 22.21 | 22.43 |
| STD [°C] | 1.06 | 1.09 | 0.72 | 0.77 | 0.71 |

On the basis of the investigations carried out, the shielded and ventilated thermocouple *(Sh+Vent)* was chosen as the most reliable one and finally used for the measurements in the test facility at the Politecnico di Torino.

**Cross-test**

The two best performing techniques, one from Politecnico di Torino and another one from Aalborg University, were tested together.

The tested techniques were:

- Silver coated thermocouple type K, shielded by a silver coated tube and ventilated by a minifan (Aalborg University)
- Type J armoured thermocouple, shielded by a chromium-plated brass pipe and ventilated by a DC axial centrifugal ventilator (Politecnico di Torino)

The duration of the experiment was 09:00-17:00, and the experimental setup was under the direct solar radiation from 10:00 to 16:00, this is the period used for the statistical analysis of the experimental data.

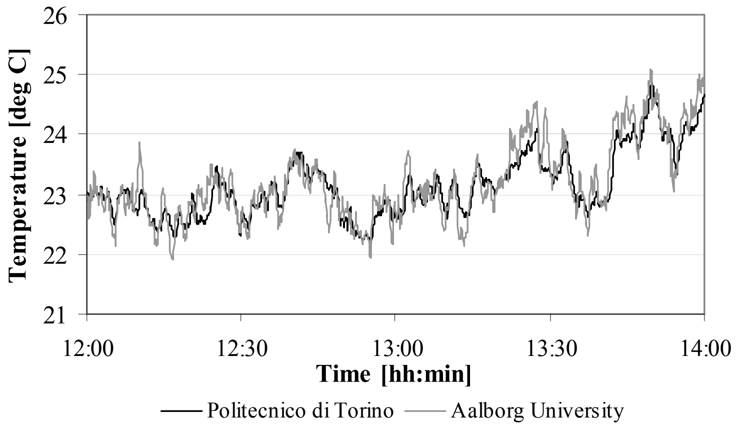



Figure 7. Air temperature measured with the ventilated sensors developed at Politecnico di Torino and Aalborg University.

The experiment shows a good correspondence of the results obtained with the two probes (Table 4 and Figure 7). In the presence of direct solar radiation the difference among mean temperatures is 0.09°C, the mean absolute difference is 0.28°C. Aalborg University thermocouple provides a slightly lower mean temperature (22.50°C vs. 22.59°C); Politecnico di Torino one seems to be more stable and less fluctuating (STD 1.62°C vs. 1.80°C) probably because of the speed of ventilation air.

Table 4. Statistical analysis of the experimental data from the cross-test

| Shielding technique | Mean meas. temperature [°C] | STD [°C] | Min absolute difference [°C] | Mean absolute difference [°C] | Max absolute difference [°C] |
|---|---|---|---|---|---|
| Politecnico di Torino | 22.59 | 1.62 | 0.00 | 0.28 | 1.90 |
| Aalborg University | 22.50 | 1.80 | | | |

## CONCLUSIONS

Different techniques for measuring air temperature under solar radiation are compared in this article. Bare or shaded and naturally ventilated thermocouples are unsuitable to obtain reliable measurements and a mechanically ventilated shielding pipe was chosen by both research groups. Nevertheless, the solutions adopted to avoid the common problem of the overheated shield are based on different approaches.

In Politecnico di Torino solution the main strategy is based on a higher air speed in a shielding tube (3.8 m/s) to increase the convective coefficient and, thus, to limit the radiative heat flux affecting the sensor. No specific devices to further reduce long-wave radiation are adopted.

Aalborg University thermocouple presents a combination of techniques to improve convection, using a mini-fan producing a lower speed air flow (1.5 m/s), and to further limit affecting radiation, using a silver coated tube and a silver coated thermocouple.

The combined radiative-convective approach (Aalborg University solution) provides a slightly lower mean temperature (22.50°C vs. 22.59°C); the high ventilation approach (Politecnico di Torino) seems to be more stable and less fluctuating (STD 1.62°C vs. 1.80°C).

The long-wave heat flux affecting the finally measured air temperature is reduced in both of the techniques leading to very similar results. In Aalborg University approach, the effect of radiation heat flux is reduced both directly, reducing the radiative exchange by means of coatings, and indirectly, increasing convection by means of ventilation. Politecnico di Torino approach, adopting a higher air ventilation speed, is better to increase the convective coefficient and is thus mainly focused on an indirect reduction of radiation. It is reasonable that different weights of the direct and indirect reduction of long-wave heat flux in the two solutions compensate each other and both of the techniques lead to the similar outcome.

Experimental results described in this paper demonstrate the need and possibility for improvement of the air temperature measurements in the direct solar access. It is shown that although some results are available and can be implemented in practice, there is still a need for further investigations. Following investigations are suggested for future testing of protective techniques:

- Test of various ventilation flows in the protective shields in order to estimate influence of the convective coefficient
- Test of various coating materials
- Test of various dimensions of the protective shields
- Test of a thermocouple protected from the solar access by a tube with a perforated top and bottom shielding to avoid radiation component from the sky and ground reflection
- Test of very thin thermocouples in comparison with already tested ones in order to evaluate reduction of radiative heat exchange due to the small area of sensor.

In the meantime both of the described techniques are implemented and prove to be a better solution than a bare or a naturally ventilated thermocouple when measuring air temperature in the direct solar access.

## ACKNOWLEDGEMENT

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