COOL FLUOROCARBON COATINGS IN INDUSTRIAL BUILDINGS: OPTICAL PROPERTIES AND ENERGY PERFORMANCE

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ABSTRACT

Rejection of solar gains is the aim of passive cooling strategies in any type of building and any climatic region. The extent of cool materials usefulness is dependent on the severity of external conditions and internal heat gains. The aim of the present paper is to underline the contribution of an innovative cool fluorocarbon coating in the reduction of energy demand for cooling in an industrial building with increased heat gains under temperate climatic conditions. The material is tested using accelerated weathering procedures and its optical properties, i.e. solar reflectance and infrared emmitance are measured. There is an increase of 120% of the roof's albedo by the application of cool material. Regarding the heating and cooling loads there was a decrease of 73% for cooling while there was a minor heating penalty of 5%.

Keywords: cool materials, industrial building, temperate climatic conditions, energy efficiency, reduction of cooling load

1 INTRODUCTION AND STATE OF THE ART

Rejection of solar gains is the aim of passive cooling strategies in any type of building and any climatic region. The extent of cool materials usefulness is dependent on the severity of external conditions and internal heat gains (Kolokotroni & Kolokotsa, 2013). Cool materials work by reflecting solar radiation and therefore rejecting solar heat gains at the opaque external surfaces of the building (Synnefa, Santamouris, & Apostolakis, 2007; Synnefa, Santamouris, & Livada, 2006). Heat transfer to the internal space by conduction is therefore reduced while the magnitude of the reduction will be determined mainly by the solar radiation intensity, the temperature difference between inside and outside as well as the constructional characteristics of the roof.

Climates with high solar radiation are usually associated with high external air temperatures in the summer and mild temperatures in winter. In buildings of such climates rejection of heat gains is essential to maintain comfortable conditions inside the building or the use of high quantities of air conditioning for cooling. The effect of cool materials in hot climatic conditions are studied by various researchers (H Akbari, Damon Matthews, & Seto, 2012; Boixo, Diaz-Vicente, Colmenar, & Castro, 2012; Kolokotsa, Diakaki, Papantoniou, &

Vlissidis, 2011; Romeo & Zinzi, 2011; Rose, Akbari, & Taha, 2003; Synnefa, Saliari, & Santamouris, 2012). In most cases a reduction of the cooling load varying from 20-40% is revealed by the application of cool roofs while a considerable indoor comfort improvement is noticed. Although cool materials are considered a reliable solution for hot climatic conditions, they can be a feasible solution in temperate climatic conditions, i.e. low solar radiation, moderate air temperatures in the summer and cold temperatures during the winter. In buildings of such climates, rejection of heat gains should be considered carefully because they can be useful to reduce heating requirements. On the other hand depending on the use of the building internal heat gains might be so high that air conditioning may be required throughout the year. Recent developments in materials' technology provide extra functionalities leading to the term of smart materials that provide a desired response to external stimulus, such as temperature, light, humidity, etc. Innovative materials for buildings and outdoor spaces have been developed and tested (Fufa, Hovde, Talev, & Jelle, 2010; Gustavsen, Grynninga, Arasteh, Jelle, & Goudey, 2011; Karlessi, Santamouris, Apostolakis, Synnefa, & Livada, 2009; Kolokotsa et al., 2012; Santamouris, Synnefa, Kolokotsa, Dimitriou, & Apostolakis, 2008; Syneffa, Dandou, Santamouris, Tombrou, & Soulakellis, 2008). Their durability, ageing features, UV degradation, and contribution to energy efficiency impact are still under investigation. Such materials include innovative cool coatings, phase change materials, chromotropic and photocatalytic coatings with self-cleaning functionalities, nano-composites etc. Innovative materials will have a significant impact on the built environment in the near future and their effects should be sufficiently well understood in the context of energy conservation and environmental impact.

To this end the aim of the present paper is to underline the contribution of an innovative cool fluorocarbon coating in the reduction of energy demand for cooling in an industrial building with increased heat gains under temperate climatic conditions. The material is tested using accelerated weathering procedures and its optical properties, i.e. solar reflectance and infrared emmitance are measured. The coating is then applied in an industrial building situated in the Netherlands where its contribution to the reduction of energy demand is assessed.

2 MATERIALS AND METHODS

2.1 Technical specifications of the coatings

The studied coating is a tetrafluoroethylene monomer fluorocarbon coating in a water-borne (FC coating) formula which is applied on a cement tile (7x7cm) and on an aluminum substrate (10x10cm). Each substrate was coated at a thickness of approximately 110μm.

This study includes for each sample:

- Spectral reflectance measurements over the spectrum 300-2500nm (UV-VIS-NIR)
- Calculation of the Solar Reflectance (%)
- Calculation of the Solar Reflectance Index (SRI)
- Measurement of the infrared emittance
- Calculation of maximum surface temperature
- Accelerated ageing of the samples in an Accelerated Ageing Xenon Test Chamber.

2.2 Accelerated weathering

Accelerated ageing of the concrete substrate sample (S4, cement tile) was performed in an Accelerated Ageing Xenon Test Chamber (Q-SUN, Xe-3HS) for a 60days period in a 24 hours basis according to the specifications and requirements of ISO 11341 (ISO, 2004).

With a nominal cut-on of 295 nm, the daylight filter used, provides the most accurate spectral match with direct sunlight. The filter is recommended for the best correlation between the accelerated ageing test chamber and natural outdoor exposures and conforms to the spectral requirements of ISO 4892, ISO 11341, ASTM G155, SAE J1960 and SAE J2527.

The test chamber is equipped with a precision light control system which allows the choice of the desired level of irradiance. Irradiance is monitored and controlled at 340nm.

Temperature monitoring and control is performed by a black panel temperature sensor which controls the specimen's surface temperature and simultaneously by the chamber air temperature control to give the ultimate determination of the specimen temperature. The effects of outdoor moisture are simulated by direct, pure water spray and by relative humidity control. The samples before and after weathering are depicted in Figure 1.

Figure 1 The samples before and after accelerated weathering

2.3 Solar reflectance

The spectral reflectance of the sample is measured in the range of 300-2500nm. The measurements for the solar spectral reflectance are conducted according to the ASTM Standard E903-96 (ASTM, 1996). The results from the spectrophotometric measurements for the specific sample before (black line) and after (red line) the artificial aging is shown in Figure 2.

The spectral reflectance data are used in order to calculate the solar reflectance of the samples. The term solar reflectance (SR) designates the total reflectance of a surface, considering the hemispherical reflectance of radiation, integrated over the solar spectrum, including specular and diffuse reflection. The calculation is done by the weighted averaging method, using a standard solar spectrum as the weighting function. The spectrum employed is that suggested by ASTM standards (ASTM, 1996, 2012a). Additionally the solar reflectance in the ultraviolet (UV: 300-400nm), the visible (VIS: 400-700nm) and the near infrared (NIR: 700-2500nm) part of the electromagnetic spectrum is calculated. The calculated values of solar reflectance are shown in Table 1.

Table 1 *Calculated values of solar, UV, VIS and NIR reflectance for all the samples.*

Sample	**Description**	**SolarReflectance (SR)**	**SR_{UV} (300-400nm)**	**SR_{VIS} (400-700nm)**	**SR_{NIR} (700-2500nm)**
S4 before	FC coating	0.89	*0.0*9	0.96	0.88
S4 after	FC coating	*0.87*	0.0*7*	*0.92*	*0.88*

The solar reflectance for the tested sample is high before the accelerated aging. The sample is characterized by high reflectance values in the visible (0.94 – 0.97) and the near infrared part of the spectrum (0.87-0.88). It exhibits strong absorption (0.08-0.09) in the UV range (300-400nm). After the accelerated aging the solar reflectance values are reduced by 0.02. Reflectance values in the near infrared part of the spectrum remained almost the same.

2.4 Measurement of the infrared emittance

The infrared emittance (e) specifies how well a surface radiates energy away from itself as compared with a black body operating at the same temperature. The measurements for the infrared emittance were conducted according to the ASTM Standard E408-71 (ASTM E408-71 (2002) - Standard Test Method for Total Normal Emittance of Surfaces Using Inspection-Meter Techniques) by using the Emissometer Model AE (Devices & Services). The results of the infrared emittance measurements are presented in Table 2 . The samples have suffered from a small reduction to the infrared emmitance values.

Table 2 Infrared emmitance for the samples

Sample	**description**	**Emmisivity**
S4 before	FC coating	0.88
S4 after	FC coating	*0.87*

2.5 Calculation of the Solar Reflectance Index (SRI) and maximum surface temperature

Based on the results of the solar reflectance and infrared emittance measurements the Solar Reflectance Index of the sample is calculated. The Solar Reflectance Index (SRI) is a measure of a surfaces ability to reject solar heat, as shown by a small temperature rise. It is defined so that a standard black (reflectance 0.05, emittance 0.90) is 0 and a standard white (reflectance 0.80, emittance 0.90) is 100 (Zerlaut, 1989).

The calculation was performed according to the ASTM standard E1980-01: Standard Practice for calculating solar reflectance index of horizontal and low sloped opaque surfaces. The SRI was calculated for medium wind conditions (convective coefficient h_c=12W/m^2 K).

The calculation of the steady state maximum surface temperature is performed as well according to the ASTM standard E1980-01 (ASTM, 2001).

The results of the calculations are shown in Table 3. The samples are characterised by very high solar reflectance index values (over 100) even after the reduction of its values after the artificial aging. SRI values exceeding 100 can be explained by the way SRI is defined: the value 100 corresponds to a standard surface with a solar reflectance of 0.8 and an infrared emittance of 0.9.

Table 3 Calculated values of Solar Reflectance Index (SRI) and maximum surface temperatures for the samples.

Sample	**description**	**SRI**	**$T_{surface}$^{o}C**
S4 before	FC coating	113	39.8
S4 after	FC coating	*110*	*41.0*

3 EXPERIMENTAL PROCEDURE

The specific sample is applied in an industrial building located in Oss, Netherlands in order to perform large scale measurements. The experimental procedure is performed in two phases, i.e. before (1st Phase) and after (2nd Phase) the FC coating application on the roof. The measurements performed are: Measurement of the roof's albedo. Thermal imaging of the roof on hourly basis. Thermal imaging of the interior spaces at 8:00, 12:00 and 16:00 Measurement of indoor temperature and humidity.

The climatic characteristics of the region are temperate, marine with cool summer and mild winter. The average air temperature is 11ºC while the relative humidity is quite high throughout the year.

3.1 Description of the Building

The building located in Oss, Netherlands has a surface area of 1685 m^2 and 7.58m height. The specific dwelling houses the production unit and storage of a chemical company and is constructed in October 1997. Its characteristics are tabulated in **Error! Reference source not found.**.

Table 4. The building's constructional and operational characteristics

	Characteristics	**Value - Description**
1.	No of stories	1
2.	Thermal zones	1
3.	Total Surface	1685 m^2
4.	Building height	7.58m
5.	Wall construction	100 mm brick-50mm insulation-19mm

		gypsum board
6.	Roof Construction	8mm metal surface-50mm insulation-8mm metal surface. Sloped roof
7.	Window type	Double U=2.720 W/m2K
8.	Overall heat transfer coefficient of walls (U_{wall})	0.482 W/m^{2}K
9.	Overall heat transfer coefficient of roof (U_{roof})	0.591 W/m^{2}K
10.	Orientation of openings	North-South.
11.	Internal gains	Electric lighting: 5.4kW Electric equipment: 43kW.
12.	Infiltration rate	3000m^3/hour
13.	Set point winter	20 ˚C
14.	Set point summer	26˚C

3.2 Measurement of the roof's albedo

The building's roof is a metal one with 50 mm insulation. The roof's characteristics are tabulated in **Error! Reference source not found.**. The roof's albedo is measured using two two Kipp & Zonen pyranometers that are positioned at 1.5m above the roof surface. Their spectral range from is from 300 to 2800nm, their response time is less than 18s, non-linearity for 0-1000W/m^2 less than 1%, temperature dependence of sensitivity from -10^{o}C to 40^{o}C less than 5%. The first pyranometer measures the incident solar radiation and the second one the reflected radiation from the roof. The albedo is measured before and after the FC coating application. The ratio between the reflected radiation from the roof and the incident solar radiation is the albedo. The average albedo is 0.3 and 0.67 for the 1st and 2nd phase of measurements respectively.

3.3 Measurement of the indoor temperature and humidity

Five TinyTag Data Loggers TGP-4500 are used for the measurement of indoor temperature and humidity (Figure 2). The reading range is from -25^{o}C to 85^{o}C and the reading resolution is 0.01^{o}C.

The maximum indoor temperatures for all sensors are recorded before the installation. The highest maximum temperature during both phases is recorded by sensor 5 is equal to 39.4°C and 30.6°C for the first and second phase respectively (Table 5). This is explained by the fact that this position is very close to the production area where heat is extracted by the machinery. The indoor temperatures measurements are used for the model validation in order to assess the energy performance of the cool material in the industrial building under temperate climatic conditions.

Table 5 Maximum and minimum temperatures for all sensors during 1st and 2nd phase of the experimental procedure

Sensor no	**T(^{o}C)**	**1st Phase**		**2nd Phase**	
		24/7/2012	**25/7/2012**	**29/8/2012**	**30/8/2012**
1	T_{max}	35.8	**36.8**	29.6	27.0
	T_{min}	21.6	23.2	22.9	21.2
2	T_{max}	**33.8**	31.0	28.5	25.5
	T_{min}	21.5	22.4	22.0	21.0
3	T_{max}	35.5	**36.6**	28.8	26.8
	T_{min}	21.7	22.4	22.2	21.0
4	T_{max}	33.3	**34.3**	29.0	25.4

	T_{min}	21.9	22.4	22.1	21.1
5	T_{max}	38.4	***39.4***	30.6	28.9
	T_{min}	21.7	22.3	22.3	21.0

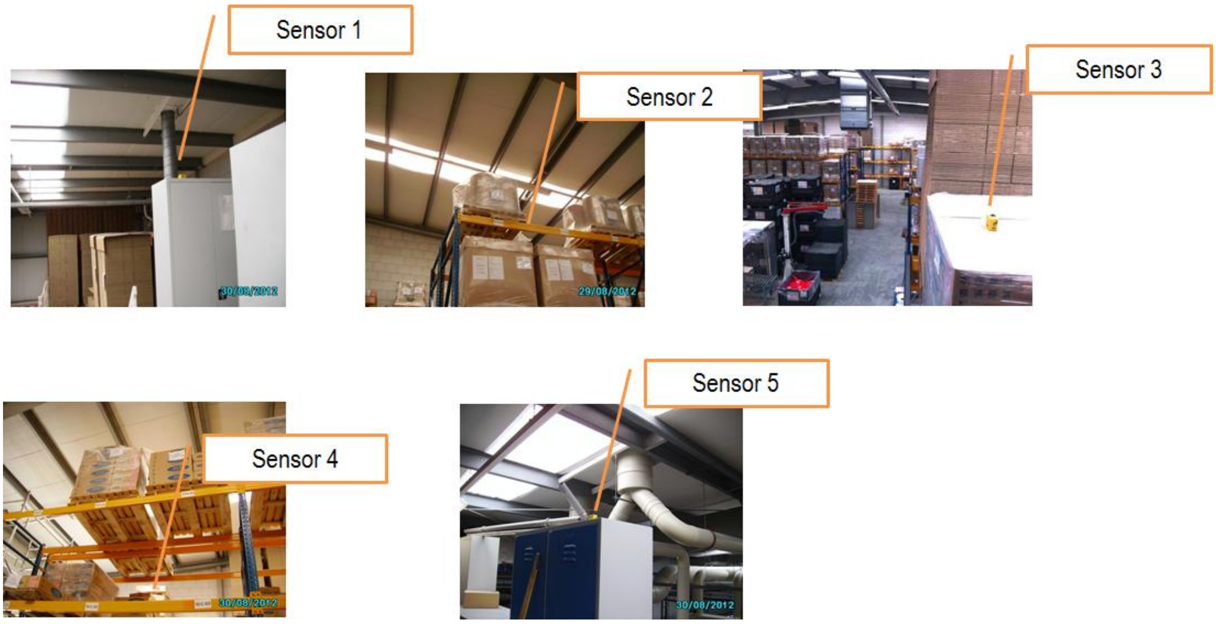

Figure 2. The temperature and humidity sensors

4 THE ENERGY PERFORMANCE OF THE COOL ROOF APPLICATION

The aim of the present analysis is to provide quantitative results on the energy efficiency that can be achieved by the application of the cool material in the specific building. The building's cooling and heating loads are calculated for the 1^{st} and 2^{nd} phase using EnergyPlus thermal load simulation program. The calculations are performed with an hourly time step. The values of the albedo measurements are inserted in the model together with the thermal properties of the materials. The solar absorptance of the actual roof material was set equal to 0.7 and 0.3 before and after the FC coating installation respectively. Regarding internal gains, the electric lighting is equal to 5.4kW while all the other electric equipment is measured equal to 43kW. Infiltration rate is set equal to $3000m^3$/hour. The first step towards the evaluation of the energy performance is to develop validated models of that are representative of the 1^{st} and 2^{nd} experimental phase. The model of building that is representative for the 1^{st} phase (before cool roof application) and its validation against the real measurements is depicted in. The specific figure illustrates the temperature variation before the application as it is derived from the measurements (red line) and from the simulation (blue line).

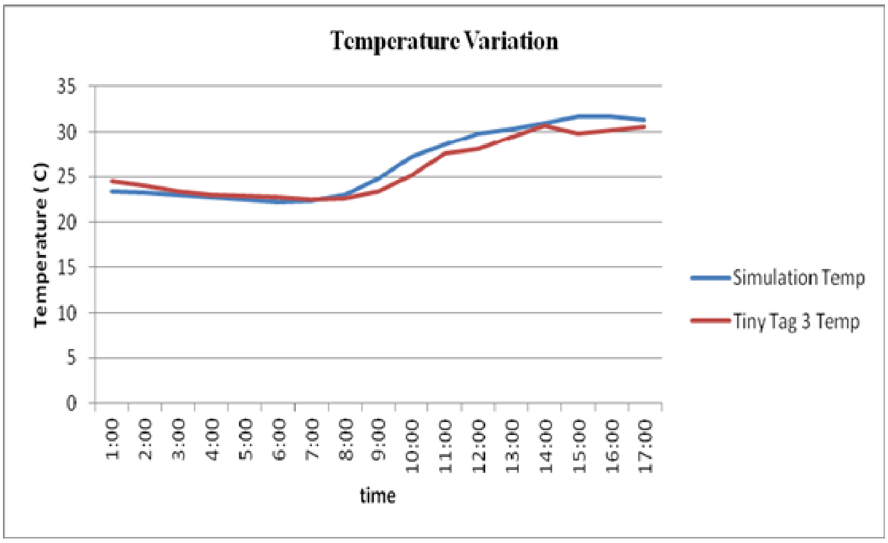

Figure 3. The measured and modeled indoor temperature fluctuation for the 24/7/2012 (1st phase)

The results indicate that before the application the indoor temperatures as calculated from the simulation vary from 22.3°C to 31.7°C while indoor temperature as recorded from sensor 3 vary from 22.4 °C to 30.7°C. After FC coating application the indoor temperature as calculated from the simulation varies from 19.4°C to 22.1°C. Maximum indoor temperature as recorded from Sensor 1 is 21.6°C and minimum indoor temperature is 20.6°C. The results show that there is a very good match between the calculated and the measured temperature values.

Furthermore, for estimating the energy demand for heating and cooling before and after the FC coating application the simulations are repeated using test reference year data on yearly basis. The thermostat set point temperatures are set equal to 26^{o}C and 21^{o}C for the summer and winter period repsectively. As expected, increasing roof reflectance results to reduced summer cooling loads.

The results indicated that before the application the annual cooling load was 9.7 kWh/m^{2}. After the application the cooling loads are equal to 2.6 kWh/m^{2}. The decrease in the cooling loads for an increase in roof solar reflectance of 0.4 was 73%. In order to estimate the heating penalty from increasing solar reflectance, heating loads are also calculated. Before the installation the annual heating loads are 139 kWh/m^{2} and after the installation the annual heating loads are calculated to be 146 kWh/m^{2}.

By transforming the energy demand into final delivered energy using Energy Efficiency Ratio of 2.6 (average system efficiency) and for heating efficiency 0.75 then the energy conservation for cooling is 18.5kWh/m2 while the heating penalty is 5.3kWh/m2.

5 CONCLUSIONS

In the present study the thermal and optical characteristics of a fluorocarbon cool material are measured. The cool material is applied in an industrial building with increased internal heat gains targeting to minimise the energy demand for cooling. The value of the roof albedo has changed from 0.3 to 0.67 after the application of the cool coating. There is an increase of 120% of the roof's albedo. Regarding the heating and cooling loads there was a decrease of 73% for cooling while there was a minor heating penalty of 5%.

The overall study showed that cool materials can be a viable solution even for temperate climatic conditions and for industrial buildings where usually there is a significant burden in the cooling load due to machineries and production lines. This can make a significant difference in the use of air conditioning especially in mid seasons.

6 ACKNOWLEDGMENTS

Herewith we are acknowledging TecneXum GmbH, Essen, Germany, and Daikin Chemical Europe, Düsseldorf, Germany, for their support and to enable us to perform these studies and to publish the results.

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