Paper No 125: Simulation-based Assessment of the Prospects of Cool Paints in the Built Environment in the UK

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Abstract
This paper presents research that uses building performance simulation to assess whether cool paints could contribute to a reduction of the cooling needs in more temperate climates, like for instance the United Kingdom. To this end, one type of commercial building (an industrial hall) and one type of domestic building (a terraced house) have been simulated using the EnergyPlus transient thermal simulation program. For these buildings, the application of cool paint has been compared with a finish in a normal coat of grey paint (industrial hall) or no paint at all (slate roof on domestic buildings). The impact of cool paint on overheating (free-running situation, showing extent and duration of overheating) as well as on cooling needed to prevent overheating (cooling energy and peak cooling load) have been examined. Results indicate that cool paints can indeed help to reduce internal temperatures and energy use, but that their application is most appropriate in simple, industrial structures. Under the current and predicted future climate for the UK cool paints do not seem of benefit to the domestic sector.

Keywords: cool paint, building simulation, peak temperature, energy use

1. Introduction

In most parts of the world the cooling of buildings is becoming increasingly important. This is caused by different trends. Building occupants demand more control over indoor air temperatures in indoor spaces, similar to the control they have in automobiles equipped with air-conditioning systems. At the same time it is believed that extremes in the climate, including summertime heat waves, are becoming more frequent. The cost of such heat waves (in terms of lost productivity, occupant health and wellbeing) is becoming more obvious with ongoing research. A major way of providing for this demand in cooling is the use of active cooling systems. However, in most cases the use of passive systems is preferable from a sustainability point of view.

One passive method to reduce the cooling demand of buildings is the use of 'cool paints' on the building exterior. These paints have a high reflectivity as well as a high emissivity. This allows such paint to prevent solar irradiation from heating up a building, while still allowing for good heat transfer away from the building to its surroundings. Cool paints have been demonstrated to significantly reduce cooling loads in buildings hot and humid climates, and are in regular use in the Southern parts of the United States. See for instance Berdahl and Bretz, 1997 [1], Parker *et al*, 2000 [2] and Wang *et al*, 2008 [3].

This research investigates the prospects of cool paints in the United Kingdom under both current and future climate condition, studying their impact on heating, cooling and thermal comfort.

Cool paints are a sub-category of cool roofing products that aim to reduce heat gain by reflecting away as much solar irradiation as possible, while at the same time having properties that allow to release any heat in the material. In scientific terms this translates to materials that have a high reflectivity (ρ) and a high emissivity (ε). There are some specific systems available like reflective tiles and shingles; however, the main products used for cool roofing are liquid applied (elastomeric) coatings, named cool paints in this paper. Cool paints sometimes have the additional function of supplementary water-proofing, and might contain additives to improve resistance to algae and fungi. However, many cool paints have only a limited lifetime of a couple of years, wearing away rather quickly. As a result cool paint needs to be frequently re-applied. Plate 1 shows a roof covered with cool paint in the Caribbean, showing degradation of the membrane on the right hand side.

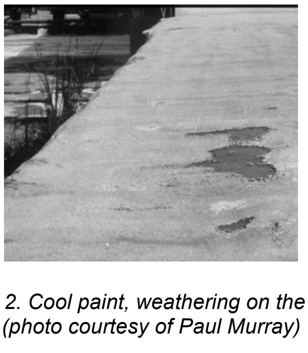

Plate 2. Cool paint, weathering on the right (photo courtesy of Paul Murray)

2. Methodology

The research described in this paper is based on transient thermal building simulation using the program EnergyPlus Version 2.1.0 Build 023 [4]. EnergyPlus is extensively validated through ASHRAE Research Project 1052; ANSI/ASHRAE Standard 140-2004 Envelope, HVAC E100-200, and HVAC E300-500 test suites; the IEA SHC Furnace BESTest; EnergyPlus HVAC Component tests; and EnergyPlus Global Heat Balance tests.

As main object of study this research focuses on an industrial hall, with and without cool paint. To study impact on the domestic sector, a regular domestic property has been studied with and without cool paint as well.

2.1 Building model and operational regimes

A model was created in EnergyPlus that represents a simple industrial hall, laid-out as a simple box with average dimensions: a width of 22.0 m, a depth of 48.0 m, and a height of 4.4 m. Three main constructive variants were developed:

- A simple hall, with a concrete floor (300 mm) and all walls and roof just consisting of profiled aluminium panels (3 mm) as is often used for sheds and industrial storage.
- A regular hall, again with a concrete floor (300 mm) but now with walls consisting of bricks (100 mm) and a roof constructed out of steel sandwich panels (steel, 3 mm; polystyrene, 30 mm; steel, 3 mm).
- An improved hall, still with a floor of concrete (300 mm) but now with both walls and roof made from aluminium sandwich panels (aluminium, 3 mm; polystyrene, 30 mm; aluminium, 3 mm).

In terms of building use, three scenarios have been simulated:

- A 'low loading' scenario, which combines a low load for electrical lighting (2.5 W/m^2), a low internal load (10 W/m^2) and a relatively low ventilation rate (1.0 ACH).
- A 'normal loading' scenario, which combines a average load for electrical lighting (5.0 W/m^2), a normal internal load (20 W/m^2) and an average ventilation rate (1.5 ACH).
- A 'high loading' scenario, which combines a high load for electrical lighting (10 W/m^2), a high internal load (40 W/m^2) and a relatively high ventilation rate (2.0 ACH).

The hall has been equipped with an 'idealized' HVAC system, using the 'purchased air' option within EnergyPlus; this allows to inject or extract unlimited amounts of energy from the building in order to guarantee that the climate meets specified set point values, without running into boundaries resulting from the physical sizing of actual equipment. Again, three variants have been studied:

- A free running situation, where there is neither heating nor cooling; this allows to assess to study overheating and undercooling of the building in reaction to the internal loads, ventilation and external climate.
- A cold climate regime, where the temperature is kept within a bandwidth of 3°C - 5°C, as would be the case in a typical warehouse used for the storage of food, flowers etc.
- A normal climate regime, where the temperature is kept within a bandwidth of 16°C - 22°C, as would be the case in a typical warehouse with non-perishable stock, or a factory.

To study the prospects of cool paint on the domestic sector, cool paint has been applied to a pre-existing model of a typical terraced house in the UK, consisting of a ground floor, first floor and attic. This model has been described in other papers by Y *et al*, 2008 [5].

Buildings have been simulated under three climate conditions:

1. Miami, FL, USA (a standard southern USA city, where cool paints are currently used)
2. Birmingham, UK (a current, average British climate to which many industrial buildings in the Midlands are subjected)
3. Rome, Italy (a climate which can be substituted for future British climate conditions to represent the potential impact of climate change on the UK, according to Gaterell and McEvoy, 2005 [6].)

2.1 Modelling of Cool Paint

In order to model cool paint within EnergyPlus the specific reflectivity (ρ) and a emissivity (ε) need to be represented in the input file. This is achieved by modifying the following material properties:

- Absorptance: thermal
- Absorptance: solar
- Absorptance: visible

in which the first parameter is used to calculate radiant exchange between various surfaces, the second to define the fraction of incoming solar radiation absorbed by the material, and the third to define the fraction of incoming visible radiation absorbed by the material [4].
Accordingly, 'absorptance: thermal' is equal to emissivity (ε), applying Kirchhoff's law, while solar and visible absorptance (α) can be calculated as $\alpha = 1 - \rho$. The values in table 1 have been used to represent different surface finishes in the simulation work. As a reference situation, all halls have been assumed to have a standard external finish which consists of a coat of a light colour, either grey or green, which can be replaced by cool paint. Inside the building EnergyPlus default values are used.

Table 1: absorptance values used to model different coatings

	Thermal	solar	visible
E+ default	0.9	0.7	0.7
Light colour, (grey/green)	0.9	0.3	0.3
Cool paint	0.999	0.1	0.1

Apart from the modelling of the specific reflectivity and emissivity of cool paint, one might also need to consider whether the cool paint needs to be represented as an additional material layer in EnergyPlus models. When newly applied a cool paint coating can have a substantial thickness, especially when multiple layers have been specified. However, the cool paint membrane often weathers and wears away quickly, reducing the layer thickness. To deal with this, two variants of cool paint have been considered: a worst case variant, where the only difference between normal coating and cool paint is the change between absorptances as represented in table 1, and a best case scenario, where the cool paint is actually modelled as an additional construction layer. For that additional layer, a thickness of 1.0 mm has been assumed, together with a density of 720 kg/m^3, a thermal conductivity of 0.13 W/mK, and a specific heat capacity of 1000 J/kgK.

3. Results

3.1 Reflectivity and emissivity only

The temperature series over a full year, for a simple hall under Birmingham climate conditions without any HVAC system, are presented in figure 1. Over the year, the external temperature fluctuates between -7.2^{o}C and 30.1^{o}C. In a building finished with a normal, grey coat of paint the temperature varies between 1.4^{o}C and 34.7 ^{o}C; if the building is finished with cool paint it varies between 1.4 ^{o}C and 31.8 ^{o}C. In other words, the use of cool paint reduces the maximum summer peak temperature with 2.9^{o}C.

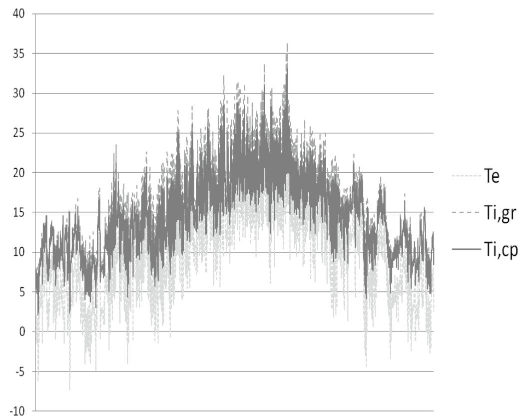

Fig 1. Temperature series, simple hall, Birmingham UK, over a full year
Te: external temperature
Ti, gr: finish: a grey coat of paint
Ti, cp: finish: cool paint

The impact of the use of normal grey paint or cool paint on a warm summer day, for the same hall in the same Birmingham climate, is shown in figure 2. Again, the impact of the use of cool paint is a reduction of the peak temperature of about three degrees.

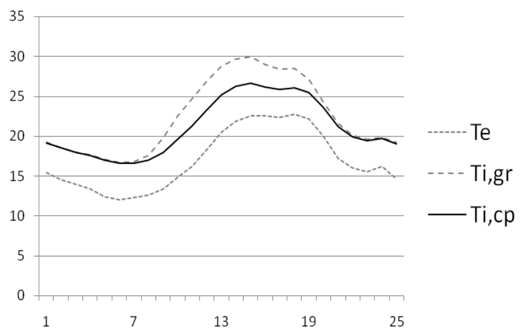

Fig 2. Temperature series, simple hall, Birmingham UK, over a single summer day (15 August)
Te: external temperature
Ti, gr: finish: a grey coat of paint
Ti, cp: finish: cool paint

A comparison with the impact under different climate regimes (Miami, USA, and Rome, Italy representing a potential future UK climate) is presented in table 2. From table 2 it can be seen that the application of cool paint in Miami currently reduces the peak temperature with 3.3^{o}C, while under Rome conditions the reduction would be 3.4 ^{o}C.

Table 2: minimum and maximum temperatures outside and inside a simple hall within one year for the climates of Miami, Birmingham and Rome, for a simple hall with grey and cool paint finish

	Te (^{o}C)	Ti,gr (^{o}C)	Ti,cp (^{o}C)
Miami, USA	05.2 - 35.4	10.9 - 41.3	10.8 - 38.0
B'ham, UK (current UK)	-7.2 - 30.1	01.4 - 34.7	01.4 - 34.8
Rome, Italy (future UK?)	-4.0 - 31.5	03.2 - 38.1	03.1 - 34.7

The impact of the use of cool paint on heating and cooling energy needed to maintain temperature in a normal range (16^{o}C to 22^{o}C) on the basis of a normal, average internal heat load in a simple hall is depicted in figure 3.

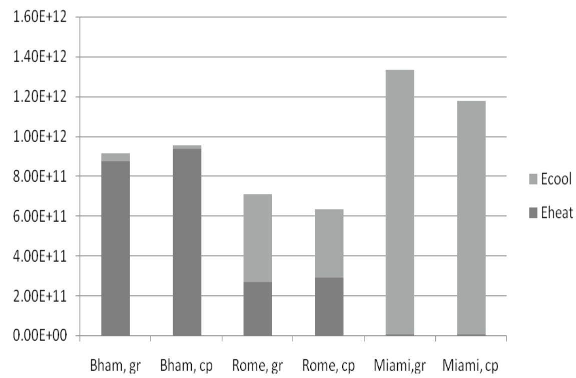

Fig 3. Heating and cooling energy per year (J) for a simple hall in Birmingham, Rome and Miami climates, with grey paint or cool paint on the exterior.

Note that in the current UK climate heating energy is dominant, and the impact of cool paint on overall energy consumption is negative through its impact on heating requirements. If the climate where to change to one similar to Rome, cooling becomes slightly dominant, and the use of cool paint would lower overall energy use for the simple hall.

The impact of the use of cool paint on heating and cooling energy needed to maintain temperature in a normal range in a regular hall, with brick walls and sandwich panel roof, is depicted in figure 4. Clearly the regular hall has a much better insulation of walls and roof, reducing overall energy consumption in the current UK climate with almost a factor three. However, the impact of application of white paint still results in a negative effect, albeit only small (2%). Again, the use of cool paint in a Rome-like climate or in Miami conditions does result in overall energy savings, in this case of approximately 3%.

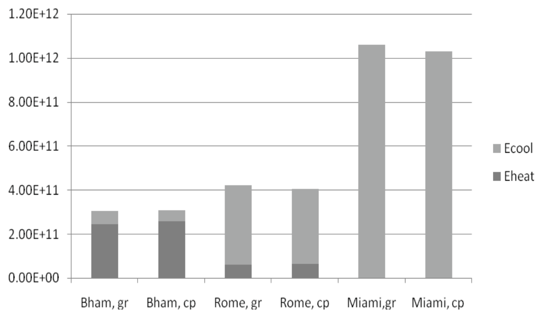

Fig 4. Heating and cooling energy per year (J) for a regular hall in Birmingham, Rome and Miami climates, with grey paint or cool paint on the exterior.

The impact of the use of cool paint on heating and cooling energy needed to maintain temperature in a normal range in an improved hall, with insulated sandwich panels for both walls and roof, is depicted in figure 5.

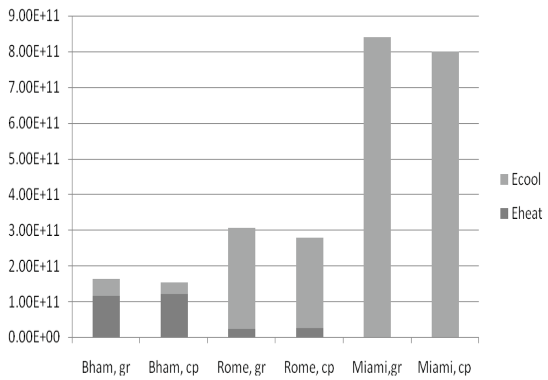

Fig 5. Heating and cooling energy per year (J) for an improved hall in Birmingham, Rome and Miami climates, with grey paint or cool paint on the exterior.

Again, overall energy use is lowered in comparison with the simple hall, in this case with almost a factor six. As the heating fraction is further reduced, the penalty of applying cool paint to the outside and hence reducing solar gain is further diminished, resulting in cool paint helping to now reduce overall energy usage in the current UK climate (order of 5%), with continued trends for the climate of Rome (reduction of 9%) and Miami (5%).

More complexity is introduced into results if one considers the different types of halls (simple, regular or improved), different uses resulting in different temperature control settings (cold storage of 3°C-5°C, or a normal regime of 16°C-22°C), and different internal heat loads. Out of this range two different sets of results are presented in this paper: a regular hall used in a cold temperature range (figure 6), and an improved hall used in a normal temperature regime (figure 7).

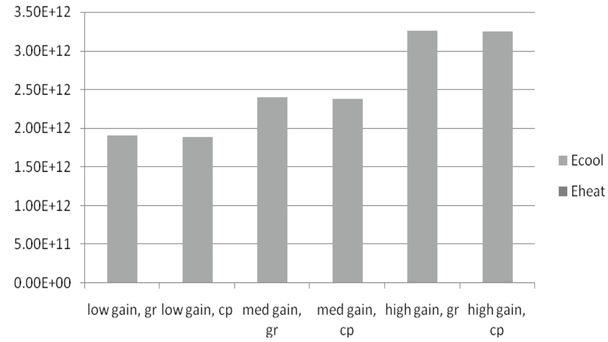

Fig 6. Heating and cooling energy per year (J) for a regular hall in Birmingham used at low settings with a low, medium and high internal gain, with grey paint (gr) or cool paint (cp) on the exterior.

The results in figure 6 show a situation that is dominated by cooling loads. Cool paint does reduce the energy demands per year, but only in the order of 1 percent, as the effect is tempered by cool paint being applied to the outside of the insulated sandwich panel roof.

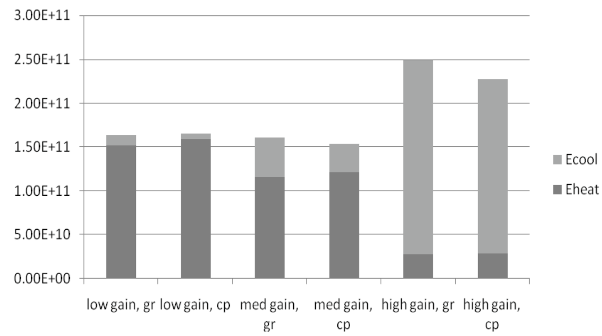

Fig 7. Heating and cooling energy per year (J) for an improved hall in Birmingham used at a normal temperature with a low, medium and high internal gain, with grey paint (gr) or cool paint (cp) on the exterior.

The results in figure 7 are a good summary of the impact of reflectivity and emissivity properties of cool paint: while the coating reduces the energy use for cooling, it might carry a penalty in terms of heating energy used. Whether cool paint reduces the overall energy use is therefore very dependent on the relation between heating and cooling demands; where heating dominates the overall effect might be negative; where cooling dominates it can have a positive contribution.

The impact of applying cool paint to the roof of domestic properties is represented in table 3. In line with the observations for the industrial hall, cool paint does not help to reduce the overall energy load of a house when the heating load is dominant, as is the case in the current UK climate. In a climate like that of Rome, Italy, the relation between heating and cooling load is still such that cool paint does not contribute to lowering energy needs. Note that the climate of Rome can be used to represent a significant warming up of the UK climate. In an even warmer climate, as represented by Miami, USA, cooling loads do become dominant and the use of cool paint significantly reduces overall energy use.

Table 3: impact of applying cool paint to the roof a domestic dwelling on energy use for heating and cooling for the three different climates.

		Eheat (J)	Ecool (J)
B'ham, UK	normal	2.22E+10	9.73E+06
(current UK)	cool paint	2.29E+10	2.32E+06
Rome, Italy	normal	8.45E+09	1.28E+09
(future UK?)	cool paint	8.98E+09	1.18E+09
Miami, USA	normal	6.59E+07	1.43E+10
	cool paint	8.84E+07	1.29E+10

3.2 Reflectivity and emissivity plus layer properties

The same series of simulations was repeated for EnergyPlus models that not only take into account the reflectivity and emissivity properties of cool paint, but also the properties of adding a thin layer of 1 mm.

Table 4 compares the impact of modelling the layer for a free running simple hall, without HVAC, in the three different climates. It can be seen that the inclusion of the paint slightly improves the insulation of the hall, thereby resulting in a slightly higher minimal temperature. A similar effect can be observed in reducing the peak temperature.

Table 4: minimum and maximum temperatures outside and inside a simple hall within one year for the climates of Miami, Birmingham and Rome, for a simple hall with grey and cool paint finish.
Ti,cp: cool paint modelled just by reflectivity/emissivity
Ti,cpL: cool paint modelled by including a 1mm layer

	Ti,gr (°C)	Ti,cp (°C)	Ti,cpL (°C)
Miami, USA	10.9 - 41.3	10.8 - 38.0	11.0 - 37.9
B'ham, UK (current UK)	01.4 - 34.7	01.4 - 34.8	02.3 - 33.1
Rome, Italy (future UK?)	03.2 - 38.1	03.1 - 34.7	03.3 - 34.6

The impact of modelling cool paint as just reflectivity and emissivity, or as reflectivity and emissivity as well as a small additional layer on overall heating and cooling energy is exemplified in figure 7, which compares the impact on simple hall in the different climates.

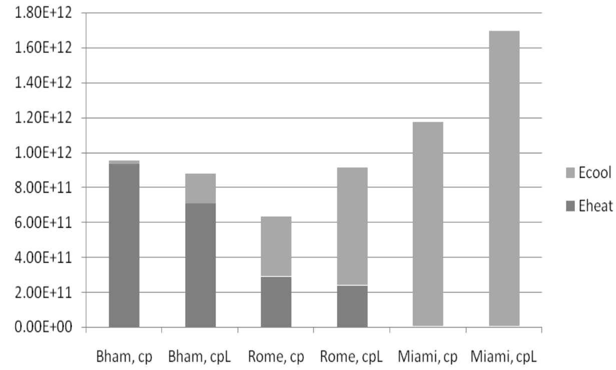

Fig 7. Heating and cooling energy per year (J) for a simple hall, for modelling cool paint as just reflectivity and emissivity (cp) or including a layer (cpL).

As can be seen the inclusion of the additional insulating layer (with the reflectivity and emissivity properties of the cool paint) in the model of a simple hall reduces overall energy use in cases where the heating load is dominant, however the effect is negative where cooling dominates. The same impact has been found by simulating the regular and improved halls; for these halls, that are better insulated, the cooling load becomes more dominant.

4. Conclusions and Remarks

This paper discusses a study for the quantification of the impact of application of cool paint on the internal temperature of buildings, and on heating and cooling energy demands. It demonstrates how cool paint can be modelled within the EnergyPlus thermal simulation tool using two main approaches: by modelling of reflectivity and emissivity properties, and by modelling reflectivity, emissivity and paint as a thermal layer. The effect of modelling cool paint as a layer has a slight impact on computational findings; depending on the situation the additional insulation layer can be of use (lower heating energy demand) or disadvantageous (making it harder to dissipate heat).

The thermal simulations described in this paper demonstrate that cool paint can indeed help to reduce the peak temperatures occurring in a free running building, or to reduce energy demands in a climatized building. However, the net effect of using this material is dependent on the specific situation. Factors to be taken into account are the following:

- In constructions where the building shell has low insulating properties, the use of cool paint might reduce solar gains. If this coincides with buildings where the heating load is dominant (like the simple hall in the current UK climate), the aditional energy use for heating might offset any benefits in reducing the cooling load.

- In cases where the cooling load is dominant the application of cool paint mostly will lead to a reduction of overall energy use. However, if the building shell has a reasonable insulation quality the impact might be rather small, only in the order of a few percents.

Translating this into the context of the prospects of applying cool paint in the UK, it appears that under current climate conditions this can indeed have benefits, but only in buildings where the cooling load is already dominant, or where the shell has such low insulating properties that the additional layer of paint helps to reduce heating loads.

As a general trend, climate change studies predict warmer conditions for the UK. If that is indeed the case, cooling loads will increase, and application of cool paint will make sense in more instances.

The study of a terraced house under both current UK climate conditions (Birmingham) and approximate future conditions (simulated by applying the current climate conditions for Rome, Italy) seem to indicate that cool paint will not really be of much benefit to adapt the domestic sector to climate change predicted for the UK.

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