Étude expérimentale pour évaluer l'effet des propriétés radiatives des revêtements sur la température d'une ruche Dadant

Experimental study to assess the effect of coatings radiative properties on the temperature of a Dadant hive

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Résumé –Les ruches échangent de l'énergie avec leur environnement essentiellement via la convection, le rayonnement solaire et le rayonnement infrarouge. En été, le rayonnement solaire peut être assez fort pour affecter l'activité des abeilles. Afin de protéger la ruche des fortes températures, l'effet de différents revêtements sur la température d'une ruche Dadant est étudié. L'absorptivité normale spectrale de ces revêtements est déterminée à l'aide de sphères intégrantes et un modèle thermique du toit de la ruche est développé pour relier ces données spectrales aux températures mesurées.

Abstract – Beehives exchange energy with their environment mainly via air convection, solar radiation and infrared radiation. In summer, solar radiation can have a strong effect on the colony activity. To protect the hive from extreme temperatures, the effect of several coverings on the temperature of a Dadant hive is studied. The normal spectral absorptivity of the tested paints and materials is estimated using two integrating spheres and a thermal model is developed to relate these spectral data to temperature measurements provided by instrumented beehives.

Nomenclature

$A(\lambda)$	normal spectral absorptivity
T	temperature, °C or K if precised
T_{air}	outside air temperature, °C or K
Greek symbols	
ϵ	hemispherical emissivity
θ	averaged temperature difference, °C
λ	wavelength, µm
Index and exponent	
ref	relative to reference hive
test	relative to test hive
sun	relative to visible wavelength range
ir	relative to infrared wavelength range

1. Introduction

The temperature in a beehive is the result of the bees thermoregulation activity and daily weather variations. Over the last few years and the occurrence of extreme temperature events, some beekeepers have experienced wax frames collapsing in their hives [1]. Indeed, pure bee wax melts around 65°C while in the south of France, the hive roof temperature can reach 70°C to 80°C for standard galvanized steel roof. These temperature threats also affect the normal behavior and the health of bee colonies resulting in financial losses due to mortality and reduced productivity [2]. The in-hive temperature is the result of a balance between (1) colony activities, (2) weather conditions (solar irradiance, cloud covering, air temperature, clear sky temperature, wind speed and direction), (3) close environment properties (surroundings

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objects, reliefs, ground type), (4) beehive materials and coverings, (5) beehive configuration (feeders, supers, closed/opened floor, vent holes, etc.).

The main aim of this study is to provide quantitative data of the thermal efficiency [3] and the thermal properties of some beehive coverings used by beekeepers to limit the effect of solar radiation on their hives, particularly in the case of hives exposed to direct sunlight. Section 2 presents the experimental setup. Section 3 focuses on the effect of different coatings on empty hive thermal behaviour. In section 4, the normal spectral absorptivity of the tested coatings is estimated. Finally, a thermal model of the radiative behaviour of roof coatings is being developed in section 5 on the basis of experimental measurements of roof temperature and spectral absorptivity measurements, so that the effects of coatings on roof temperature could be estimated from laboratory characterizations of radiative properties.

2. Description of the experiments

2.1. Experimental apiary

This study focuses on the commonly used Dadant beehive which is a movable-frame based hive with rectangular section. It is made of solid chestnut wood walls and a standard galvanized steel roof. Like most hives, Dadant hives are made of several parts that can be stacked up depending on the season and needs. For example, if bees are running out of space to store nectar/honey/larvae/etc., beekeepers may add a “honey supers” above the hive body. In this work, only the hive body is used in the tests (no additional part). The experimental apiary (Figure 1) is in the Cévennes region (southern France). It comprises 2 Dadant hives with bee entrances facing south. Each hive is equipped with 5 sensors: 1 temperature sensor (TC74 chip, 8 bits) glued and centered inside the roof and 4 other temperature sensors (NCT75 chip, 12 bits) located respectively (1) on the bottom side of the overframe (around 2cm below the roof), (2) at the top of the body part, (3) at the bottom of the body part and (4) below the hive (around 0.5cm below the bottom face) (Figure 2). The outside air temperature is monitored using an HIH8121 chip (14 bits) installed inside a radiative shield. The wind speed and direction are given by a Sparkfun weather sensor. Incoming sun radiation on the hive roofs is monitored using one ambient light sensor (VEML7700, 14bits, 0-10^5 Lux) pointing south and titled by 45° to limit the effect of seasonal variations of the solar elevation angle. The wavelength sensitivity window is 500-900 nm.

All sensors are based on integrated chips with a response time between 30 s and 1 min. An inter-calibration procedure was carried out to limit their biases. The acquisition system is based on an AVR microcontroller. The acquisition period is set to one minute except for the wind speed data which are acquired every 2 s and averaged over 1 min.

1.1. Experimental tests

An experimental parametric study is carried out to estimate the effect of paints on the in-hive temperatures. One hive is kept unchanged during the experiment and is therefore called the reference hive (Figure 1). The other hive, called “test hive”, underwent seven successive modifications to either the hive roofs (Figure 5.a-c) or the walls (Figure 5.d-f). In configurations (a) and (b), the roof is painted black and white respectively. In configuration (c), the roof is replaced by a multi-layer insulated roof (polymer roof + ventilated air space + 2 cm of aluminized insulation, made by BALBImax®, www.balbimax.fr).

In configuration (d), (e) and (f), the hive walls were painted with commercial aluminium-based Thermopeint® (frequently used by beekeepers), white and black paints respectively. Ideally, the walls should be painted directly, but for successive tests of different paints on

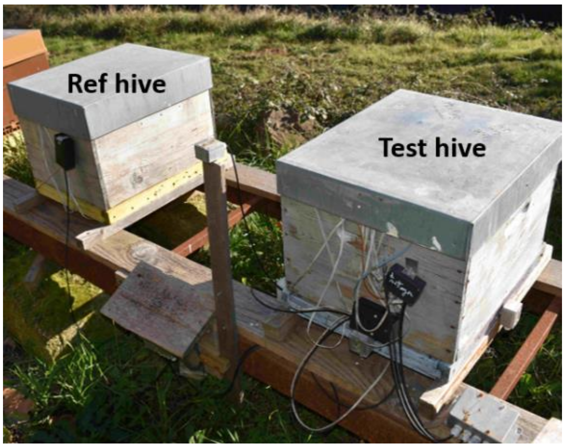


Figure 1 : *Experimental apiary with 2 instrumented Dadant hives (test hive and reference hive) and a weather station.*

Figure 2 : *Position of the 5 sensors in the two hives.*

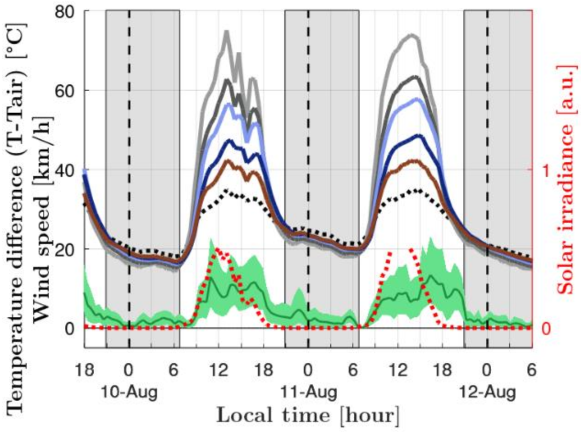


Figure 3 : *Temperatures of the reference hive with a galvanized steel roof (08/2023)*

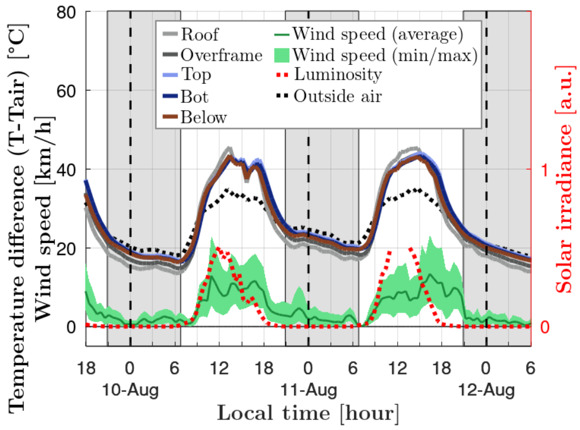


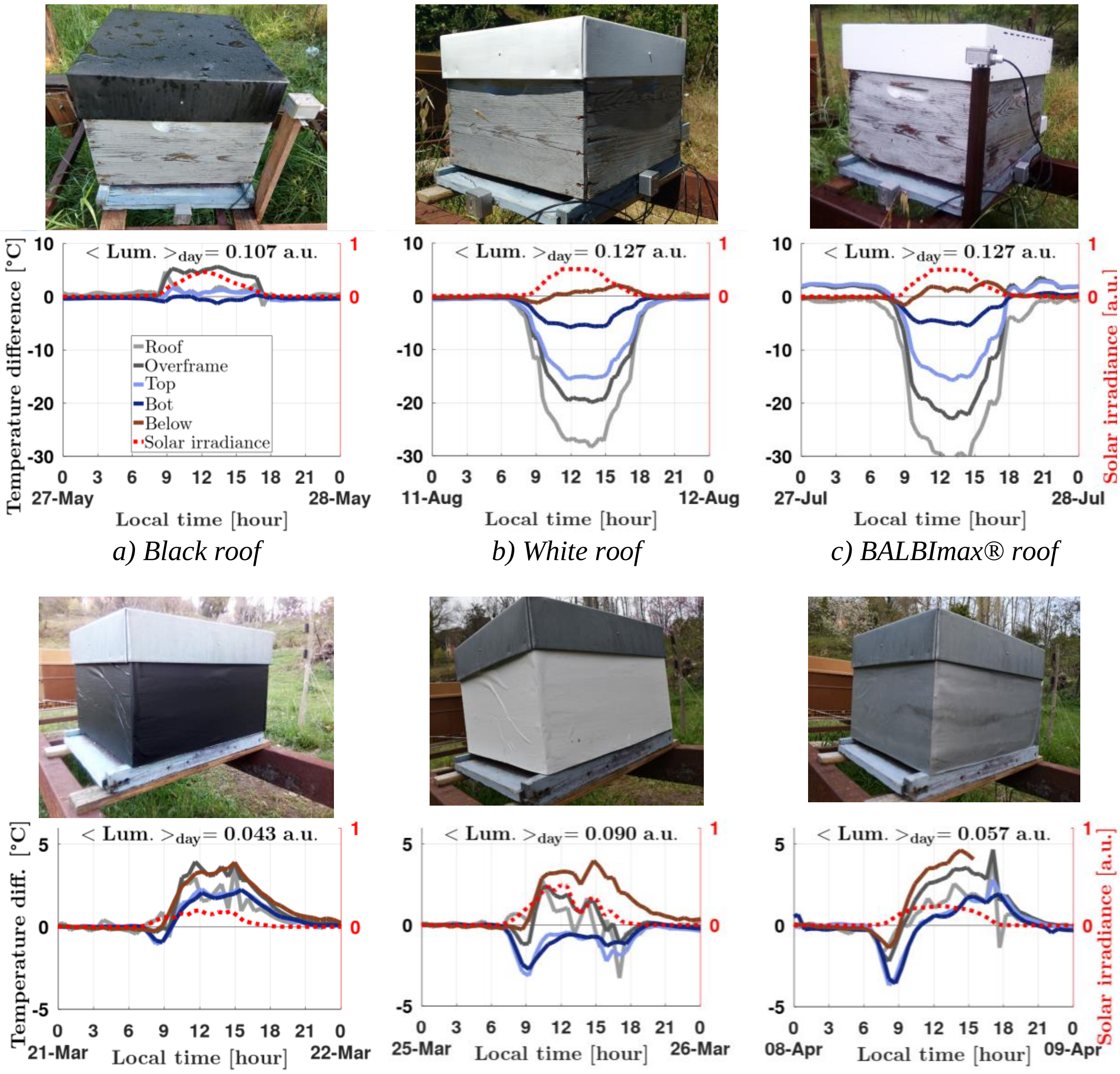
Figure 4 : *Temperatures of the test hive with a white roof (08/2023)*

the same hive, the use of a plastic film glued to the hive is essential to restore the test hive to its original state. If correctly glued, such plastic film does not alter the thermal resistance of the walls.

3. Effect of coatings on empty hive temperatures

Figure 3 and Figure 4 present the temperature evolution during two days with sunny weather for the reference and test hives in configuration (b) (white roof) and for each of the five sensors. The reference hive exhibits large temperature variations: the roof temperature exceeds $70°C$ at midday and is about $20°C$ during the night, few degrees below air temperature T_{air} due to heat radiation heat flow with the clear cold sky above the hives.

With the white paint, the roof temperature is decreased by about $27°C$ and the vertical temperature gradient inside the hive vanished. The test hive is still $10°C$ warmer than outside air during the day which results from the balance between heat radiation absorbed by the six faces and convective heat losses. To better visualize the effect of the tested coverings, the reference hive temperature T_{ref} is subtracted to the test hive temperature T_{test} for each configuration (Figure 5). The temperature difference is negative when T_{test} is lower than T_{ref}. Some data for the sensor “below” are missing due to technical issues. The solar irradiance (dotted red lines) averaged over the day denoted $< Lum. >_{day}$ is shown for each case.



a) Black roof *b) White roof* *c) BALBImax® roof*

d) Black walls *e) White walls* *f) Thermopeint® walls*

Figure 5 : *Influence of six different coverings on the hive temperature (a-c : roof ; d-f : hive walls)*

3.1 Analysis of roof coverings (Figure 5.a-c):

The black roof has nearly no effect on hive temperatures compared to the steel roof (Figure 5.a) since the temperature difference between the two hives is close to zero. As shown below in section 4 and 5, although the absorptivity of steel in the visible range is lower than black paint and should lead to a lower roof temperature, the emission of infrared radiation is lower as well. The black roof compensates the high absorptivity of solar radiations by emitting more infrared radiations. Concerning the overframe temperature, an increase of 4°C was measured. It is probably induced by slight changes of the roof geometry or of the infrared emissivity of its inner face. A different roof was indeed used to preserve our reference steel roof.

On the contrary, the white paint significantly reduces the temperature of the hive during the day (Figure 5.b): up to 27°C for the roof and about 5°C to 15°C for the hive body between 12 and 15 o'clock. The BALBImax® roof (Figure 5.c) gives similar results for the hive body. The overframe temperature dropped by $23°C$ and the roof by more than $30°C$. However, during the night, this roof induces a slight increase of a few degrees. The design of this roof and the materials used indeed reduce the heat conduction and limit the hive cooling during the night.

3.2 Analysis of hive walls paintings (Figure 5.d-f):

Painting the hive walls has little effect compared to painting the roof. The larger effect is achieved with black paint (Figure 5.d): it increases the hive temperature from 10 a.m. to 15 p.m by 2 to $4°C$. It seems small but the average irradiance on this day is $0.043\ a.u.$ which is 3 times lower than Figure 5.b-c. With a stronger solar irradiance, the black paint effect might double or triple. The white paint has a slight cooling effect from 7 a.m. to 12 p.m. (about $1°C$). No significant effect is measured with Thermopeint®. Around 9 a.m., there is temperature drop visible for the three configurations d-f. One reason may be the use of a plastic film which changes the surface finish. When the sun is "grazing" (with respect to the hive walls), more radiations may be reflected compared to untreated wood.

3.3 From empty hive to inhabited hive

In this work, hives are empty and therefore reactive to thermal changes. Their characteristic response time is about 1 to 2 hours. With an inhabited beehive, the hive's thermal capacity (which can exceed 40 kg with mostly water) dampens all variations. Depending on sensor location, it may take hours to days for a paint to have a measurable influence. It would then be difficult to separate the effect of the weather and the colony from the effect of the paint. To reduce the effect of thermal capacity, the average temperature difference $\theta = \alpha.\langle T_{test} - T_{ref}\rangle_{day}$ over one day for the six coverings tested is computed (Table 1). Although only the sunniest days were selected for data analyses, the scaling factor $\alpha = 0.127/\langle Lum.\rangle_{day}$ compensates approximately for the variable luminosity, especially for configurations d-f, due to seasonal effect. It shows that the white roof lowers the average temperatures by $2.0°C$ (bottom of the hive body) to $5.3°C$ (top). The Balbimax® roof has similar effect for the bottom but only $3.3°C$ at the top due to the insulating effect during the night.

	Sensor position				
	Roof	Overframe	Body Top	Body Bottom	Below
Black roof	+0.9	+1.8	0,0	-0.5	*NA*
White roof	**-9.0**	**-6,4**	**-5.3**	**-2.0**	+0.2
Balbimax® roof	**-10.4**	**-5.6**	**-3.3**	**-2.1**	+0,4
Black walls	+2.0	+3.2	+1.8	+1.7	*NA*
White walls	+0.2	+0.4	-0.9	-0.8	*NA*
Thermopeint® walls	+1.0	+2.1	+0.3	0,0	*NA*

Table 1 *: Averaged temperature θ (°C) difference for each covering*

4. Spectral absorptivity laboratory measurements

In order to understand the observed thermal effects of roof coatings (§3.1), normal spectral absorptivity $A(\lambda)$ measurements of these coatings were estimated from 0.6 to 20µm (Figure 6) in CEMHTI laboratory [6] (Orléans, France) using the measurements of normal hemispherical spectral reflectivity $R(\lambda)$ with relation $A(\lambda) = 1 - R(\lambda) - T(\lambda)$. The transmittivity is 0 for the samples used in this work. It involves two integrating spheres (Figure 7), respectively in the visible range (0.6 to 1.5µm) and in the infrared range (1 to 17µm). The black paint exhibits a constant absorptivity of 95% to 97%. The white paint absorptivity is low in the visible range (about 15% for galvanized steel and 20% for sanded chestnut wood). It means 80% to 85% of the incoming light is reflected back to the sky. Despite the three coats of paint, the white paint is partially transparent, especially in the [0.6; 2] and in [4; 6] µm wavelength ranges since the absorptivity is dependent on the substrate. The galvanized steel absorptivity decreases with respect to wavelength. The Thermopeint® values of solar reflectivity (37.2%) and infrared emissivity (0.56) are specified by the manufacturer [7].

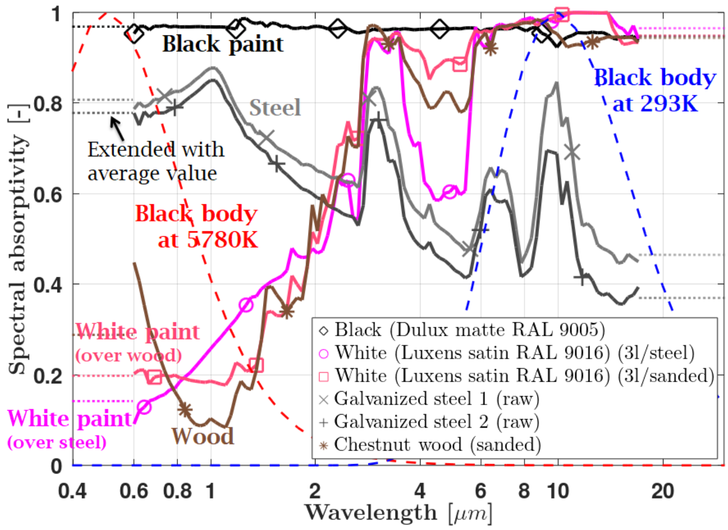


Figure 6 : *Normal spectral absorptivity of black paint, white paint over steel, white paint over sanded wood, galvanized steel (2 samples), sanded chestnut wood.*

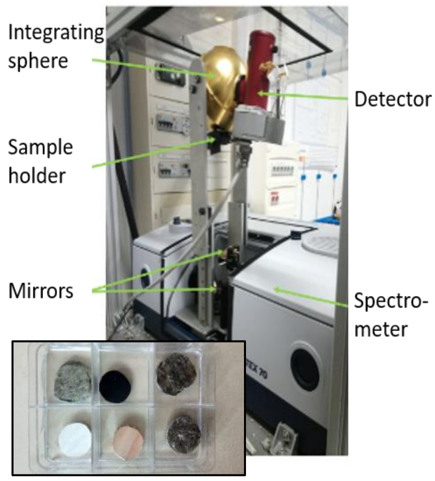


Figure 7 : *Integrating sphere and samples used for spectral absorptivity [6].*

5. Thermal modeling of hive roof

The steady state temperature T_r of the hive roof exposed to sunlight (Figure 8) can be estimated by solving the energy conservation equation:

$$0 = \epsilon_{sun}.\phi_{sun} + \epsilon_{IR}.\sigma\left(T_{sky}^4 - T_r^4\right) + h_{conv}(T_{air} - T_r) + g(T_{hive} - T_r) \quad (1)$$

With ϕ_{sun} the solar radiation absorbed by the roof (direct, diffused and reflected components). With ϵ_{sun} and ϵ_{IR} the hemispherical emissivity for the sun ($\lambda = 0.2$ to $2\mu m$) and for infrared radiation at ambient temperature ($\lambda = 4$ to $30\mu m$) respectively. With h_{conv} the convection coefficient and g the conductance between the roof and the hive defined here by a unique characteristic temperature T_{hive}. The sky is assumed to be the only object visible from the roof and is considered a black body at temperature T_{sky}. The infrared radiation heat flow with the sky is given by the Stefan-Boltzmann law. Hemispherical emissivities ϵ_{sun} and ϵ_{IR} are estimated by integrating the normal spectral absorptivities $A_x(\lambda)$ (Figure 6). Since this work focuses on situations where the sun is high in the sky, it is assumed spectral absorptivity of the steel is constant for directions close to the vertical. The white and black paints are assumed Lambertian. The hemispherical emissivities are then:

$$\epsilon_{x,T} = \int_0^\infty A_x(\lambda).I(\lambda,T)d\lambda / \int_0^\infty I(\lambda,T)d\lambda \quad (2)$$

With $I(\lambda, T)$ the hemispherical intensity of light emitted by a blackbody. ϵ_{sun} is computed with $T = 5780K$ and ϵ_{IR} is computed with $T = 293K$. Due to the limited wavelength range of the experimental setup, normal spectral absorptivities are extrapolated with the average value on each boundary (dotted lines in Figure 6). Let Ra and Pr denote the Rayleigh and the Prandtl number. Convection coefficient h_{conv} is computed using Nusselt-based correlations $h_{conv} = \lambda_{air}Nu/L$, with $Nu = 0.622Ra^{1/4}$ [4] and $Nu = 0.664Re^{1/2}\mathrm{Pr}^{1/3}$ [5] respectively for natural convection and forced laminar convection. Transition occurs at Reynolds value $Re = 5.10^5$.

The relative temperatures $\theta_r = T_r - T_{air}$ for the three types of roof mentioned above (white, black and galvanized steel) are shown in Figure 9 for different wind speeds as well as numerical value of constants involved in Eq.1. For simplicity, the heat transfer between the roof and the body top part is neglected. In general, the heat flow through the roof is much lower ($< 50\ W.m^{-2}$) than convective heat transfer (about $200\ W.m^{-2}$ in Figure 3).

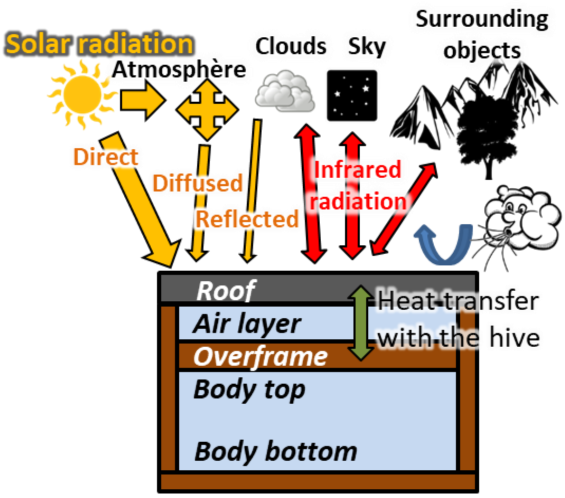


Figure 8 : Heat transfers between the roof, the hive and the environment.

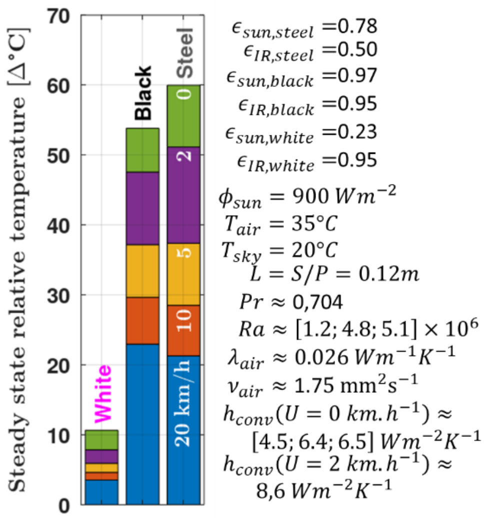


Figure 9 : Relative temperature θ_r with respect to paint and wind speed.

For the white roof, the steady state temperature is $\theta_r^{white} = 11°C$ in no wind condition, quickly decreasing as the wind speed increases. For the black and galvanized roof, the temperatures are close to $55°C$, i.e., $T_r = 90°C$. This model confirms the potential overheating of a Dadant hive with a standard galvanized steel roof (assuming there is no insulating material placed under the roof). The overheating problem can only occur in light wind condition ($< 10km/h$), since the temperature increase is lower than $30°C$ for stronger wind.

To estimate the temperature sensitivity to emissivities in the visible and infrared ranges, the differential of Eq.1 is retrieved. Linearizing radiation heat transfer with $\mathrm{h_{rad}} = \sigma(\mathrm{T_r^2} + \mathrm{T_{sky}^2})(\mathrm{T_r} + \mathrm{T_{sky}})$ and assuming environmental conditions are constant, it comes:

$$(\epsilon_{IR}h_{rad} + h_{conv} + g)\boldsymbol{dT_r} = \phi_{sun}\boldsymbol{d\epsilon_{sun}} - h_{rad}(T_r - T_{sky})\boldsymbol{d\epsilon_{IR}} \tag{3}$$

Eq.3 shows that if the roof is warmer than the sky, increasing emissivity $\boldsymbol{\epsilon_{IR}}$ reduces the roof temperature T_r. Increasing the visible emissivity $\boldsymbol{\epsilon_{sun}}$ always increases T_r. To identify in which case a paint has no effect on roof temperature, $\boldsymbol{dT_r}$ is set to 0 and Eq.3 becomes:

$$\boldsymbol{d\epsilon_{IR}} = \gamma\boldsymbol{d\epsilon_{sun}} \quad \text{with} \quad \gamma = \frac{\phi_{sun}}{h_{rad}(T_r - T_{sky})} \tag{4}$$

Using the temperature of the steel roof in Figure 3, γ is around 2.2 with $T_r = 75°C$; $T_{sky} = 20°C$; $h_{rad} = 7.5\ Wm^{-2}K^{-1}$; $\phi_{sun} = 900\ Wm^{-2}$. A black paint increases the infrared emissivity by $\boldsymbol{d\epsilon_{IR}} = \epsilon_{IR,black} - \epsilon_{IR,steel} = 0.45$ and the visible emissivity by $\boldsymbol{d\epsilon_{sun}} = 0.19$. The ratio is $\gamma = d\epsilon_{IR}/d\epsilon_{sun} = 2.4$ which is reasonably close to 2.2 compared to the white paint case: $\gamma = 0.45/-0.55 = -0.82$. With a black paint, Eq.4 is nearly satisfied confirming that painting the roof black has minor effect on the roof temperature. It should be noted steel and black roof (Figure 5.a) have the same temperatures throughout the day and not only at midday. It suggests Eq.4 is satisfied for all times and γ is nearly constant. Eq.1 shows it is indeed the case if h_{conv} and g are negligible.

6. Conclusions

The temperature measurements of two empty Dadant hives are compared to perform experimental parametric study on the influence of coverings and paints on the hive temperature. From a methodological point of view, the benefit of using empty hives is to prevent any unpredictable effects induced by a bee colony. The effect measured on empty hives was then averaged over one day to get an estimation of the temperature change that would be measured on averaged with inhabited hives. The average value is indeed less sensitive to the hive thermal capacity. The weight of inhabited hives may exceed dozens of kilograms.

The results show a significant reduction of the roof temperature (up to $-28°C$ around midday and $-9°C$ on average) when painted white in the summer period. As shown by the normal spectral absorptivities, this is due to the low absorptivity (23%) in the visible range and the high emissivity in the infrared range (95%). Concerning the galvanized steel roof, it was shown to be roughly equivalent to black roof. Following the usual trend of metallic surface, the steel roof has a higher absorptivity in the visible range (78%) than in the infrared range (50%) which led to potential overheating issue. Finally, painting the hive walls with white had only minor effect compared to the untreated wood. No temperature decrease was measured for the commonly used Thermopeint® which is supposed to lower hive temperatures thanks to aluminium particles. Considering its significant solar absorptivity and its low infrared emissivity, Thermopeint® is outperformed by the white paint for cooling the hive. As expected, it was shown that painting the hive walls with black paint has a measurable effect by increasing the temperature of the body part by about $2°C$.

A steady state model of the hive roof is developed to predict the roof temperature based on radiative and convective properties. The model predictions are confirmed by the observations on instrumented hives. It also shows that with strong solar irradiance, the overheating issue encountered by beekeepers is unlikely to occur in windy weather since a slight wind of 2km/h is sufficient to lower the temperature by 20°C of a steel or black roof.

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