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The Thermal Diffusivity of Biochar Coating Deposited on a Heat Exchanger †

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Abstract: Biochar is a charcoal-like material obtained by burning organic wastes, coming from agricultural and forestry, in a controlled pyrolysis process. In this application, it is deposited on an aluminum foil of thickness 100 µm, which is used as a part of an heat exchanger. The thickness of the deposition of biochar on the aluminum foil ranges from 75 to 250 µm. The result coating is rough and, therefore, it is supposed to improve the heat exchange with the ambient environment, depending on the granulometry of the deposit. One key feature of the deposit is its thermal conductivity. In this work, it is determined by means of IR thermography used as a detector in a Laser Flash configuration. This allows us to evaluate the out-of-plane thermal diffusivity. Such measurements are complemented by density obtained by hydrostatic balance and specific heat by a differential scanning calorimeter.

Keywords: biochar; infrared thermography; thermal diffusivity

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1. Introduction

Indirect evaporative cooling is a process that uses a heat exchanger where, on the one hand, air is cooled by passing it over a wet surface and, on the other hand, a separated air flow is cooled by coming into contact with the cold surface without increasing its absolute humidity. A recent improvement in indirect evaporative cooling is provided by the so-called Maisotsenko cycle (M-cycle). In this cycle, the air flow to be saturated consists of a part of the air flow that has been cooled, which is reintroduced into the heat exchanger. As a result, the limit temperature, to which the remainder of the cooled air flow can theoretically be brought, is not the wet bulb temperature, but the dew point temperature [1]. Despite reaching coefficients of performance 5–6 times higher than traditional cooling systems [2], evaporative coolers are often penalized by continuous water pump operation, due to the constant spray of water in the wet duct, to homogenize the humidification of the heat transfer surface [3]. Considerable efforts have been made over the years to improve the water retention and water diffusion of heat transfer surface materials, aimed at reducing the energy consumption for water pumping and further improve the COP. Several studies focused on the study of porous materials for the wet duct of the heat exchanger, such as: cellulose fiber coating for metal foils, cotton wool, honeycomb structures, coconut fibers, polymer sheets, stainless steel with sintered nickel layers, etc. [4,5]. This work aims to study the thermophysical properties of aluminum heat transfer surfaces coated with biochar powder to estimate its performance on an indirect evaporative heat exchanger. Biochar is a highly porous vegetable charcoal, similar to an activated carbon, that is produced through the pyrolysis or gasification of woody biomass, and is recognized globally as one of the methods of bio-energy carbon capture and storage (BECCS), finding several applications in the agronomic field as a soil improver. This material has a high carbon content (up to 80–90%), a high chemical recalcitrance, and a resistance to biological decomposition, which allows it to remain stable for decades [6]. Thanks to its high porosity, which leads to high surface area (hundreds of m^2g^{-1} [7]), it is able to absorb and retain large quantities of water. Unlike the agronomic field, there are still few works that investigate the exploitation of biochar to improve heat and mass transfer in evaporative cooling systems. It has been tested as a porous component in lightweight concretes [8], and as an additive in fabrics that serve as wet surfaces in direct evaporative coolers [9]. With reference to indirect evaporative heat exchangers, it is crucial to both guarantee a high evaporation rate on the wet side, and to obtain a heat transfer surface capable of effectively transferring heat from the dry to the wet duct. The methods adopted in this work aim to measure the thermal diffusivity of an aluminum sheet coated with biochar powder with different grain sizes obtained by sieving commercial charcoal according to the reference standard [10]. The grain size of the carbon used for the coating is between 75 and 250 µm. The adhesion of the material to the aluminum surface is guaranteed by a layer of epoxy resin.

2. Materials and Methods

To understand the effect of depositing the biochar onto the surface of the heat exchanger, 8 samples have been prepared. The base material is aluminum, which the heat exchanger is made of, with a nominal thickness of 100 µm and lateral dimension of 4×4 cm. On each sample (apart the first), a layer of epoxy resin is deposited, which is needed to glue the biochar particles spread over the aluminum layer with different granulometries. Table 1 reports the main characteristics of each sample, together with the thickness measured and averaged on five points, by a Mitutoyo QuantuMike IP65 micrometer, 0.001 mm resolution. The samples are coated twice with opaque black paint on the aluminum side. It needs to improve the absorption coefficient of the light being shot to heat the sample. Figure 1 shows one sample on the aluminum side and one on the biochar side as well. The experimental layout is shown in Figure 2. A laser pulse (2 ms duration) is sent to the surface of the specimen (aluminum side). The beam is spatially distributed as a top-hat shape with diameter of 1 cm. The wavelength is 1064 nm. The IR camera (FLIR SC6000, focal plane array 640 by 480 pixels, InSb MW detector working at 1039.9 Hz) observes the sample on the other side, where the biochar is glued.

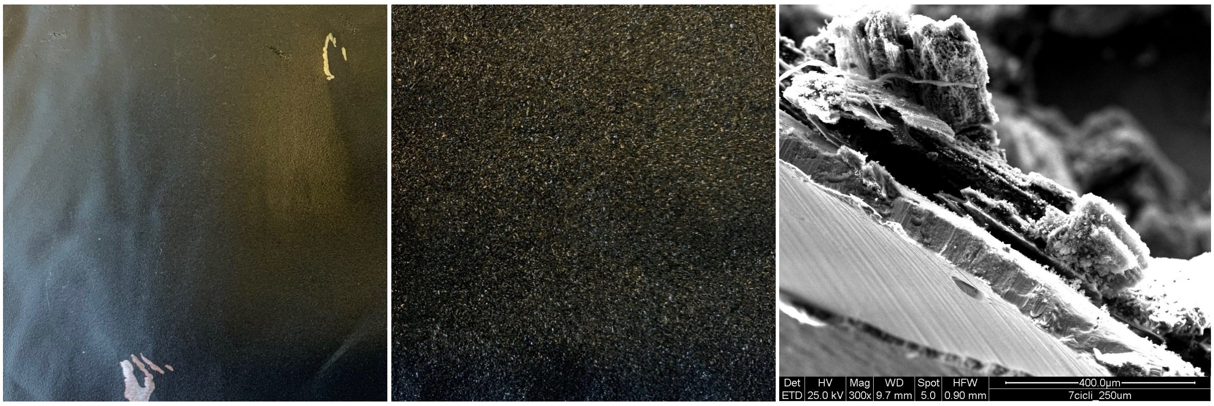
Table 1. Main characteristics of the tested samples. These are multilayer samples made of aluminum, epoxy resin, and biochar of different granulometries. The overall thickness is given as well. Each sample has sides of 4×4 cm.

Code	Al	Epoxy Resin	Biochar	Granulometry Φ [µm]	Thickness [µm]
Al	√	-	-	-	143 ± 5.5%
Al+R	√	√	-	-	239 ± 7.7%
75	√	√	√	<75	280 ± 5.8%
150	√	√	√	75–150	324 ± 5.9%
250	√	√	√	150–250	378 ± 10.5%
Mix75-150	√	√	√	50–50 [1]	338 ± 10.4%
Mix75-250	√	√	√	50–50 [2]	409 ± 1.9%
Mix150-250	√	√	√	50–50 [3]	470 ± 6.8%

[1] Mix of 50% plus 50% volumes of biochars previously defined with Code 75 and 150. [2] Mix of 50% plus 50% volumes of biochars previously defined with Code 75 and 250. [3] Mix of 50% plus 50% volumes of biochars previously defined with Code 150 and 250.

According to Parker [11], thermal diffusivity ($\alpha[\mathrm{m}^2\mathrm{s}^{-1}]$) can be obtained by measuring the time of the half-maximum ($t_{0.5}[\mathrm{s}]$) of the back temperature rise and the sample thickness $L[\mathrm{m}]$, according to:

$$\alpha = 0.1388\frac{L^2}{t_{0.5}} \tag{1}$$



Aluminun side Biochar side SEM image of Biochar

Figure 1. On the left, the sample is shown from the aluminum side, which is coated black; in the center, the side where the biochar has been spread is shown; on the right, the SEM picture of the deposited biochar is shown.

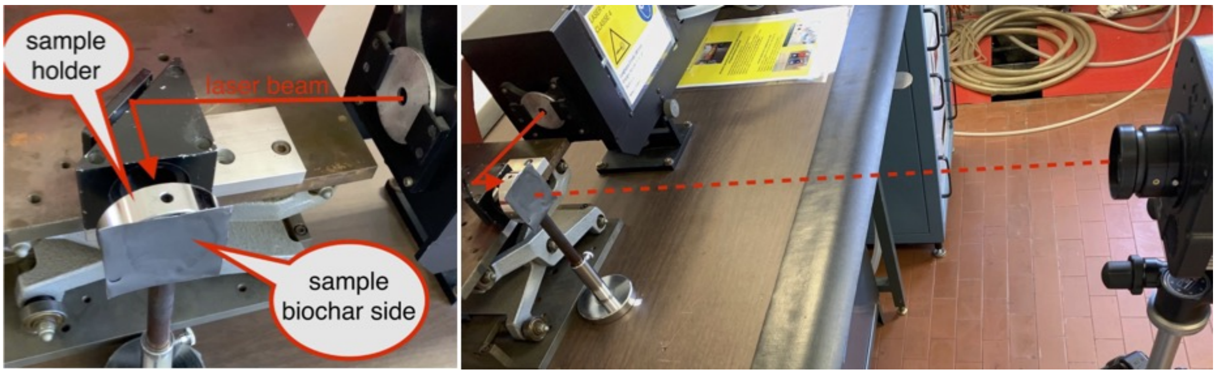


Figure 2. Experimental layout. A laser pulse strikes the back (aluminum) surface of the sample. The other surface (coated with biochar) is observed by the IR camera, which records a sequence of images after the shot.

3. Results

Results of thermal diffusivity are given in Table 2. They are complemented with densities and specific heat. In the sample composites of aluminum plus resin and biochar, thermal diffusivities are indeed *effective*, and relate to the whole multilayer sample.

On the contrary, densities are related to bulk biochar, while specific heat is obtained by measuring the biochar after detaching it from the aluminum layer. Therefore, it could contain traces of gluing resin. The specific heat is measured by a Differential Scanning Calorimeter Setaram Microcalvet, in the range between 22 and 29 °C. The samples under test are, indeed, multilayer systems made of aluminum plus biochar and a gluing resin between the aluminum and the biochar. The photothermal technique used to measure thermal diffusivity furnishes an effective value. In the current experiments, some inhomogeneities in the application of the biochar and the resin could be the cause of the high uncertainty of the thermal diffusivity values, which varies from zone to zone and depends on the type of mix in the granulometry of the applied biochar. Notwithstanding the high variability of the results, it appears evident that the effective thermal diffusivity decreases dramatically with the application of the biochar. Indeed, even if it was not possible to measure the aluminum value, because of the limitation of the experimental apparatus, we may relay on a typical value of this metal, which can be greater than $5.0 \cdot 10^{-5}[\mathrm{m^2 s^{-1}}]$, two orders of magnitude greater than the effective values obtained with our measurement.

Table 2. Thermal diffusivities.

Code	Thermal Diffusivity $[\mathrm{m^2 s^{-1}}]$	Density [1] $[\mathrm{kg\ m^{-3}}]$	Specific Heat [2] $[\mathrm{J\ kg^{-1} K^{-1}}]$
Al[3]	-	-	-
Al+R	$5.0 \cdot 10^{-7} \pm 15\%$	-	-
75	$4.1 \cdot 10^{-7} \pm 12\%$	$154.8 \pm 1.3\%$	$1360 \pm 1\%$
150	$2.4 \cdot 10^{-7} \pm 12\%$	$157.1 \pm 4.8\%$	″
250	$2.7 \cdot 10^{-7} \pm 21\%$	$157.4 \pm 3.0\%$	″
Mix75-150	$2.3 \cdot 10^{-7} \pm 21\%$	$155.5 \pm 2.7\%$	″
Mix75-250	$3.2 \cdot 10^{-7} \pm 4.2\%$	$156.8 \pm 2.2\%$	″
Mix150-250	$2.9 \cdot 10^{-7} \pm 15\%$	$154.9 \pm 1.9\%$	″

[1] Density refers to bulk biochar. [2] Specific heat of biochar from 22 to 29 °C. Sample is not pure, it could contain traces of gluing resin. [3] Thermal diffusivity of aluminum can not be measured because the $t_{0.5}$ is less than 1 ms, which is the approximate sampling rate of the IR camera.

4. Conclusions

The effect of depositing the biochar on the surface of the heat exchanger to improve the indirect evaporative cooling in a Maisotsenko cycle is studied. Eight samples made of aluminum with different types of biochar deposits was characterized by measuring their thermal diffusivity. Some preliminary results are reported. The uncertainties are relevant, because of the inhomogeneities of the deposit. The next step will be the preparation of samples with deposit of improved homogeneity. A new, fast, high-performance IR camera will achieve the thermal diffusivity of the aluminum substrate that, in this work, is assumed from the literature. More sophisticated models that take into account the effects of the single layers could be devised, for example by using the thermal quadrupoles approach. With such models, it is possible to isolate the effect of a single layer by knowing the values of the others in the compound. From this perspective, a more accurate preparation of the samples must be identified, which would allow us to evaluate the thickness of each single layer.

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