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Performances of infrared emitters applied to the porous thin materials drying

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Abstract. Drying of solids is one of the oldest and most common unit operations found in diverse processes. In this paper the drying of hygroscopic textile materials is discussed. The authors have previously investigated the drying kinetic of different fabrics dried by a hot air jet. In this paper a comparison between the convective and electric IR drying is made. In particular two fabrics with fibers which show a different hygroscopic behaviour are analysed: wool and cellulose/cotton. Unlike the convective drying, IR drying is weakly affected by the radiation properties and by the hygroscopic behaviour of the two fabrics. This is likely due to a better diffusion of the heat flux, which is constant over the entire drying surface in the case of IR heating, and produces unexpected results on the nondimensional kinetic parameter (characteristic curve). Wool shows a complete different characteristic curve if dried with IR or with convective flow. The better performances have been reached with MW emitter, but it has been observed that this advantage decreases with the distance of the source from the surface to be dried.

1. Introduction

Drying of solids is one of the oldest and most common unit operations found in diverse processes such as those used in the agricultural, ceramic, chemical, food, pharmaceutical, pulp and paper, mineral, polymer, and textile industries. It is also one of the most complex and least understood operations because of the difficulties and deficiencies in mathematical descriptions of the phenomena of simultaneous—and often coupled and multiphase—transport of heat, mass, and momentum in solid media [1].
During the drying processes the heat may be supplied by convection (direct dryers), by conduction (contact or indirect dryers), radiation or volumetrically by placing the wet material in a microwave or RF electromagnetic field. Over 85% of industrial dryers are of the convective type, with hot air or direct combustion gases as the drying medium. In the case of multiple impinging gas jets, both round and slot, Mujumdar [1] claims that entrained ambient air may cause unpredictable effects and the heat transfer performance may worsen by 20–50%. Recently the present authors have analysed the hot air drying of thin textile materials [2-4], by focusing on round nozzle jets. The prediction errors of the heat and mass transfer correlations can be very high, depending on the hygroscopic behaviour of the

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porous medium [4] even if during the first stage of drying, where only the external condition should influence the phenomenon.
Convective drying shows therefore several problems: the energy saving, the contamination (including food processing like baking, roasting, blanching and surface pasteurization), the irregular dehydration of thin sheet as paper, wood, textile and paints due to irregular mass flow rate impingent on the surface. The need for product quality puts heavy constraints on the chosen dryer and dryer operation. Quality depends on the end use of the product. For many bulk chemicals, handling considerations determine moisture content requirements. For foodstuffs, flavor retention, palatability, and rehydration properties are important. Timber must retain its strength and decorative properties after drying.
One of the increasingly popular methods to performing dehydration or a superficial treatment is infrared (IR) radiation. Some of the IR thermal treatment advantage are energy savings, simple coupling with convective heating, fast response and easy control of the device.
In the last decades IR radiations has been investigate for drying of several porous and nonporous materials as: rough rice by Abe and Afzal [5], paddy by Das et al. [6], apple slices by Nowak and Lewicki [6], banana by Pan and Shih [7], thin coated films by Navarri and Andrieu [8]-[9] and for heating of thermoplastic sheet by Shmidt and Maoult [10].
Two types of IR heaters dominate these applications: Gas Fired IR (GF-IR) emitter and Electrical IR (EL-IR) emitter. GF-IR heaters have achieved some attention in the past years with papers on experimental studies and modelling work but EL-IR are more versatile and efficient even if the literature is scarce. Studies on optimization of the EL-IR heater for the different drying applications are very fragmentary.
In this paper IR drying given by different EL-IR emitters has been experimentally compared with a convective one by drying different thin hygroscopic textile medium. The kinetic parameter of different fabrics has been evaluated, and the basic drying phenomenon has been detected for two different commercial EL-IR emitters.

2. Infrared emitters analysis

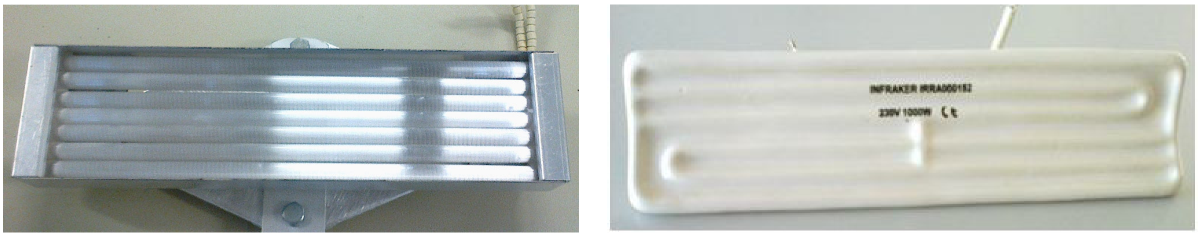
As mentioned before the IR Emitters which are installed in the most of industrial applications are Gas Fired or Electric emitters. In these types of emitters, the IR radiation is obtained by passing an electric current through a resistance, which raises its temperature. The emitters are therefore characterised by the maximum temperature of the emitting source and by the wavelength range associated with this temperature.

Table 1. Typical parameters of commercial IR emitters.

Band	Characteristics
SW	Wavelength range 0.85-1.6 μm, maximum emission at about 1.2 μm, power density 60-600 kW/m2, maximum running temperature 2800 K, response 1 s
MW	Wavelength range 2.1-2.75 μm, maximum emission at about 2.6 μm, power density 30-40 kW/m2, maximum running temperature 1800 K, response 30-90 s
LW	Wavelength range 3.5-6 μm, maximum emission at about 4 μm, power density 30-40 kW/m2, maximum running temperature 900 K, response 3-10 min

Infrared emitters can be made of various materials such as quartz glass, ceramic and metal. Generally speaking, EL-IR emitters can be classified in Long Wave (LW), Medium Wave (MW) and Short Wave (SW). Table 1 show typical EL-IR emitter bands and power capability. Because of the high

temperature and high energy density reached, SW emitters are not often used in drying and superficial heating of porous media. Excessive drying is wasteful; not only more heat, i.e. expense, is involved than necessary, but often overdrying results in a degraded product, as in the case of paper and timber.
The MW emitters are generally made of a filament, inserted into a quartz tube differently shaped (single, twin, row, etc). The backside of the lamp is usually coated with gold to ensure a high reflectivity. The chromium alloy filament is suspended in a quartz or metal sheath. Due to the material used and the relatively low temperatures, the filament can operate in open air. There are some papers which have attempted to model this kind of lamp if applied to paper pulp [12, 13].
The MW emitter which has been used in this experimental activity is shown in figure 1.a. It is made of a row of 7 quartz tubes, among which the central one is without any heating element. This element is supplied with 1kWel at maximum, and has a rectangular shape of 62x248 mm. Its peak radiation intensity is at about 2.5 μm.

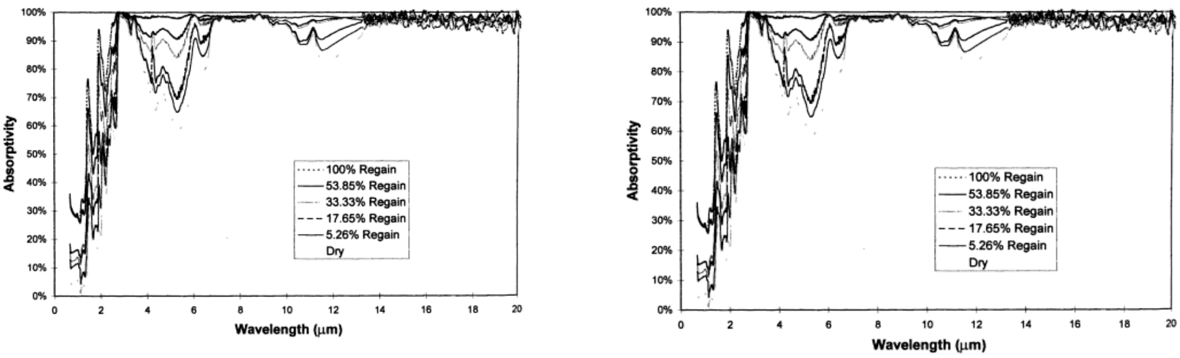


(a) (b)

Figure 1. MW IR emitter composed of 7 quartz tubes and Ni-Cr alloy filament (a), LW IR, ceramic surface (b).

The LW emitter consists of a ceramic matrix heated by an iron-chrome aluminium resistance wire. The temperature reached on the surface is lower than the other types. The maximum temperature is about 870 K, corresponding to a peak wavelength of 3.3 μm.
Usually this heater have a long start up time (7-10 minutes) but a more uniform temperature distribution, and therefore a diffuse radiative emission. The LW emitter which has been used in this experimental activity is shown in figure 1.b. This element is supplied with 1kWel at maximum, and has a rectangular shape of 60x245 mm.
Both the heaters can be tuned with a solid state power controller (GEFRAN GFX4 POWER) with a configurable proportional cycle time, which allows the power to be digitally controlled from 20% up to 100%.
The design and modeling of any radiative process always requires knowledge of the optical properties of these materials. Specifically for IR drying, this fact may be the clue to accomplish a safe and efficient process, because radiation properties of both the radiator and the material to be dried must be matched in order to obtain most efficient results. Emissivity, absorptivity, reflectivity, and transmissivity are the key radiation properties. Their relative magnitudes depend not only on the material, its thickness, and its surface finish, but also on the wavelength of the radiation. Furthermore the material soaked with water shows a different behaviour, and changes its radiative properties with respect to the dried material.
Generally, many fully wet materials have their minimum absorptivity at those wavelengths where water has its maximum transmissivity, pointing out the important role that water plays in radiation absorption. As drying proceeds, the material that is dried undergoes a change in its radiation properties, increasing its reflectivity, and consequently lowering its absorptivity at low water contents.
Water is transparent to the IR radiation (2.5 – 10 μm) with a transmittance of 0.85 at least, except for two windows (2.5 – 2.95 μm) and (5 – 7.14 μm) where the absorptivity is about 0.8. In this paper we study IR drying of textile materials. Several parameters influence the radiative properties of textile materials: areal density, fiber type and water content. The absorptivity in the NIR spectrum is however low and it is not affected by areal density. For wavelength higher than 2.5 μm, the weight of the fabric

largely affects the radiative properties. Transmittance decreases as the areal density increases, even if transmittance is never zero (20%) even for polyester fiber weighting 882 g/m^2 [14]. In the range 2.5 – 6 μm the most of fabrics are influenced by the weight and the transmittance can be 0.3 for the low density textile materials. For higher wavelengths the transmittance rapidly decreases approaching zero [14]. Fiber and water content largely influences the spectra behaviour of fabric. The spectral absorptivity at different water content is reported in figure 2 for wool and cotton, respectively.



(a) (b)

Figure 2. Spectral IR Absorptivity for wool (173 g/m^2) at different water content (a), Spectral IR Absorptivity for cotton (193 g/m^2) at different water content (b) [14]

Figure 2 shows as the presence of the water inside the fiber increases the absorptivity for both the textile materials considered. The most of the influence is in the range (2.5 – 5 μm) typical of MW emitters.

3. The kinetic of thin porous IR fabric drying

The hygroscopic-porous media are characterised by a clearly recognizable pore space and a large amount of physically bound liquid. The drying process of a porous material can be therefore divided into four main stages [1]. In a first time period, the temperature of the media is lower than the wet bulb temperature, so that the temperature increases over time jointly with the drying rate N_w, while the water content X decreases. During the second time period (Stage I) the drying rate and the temperature of the hygroscopic material stay constant up to the third period (Stage II) where the drying rate decreases and the temperature increases. In this stage dry spots appear on the heated surface, and a part of bound moisture is removed. This stage is dominated by the diffusion and the capillarity of the medium. During the last drying stage (III) only the bound water is present inside the material, the drying rate decreases with a lower slope over the time as the equilibrium moisture is reached.

During the first stage of drying the phenomenon is dominated by the local heat and mass transfer and the characteristic of material should not affect the drying rate.

When the drying rate curves are determined over a range of conditions for a given solid, the curves appear to be geometrically similar and are simply a function of the extent to which drying has occurred. If these curves were normalized with respect to the initial drying rate and average moisture content, then all the curves could often be approximated to a single curve, ‘‘characteristic’’ of a particular substance, which does not depend on the way of drying. This is the characteristic drying curve. The normalized variables, the characteristic drying rate f and the characteristic moisture content ϕ are defined as follows:

$$f = \frac{N_W}{N_c} \qquad (1)$$

$$\phi = \frac{\bar{X} - X^*}{X_{cr} - X^*} \tag{2}$$

where N_W is the rate of drying per unit surface, N_c is the constant rate during the Stage II, X is the average moisture content in the body (expressed as the moisture by weight of bone-dry material in the solid), X_{CR} is the critical moisture content, defined as the moisture content at the end of the first stage drying. Finally, the equilibrium moisture content X^* is the moisture content of the bound water, which depends on the humidity of the air. The saturation moisture content X_{sat} is defined as the maximum moisture content which the fabric can hold without dripping.

In [5] 4 different fabrics (large pore and small pore cotton, wool, cotton and cellulose) have been experimentally characterized by measuring the drying kinetic parameters for hygroscopic materials.

In [3] the authors experimentally evaluated these parameters for a wool and cotton and cellulose fabric with an accuracy of 10% by drying the media with a hot air convective flow. The drying kinetic curves obtained with a convective air drying are shown in figure 3 for wool and cellulose/cotton and the kinetic parameters are reported in table 2.

Table 2. Kinetic drying parameters for the tested samples.

Fabric type	**Dry weight [g]**	**Areal density [g/m^2]**	X_{crit} **[g_{water}/g_{solid}]**	X_{sat} **[g_{water}/g_{solid}]**	X^* **[g_{water}/g_{solid}]**	**Experimental drying rate N_c [g/s m^2]**
Cotton / cellulose	13.3	217.6	3.2	14.9	0.042	1.74
Wool	11.7	191.5	7.89	9.5	0.099	1.61

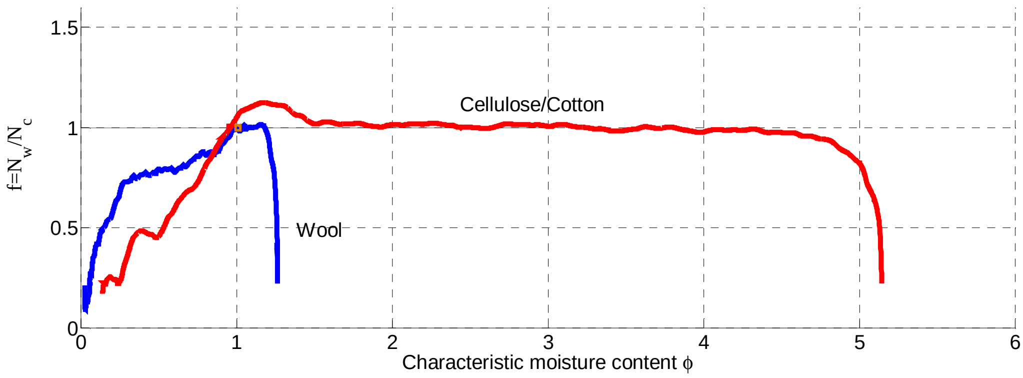


Figure 3. Characteristic drying curves for the wool and cellulose/cotton evaluated with convective drying.

4. Experimental Activity

A scheme of the experimental facility used during the tests for the IR drying analysis is shown in figure 4. It consists of a support, the heating element, the moistened fabric and of the control and acquisition devices.

The heating element and the power controller systems have been previously described in a dedicated section. The support allows the distance between the heating element and the moistened cloth to be changed with continuity in the range 5-50 cm. The electronic scale has 0.01 g of resolution and a maximum sampling rate of 10 s. The temperature spatial distribution over the moistened cloth has been observed with an infrared thermocamera, which has a focal plane array of two-dimensional micro-bolometric sensors, characterized by a digital resolution of 320x240 pixels, sensitive to wave lengths of 8÷14 μm. The minimum thermal resolution is 0.15 K. The optical system consists of a 35

mm lens, with a field of view of 25.8°x19.5°. The distance between the hot surface and the lens is 0.74 m, resulting in a pixel size of 1.04x1.04 mm^2.
For each power level, the drying rate was measured and each test was repeated 5 times. Four different fabrics were tested. Each fabric was previously completely dried in an oven, and immersed in demineralised water for 20 minutes. As the fabric was completely soaked of water, it was put on a metallic net hung to an electronic scale, to mechanically remove the water in excess by gravity. During this stage the weight of the patch linearly decreased with time first, then remained approximately constant. At that time the hygroscopic material was considered completely saturated of water, with all the excess water removed. The patch was then exposed to the IR radiation, and data were acquired every 5 seconds up to complete drying. When the moistened patch is exposed to the IR radiation, the heater had just reached a steady state operative regime.

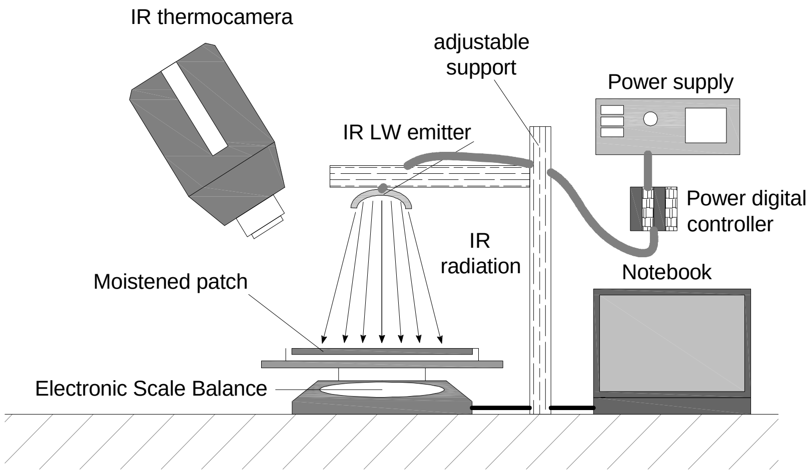


Figure 4. Scheme of the experimental facility and the acquisition systems

5. Results

This paper reports a preliminary experimental activity on the analysis of the drying of hygroscopic media in general, and fabrics in particular. The IR drying depends on the wet material which must be dried and by the emitters. The effect of the spectral radiation of two different emitters (Long Wave e Medium Wave) on two different fabrics is then investigated. The fabrics have been selected according to the hygroscopic behaviour of the materials, shown in figure 3.
If dried with a convective jet, wool shows the typical behaviour of the low hygroscopic media: no zone at a constant drying rate is observed, while for highly hygroscopic media (cellulose) the drying rate is constant for large moisture content inside the patch. These two materials show very similar density area and similar radiation properties. This experimental activity shows drying rate measured for both the emitters and the fabrics for two different distances between the patch and emitters (200 and 300 mm). For each distance the electric power of the two emitters has been tuned (from 60 to 100%) in order to change the radiation intensity and the temperature of the heating panel. The drying rate has been evaluated by measuring the mass of the fabric over time under a constant IR radiation.
An example of the weight decrease over time measured during the test is shown in figure 5. It is referred to the cellulose/cotton fabric with a distance of 200 mm. After an initial transient, the weight linearly decreases with time. All the data of this period were linearly fitted by least squares method, and the slope of this curve is the drying rate.
By knowing the drying rate over time, it is possible to evaluate also critical moisture content X_{cr} and therefore the characteristic curve for the wool and the cellulose. The characteristic curve depends only on the material and it does not depend of: drying power, emitters, distance between the emitters and the cloth. The characteristic curves evaluated for wool and cellulose are shown in figure 6.

The comparison between figures 3 and 6 shows which that in the case of wool the characteristic curves have a different shape if obtained with IR or convective drying. The characteristic curve should show the same shape at low characteristic moisture content, at least. The starting point can be different because it depends on the starting moisture content.

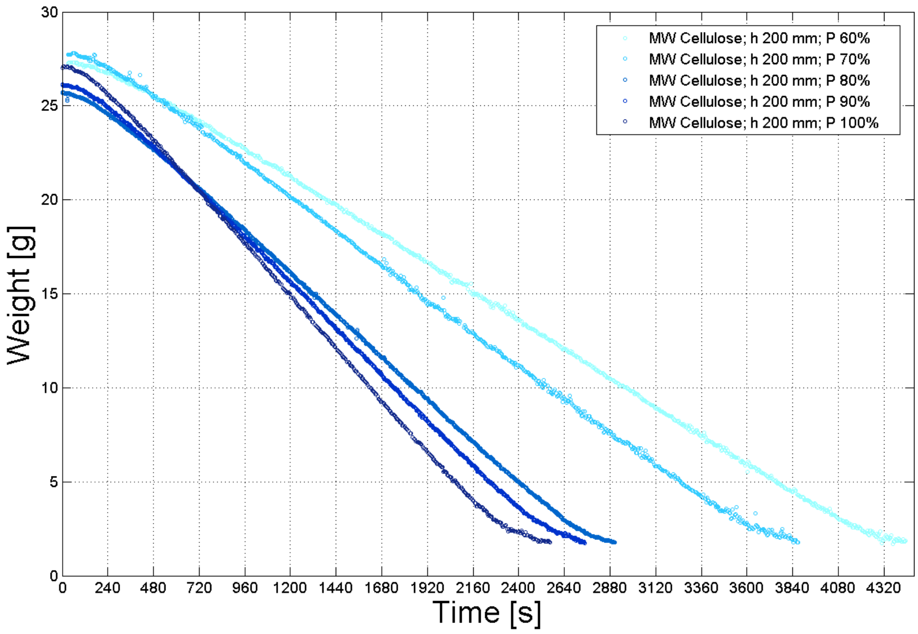


Figure 5. Weight of the wet cellulose/cotton fabric obtained with a LW emitter placed at 200 mm from the moistened fabric.

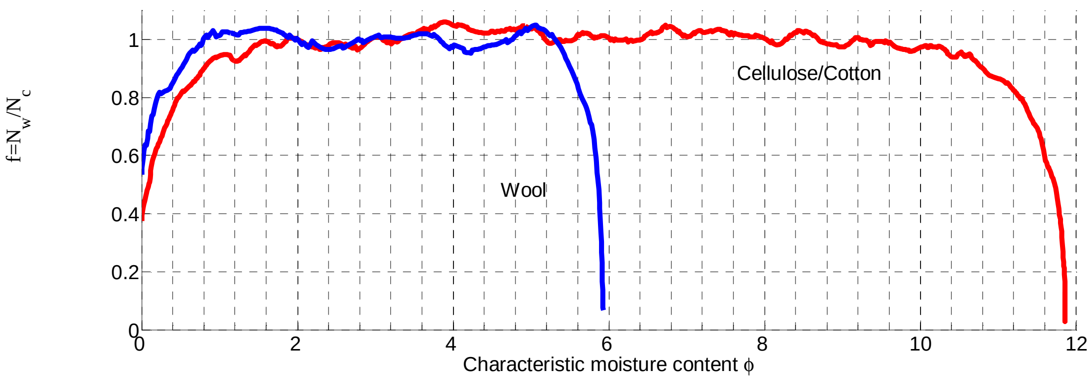


Figure 6. Characteristic drying curves for the wool and cellulose/cotton evaluated with IR drying.

This result is therefore unexpected. As the drying rate is constant, the mass flow rate of the water inside the medium is equal to the mass flow rate which evaporates from the surface. The experimental evaluation of the drying rate is however an integral method even if the local drying rate is not completely uniform. In the case of convective air jet, both in the case of slot and nozzle diffusers, the local distribution of temperature is not spatially uniform [4]. The IR drying made with the two IR panels used in this work, show a very diffuse heat flux and the spatial temperature distribution is very constant over the entire surface for both the materials, as shown in figure 7.

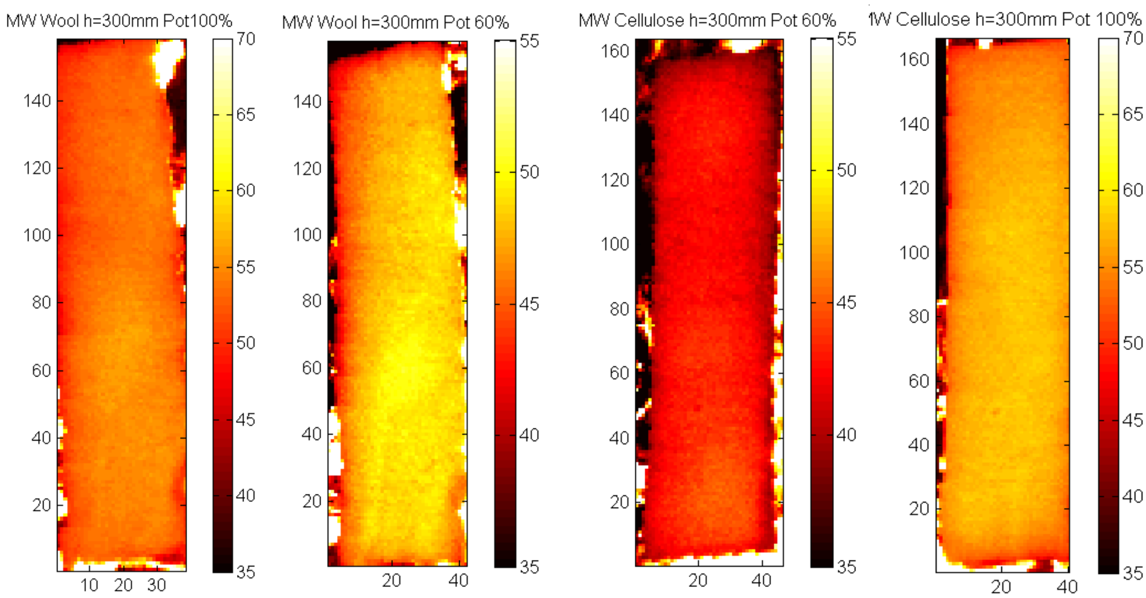


Figure 7. Temperature distribution of cellulose/cotton and wool at 600 and 1000 W at a distance of 300 mm by the MW emitter.

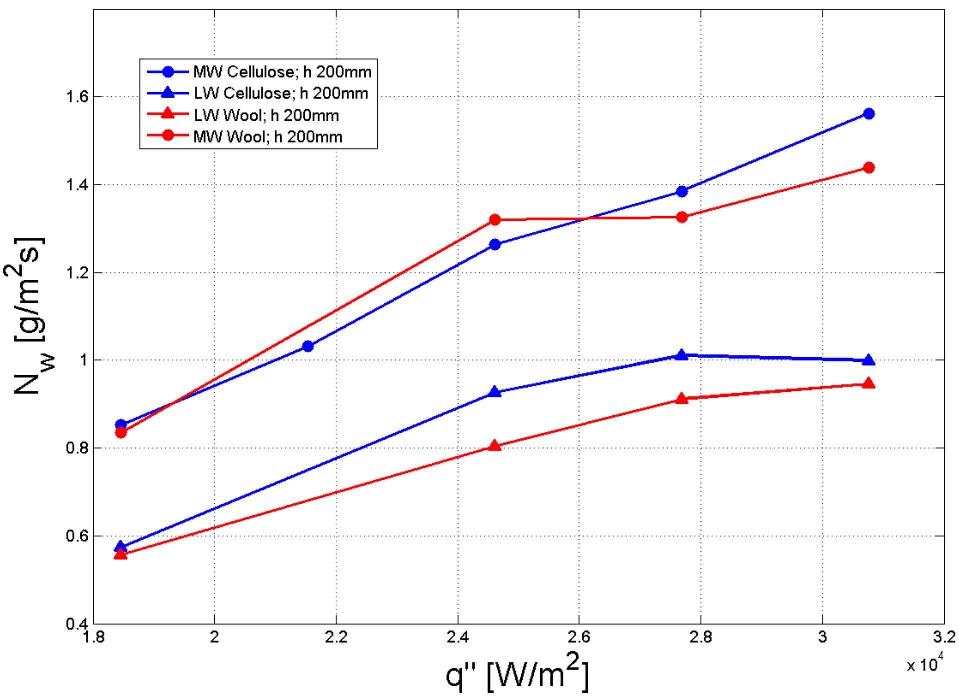


Figure 8. Drying rate of cellulose/cotton and wool at a distance of 200 mm under MW and LW emitters at different power areal density.

The mass flow rate in perpendicular direction with respect the heat flux is negligible if the heat flux is uniformly diffused, but it could be significant if the heat flux is non-uniform, as in the case of

convective drying. In the latter configuration the porous properties of the materials influence the local drying rate. In IR diffuse radiation, different hygroscopic materials show analogous quantitative behaviours (figure 6).
The drying rates obtained with an IR drying have been plotted versus the power areal density *q"*, which is here defined as half of the electric power of the emitters divided by the surface to be dried. Figures 8 and 9 show the drying rate plotted versus the power density for LW and MW emitters, at a distance of 200 and 300 mm, respectively.
Different hygroscopic materials present the same quantitative drying rate at different power areal densities both for LW and MW at different distances and, therefore, heat flux intensities. MW emitters at the same power areal density show higher drying rates than LW emitters, both at 200 mm and 300 mm. As the distance increases, MW emitters show better drying performances. At 200 mm and the maximum power, the drying rate in the case of MW emitters is about 45% more than the LW emitters, and this rate increases as the distance rises. At 300 mm the MW drying rate is about 60% more than the LW drying rate at the maximum power.

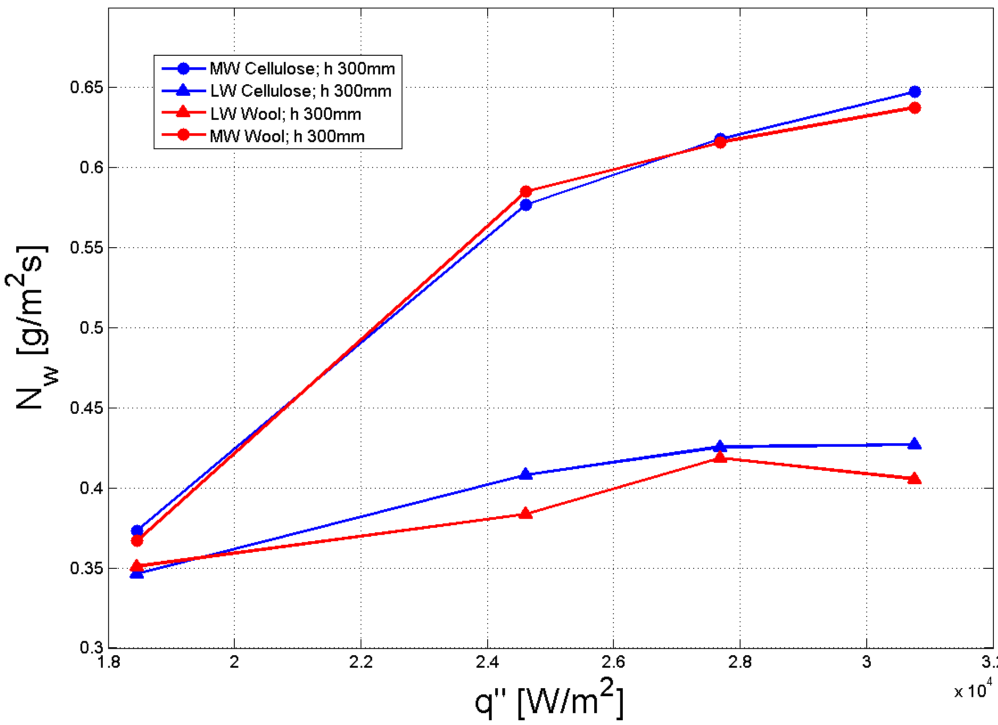


Figure 9. Drying rate of cellulose/cotton and wool at a distance of 300 mm by MW and LW emitter at different power areal density.

6. Conclusions
In this paper IR drying given by different EL-IR emitters has been experimentally compared with a convective one, by drying different thin hygroscopic textile media. In particular two fabrics with fibers which show a different hygroscopic behaviour have been analyzed: wool and cellulose/cotton. The areal densities of these two media are 217 g/m^2 for cellulose/cotton and 191 g/m^2 for wool.
In this preliminary paper, the performances of IR drying, with two different emitters, (MW and LW) has been qualitatively compared with that of a convective drying with similar power area density.
Unlike convective drying, IR drying is scarcely affected by the radiation properties and by the hygroscopic behaviour of the two fabrics. This is probably due to a better diffusion of the heat flux, which is uniform over the drying surface in the case of IR heating, and produces unexpected results on

the non-dimensional kinetic parameter (characteristic curve). In particular, wool shows a completely different characteristic curve if dried with IR or with convective flow.
The better performance has been reached with MW emitter, although it has been observed that this advantage decreases with the distance. This preliminary work does not allow for clearly detecting the influence of the distance on the drying rate for both the emitters. In the future, a wider experimental activity will be performed to clarify this aspect.

References

[1] Mujumdar A 2006 *Handbook of Industrial Drying*, 3rd edition, Taylor & Francis Group, LLC
[2] Di Marco P, Filippeschi S and Pieve M 2010 Experimental study on the drying power of a hot jet, *Proc. ASME-ATI-UIT Conference on Thermal and Environmental Issues in Energy Systems*, Sorrento, Italy
[3] Di Marco P, Filippeschi S and Pieve M 2011, Experimental study on drying of different kinds of fabric by an air hot jet, *Proc. XXIX UIT National Conference*, 20-22 June, Turin Italy
[4] Di Marco P, Filippeschi S 2012 Experimental investigation on influence of porous material properties on drying process by a hot air jet, *J. Phys.: Conf. Ser.***,** **395**, 012139
[5] Abe T and Afzal T M 1997 Thin-layer infrared radiation drying of rough rice, *Journal of Agricultural Engineering Research*, **67**(4) 289-297
[6] Das I, Das S K and Bal S 2009 Drying kinetics of high moisture paddy undergoing vibration-assisted infrared (IR) drying, *J. Food Engineering* **95** 166–171
[7] Nowak D and Lewicki P P 2004 Infrared drying of apple slices, *Innovative Food Science and Emerging Technologies* **5** 353– 360
[8] Pan Z, Shih C, McHugh T H and Hirschberg E 2008 Study of banana dehydration using sequential infrared radiation heating and freeze-drying, *LWT - Food Science and Technology* **41** 1944-1951
[9] Navarri P and Andrieu J 1993 High-intensity infrared drying study. Part I: case of capillary-porous material, *Chemical Engineering and Processing* **32** 311-318
[10] Navarri P and Andrieu J 1993 High-intensity infrared drying study. Part II: case of thin coated films, *Chem. Eng. and Processing* **32** 319-325
[11] Schmidt F M, Le Maoult Y and Monteix S 2003 Modelling of infrared heating of thermoplastic sheet used in thermoforming process, *J. Materials Processing Technology* **143–144** 225–231
[12] Petterson M and Stenstrom S 2000 Modelling of an IR heater at transient and steady state conditions. Part I: model and validation, *Int. J. Heat Mass Trans.* **43** 1209-1222
[13] Petterson M and Stenstrom S 2000 Modelling of an IR heater at transient and steady state conditions. Part II: modelling a paper dryer, *Int. J. Heat Mass Trans.* **43** 1223-1232
[14] Pastore C M, Kiekens P 2001 *Surface characteristics of fiber and textiles*, CRC Press