Experimental investigation on influence of porous material properties on drying process by a hot air jet

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Abstract. The drying process of porous media is a subject of scientific interest, and different mathematical approaches can be found in the literature. A previous paper by the same authors showed that the celebrated Martin correlation for hot air jet heat and mass transfer yields different degrees of accuracy (from 15% to 65%, increasing at high values of input power) if tested on different fabrics, the remaining conditions being the same. In this paper the fabric drying has been experimentally investigated more in depth. A dedicated experimental apparatus for hot jet drying was assembled and operated, in which a hot jet impinges perpendicularly onto a wet fabric. A calibrated orifice was adopted to measure the jet flow rate, with an accuracy better than 3%. The drying power was determined by continuously weighing with a precision scale a moistened patch exposed to the drying jet. The effect of the time of the exposure and the initial amount of water has been evaluated for each sample. During the hot jet exposure, the temperature distribution over the wet patch has been observed by an infrared thermo-camera. A mathematical model of water transport inside and outside the fabric was developed, in order to evidence the governing transport resistances. The theoretical predictions have been compared with the experimental results, and showed the necessity to modify correlations and models accounting for fabric properties.

1. Introduction

The problem of the drying process of organic and porous material involves a great technological interest for the process industry, e.g. paper mills, textile industry or food industry. The most common continuous industrial drying process is given by multiple hot air jet impingement. Usually average heat and mass transfer correlations have been used to predict the behavior of the drying process. The most of drying handbooks model the process with the correlation by Martin [1] for single and array nozzle. According to the Lewis analogy, the flow field geometry and the fluid properties establish the heat and mass transfer coefficients at the drying surface. In the case of multiple impinging gas jets, both round and slot, Mujumdar [2] claims that entrained ambient air may cause unpredictable effects and the heat transfer performance may worsen by 20–50%, depending upon flow rate, temperature difference between the jet and the ambient, and nozzle-to-surface spacing.

At present the single round hot air jet impingement drying is less studied than the multiple one. Although this configuration has not found a strong interest in the large industrial applications, because

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it relates to small surfaces and low powers, in the household drying processes (hair, textile, food) the single round nozzle shows a growing interest. Furthermore, being a relatively simple configuration, it may enlighten the fundamental physical processes governing the drying phenomena.

The study of the heat transfer in impinging hot hair jets is largely reported in literature[1],[3]-[5]. In [1] different experimental values of Nusselt number at different Reynolds numbers are shown on dependence of the ratio \( r/D \), where \( r \) is the radial distance from the stagnation point and \( D \) is the nozzle diameter. In addition, an average correlation is proposed. In 2008 Liu et al. [6] derived experimental and computational temperature distributions and flow patterns on a target surface impinged by a single air jet issuing from a plenum. The experiments cover a range of jet-to-target plate distance, \( Z/D \), from 1.5 to 12 for Reynolds number from 10 000 to 60 000. They employed temperature sensitive paints to obtain the distribution of temperature on target surface. They compared the Martin correlation [1] with their computational and experimental data, and observed that the average Nusselt raises with the ratio \( Z/D \) till to \( Z/D \) equal to 5. For \( Z/D \) equal to 1.5 and \( Re=20000 \) the overprediction errors of the Martin correlation are 6.2% and 13.3% for ratios \( r/D \) of 2.5 and 3.5, respectively. For higher \( Z/D \), the agreement with the experimental data is good for all the \( r/D \).

Furthermore, the Martin correlation was found to overpredict \( Nu \) at all \( Z/D \) for jet Reynolds number of 40000 and 60000.

In 2010, Di Marco et al. [7],[8] applied the Martin correlation to predict the drying rates of several hairdryers and four different wetted fabrics. They found that the drying rate prediction error depends on the fabrics. Generally, the average Martin correlations overpredicts the drying rate from 15% to 65%. The influence of the material on the drying rate characteristic is widely studied in the literature, but the drying of organic material like fabric has been rarely approached, and introduces additional problems in the study of the heat and mass transfer interactions.

In fact, the organic materials can be divided into main groups, as shown by Datta [9]: porous and capillary-porous materials, which can be defined as those having a clearly recognizable pore space. Examples of porous media include silica gel, alumina and zeolites, while those of capillary-porous media include wood, clay, textiles, paper, and packing of sand. As affirmed by Datta [9] the distinction between porous and capillary-porous is based on the size of pores (>10\(^{-7}\) m for porous and <10\(^{-7}\) m for capillary-porous).

Another important characteristic of the organic materials is hygroscopicity. In non-hygroscopic materials, the pore space is filled with liquid if the material is completely saturated, and with air if it is completely dry. The amount of physically bound water is negligible. In non-hygroscopic materials, vapor pressure is a function of temperature only. In hygroscopic materials, conversely, there is a large amount of physically bound water and there exists a level of moisture saturation below which the internal vapor pressure is a function of moisture level and temperature, and is lower than that of pure water. These relationships are called equilibrium moisture isotherms. Above this moisture saturation, the vapor pressure is a function of temperature only and is independent of the moisture level: thus, above certain moisture level, all materials behave as non-hygroscopic. The Martin correlation is suited to model the behavior of the non-hygroscopic materials, or hygroscopic materials when their moisture content is higher the critical one.

Many authors provide drying models for different porous solids that include: textiles, concrete slabs, burial of nuclear waste products, and flow through porous beds. In each case, the governing conservation equations were obtained and supplemented with the necessary thermodynamic and transport properties [10]. However, only limited experimental results are available for model calibration. Francis & Webfer [11] applied to the multiple slot air impingement drying correlations, developed by Martin to different porous textile materials, and compare their experiments with theoretical results. They resolved the heat and mass transport equation inside the porous materials and compared the data with the Martin correlation. They provide a new correlation for an array of slot nozzles with hot air jet impinging on a surface, based on the isotropic turbulence Kolmogroff approach. The problem of the drying process of a saturated porous material is, however, unsolved.
In this paper, the fabric drying has been experimentally investigated. A dedicated experimental apparatus for hot jet drying was assembled and operated, in which a hot jet impinges perpendicularly onto a wet fabric. The drying kinetic parameters of four different fabrics has been experimentally estimated and the transient radial distribution of the wetted fabrics has been measured and calculated.

2. Theoretical analysis

The drying process and the drying parameters of a hygroscopic material are well described in [12]. Generally there are two stages during a drying process. During the first stage the drying rate is constant, the evaporation front is located at the solid-gas interface, the temperature of the solid is the adiabatic saturation temperature and the moisture is continuously transported from the inside of the solid to the surface by capillary forces. Eventually, when the average moisture $\omega$ approaches the critical value (which is relative to the bound water), the evaporation is reduced and a further drying causes dry spots upon the surface. The drying rate $N$ decreases over time and this is the second time of drying. The behavior of an hygroscopic material is described the drying rate curves where the drying rate is plotted against the moisture of the solid. During the first stages the drying rate can be evaluated by means of the Lewis analogy: the heat transfer and the mass transfer are described by the same relations.

2.1. Zero-dimensional model

The local mass transfer due to a round jet of diameter $D$ impinging from a distance $H$ on a surface perpendicular to the jet axis has been locally experimentally measured in several works. Based on his and others’ works, Martin [1] has given a correlation for the integral heat and mass transfer over a surface of radius $r$ in the form:

$$
\frac{\bar{Sh}}{Sc^{1/2}} = \frac{\bar{Nu}}{Pr^{1/2}} = \frac{D}{r} \left[\frac{1 - 1.1 \frac{D}{r}}{1 + 0.1 \left(\frac{H}{D} \cdot 6\right) \frac{D}{r}}\right]^{2} \sqrt{\frac{Re}{200}} \left(1 + \frac{Re^{1/3}}{200}\right)
$$

where $Sh$, $Sc$, $Nu$, $Pr$, $Re$ are the Sherwood, Schmidt, Nusselt, Prandtl and Reynolds number, respectively. The correlation is valid in a wide range of parameters (2000 < $Re$ < 40000, 2.5 < $r/D$ < 7.5, 2 < $H/D$ < 12). The air parameters are evaluated at the nozzle exit.

Having determined in this way the average heat and mass transfer coefficients

$$
\bar{\alpha} = \bar{Nu} \lambda / D , \quad \bar{\beta} = \bar{Sh} \delta / D
$$

where $\lambda$ is the thermal conductivity and $\delta$ the diffusion coefficient between air and steam, the is the drying rate $N$ of water extracted per unit of surface can be calculated as

$$
N = \bar{\beta} \rho (\omega - \omega_0)
$$

where $\omega$ is the air specific humidity at the nozzle exit, while the surface is considered at the wet bulb temperature $T_0$, referred to the impinging jet conditions, and at saturation specific humidity $\omega_0$.

On the other hand, assuming that there is no other contribution to evaporation but air convection, the energy balance yields a link between the evaporating flow rate and the heat flux, $q''$

$$
q'' = N h_v = \bar{\alpha} (T - T_0) = \bar{Nu} \frac{\lambda}{D} (T - T_0)
$$

This zero-dimensional, or average, approach implies that the temperature of the evaporation film surface is constant over all the surface and it is equal to the wet bulb temperature.

2.2. One-dimensional model

A more detailed model can be set up by writing heat and mass transfer balances at different radii from the stagnation point: this approach allows $Nu$, and temperatures of air and surface, to radially change.
The local flow and temperature distribution on a flat surface has been widely described and analyzed in the literature. A wide review of a hot air jet impingement on a flat surface is reported in [13], where the local heat transfer has been measured for all the flow rate regions and compared with the main correlations presented in the literature. Considering an axisymmetric configuration, the mass and energy balances of the air jet can be written as

\[
\frac{dm_{\text{air}}}{dr} = 0; \quad \frac{dm_{\text{vapor}}}{dr} = 2\pi r N
\]

\[
\frac{d}{dr}[(m_{\text{air}} + m_{\text{vapor}}) h(r)] = 2\pi r N h_{fg}
\]

where \( h \) is the mixture enthalpy, and \( N \) is evaluated by Eq.(3), written on local basis, using Lewis analogy; this implies that the surface temperature keeps at the wet bulb value, evaluated on local air conditions. It is worth noting that air entrainment from the environment has been neglected. The heat and mass transfer balances allow to evaluate the radial trend of: surface temperature, mass transfer coefficient \( \beta \), \( \text{Nu} \) number, and several other parameters. To this aim, the surface was divided into concentric regions, and Eqs.(5) were integrated numerically with a simple forward-step scheme.

For heat and mass transfer calculation, the surface is divided in three regions: the heat transfer correlations adopted in each region are summarized in Table 1. The first region is the stagnation region, where \( r/D \) is lower than 1. The second region is characterized by the transition between the laminar flow of the stagnation region to the wall jet region. From the edge of the stagnation region \( (r/D = 1.0) \), transition region can be considered to extend up to an \( r/D = 2.5 \). A wide experimental analysis of this region is reported by Knowles and Myszko [15]. The last region is the wall jet region, where the Nusselt number drops monotonically. Decrease in the value of Nusselt numbers in this region is attributed to velocity decrease of fluid over the plate because of radial flow and exchange of momentum of wall jet with surrounding air.

**Table 1 - Correlations adopted in one-dimensional model**

| Region | Correlation | Notes |
|--------|-------------|-------|
| 1 \((r/D < 1.0)\) | \( \frac{Nu}{Re^{0.33} Pr^{0.33}} = a_1 \left( \frac{H}{D} \right)^{-0.11} \left[ 1 - \left( \frac{r}{D} \right)^2 \left( \frac{H}{D} \right)^{0.2} \right]^{-0.12} \) | Brdlik and Savin [14] \( a_1 \) and \( b_1 \) depends on H/D \( a_1 = 1.4, b_1 = 3.2 \) |
| 2 \( (1.0 \leq r/D < 0.5) \) | \( Nu = 0.2636 \ Re^{0.618} \left( \frac{H}{D} \right)^{-0.098} \left( \frac{r}{D} \right)^{-0.074} \) | Least-square correlation [13] which fits the experimental data of [15] |
| 3 \( (r/D \geq 2.5) \) | \( Nu = 0.0436 \ E \ Re^{0.8} Pr^{0.333} \left( \frac{H}{D} \right)^{-0.0976} \left( \frac{r}{D} \right)^{-1.098} \) | From [16], rearranged to use the value of \( Nu \) and \( Re \) number at the nozzle exit, \( E = 2.55 \) |

**3. Experimental apparatus and tests**

A dedicated experimental apparatus was assembled and operated to test drying of a surface by means of a hot jet. A commercial hairdryer was adopted to issue the jet. The experimental facility (figure 2) consists of a hairdryer support, a flow rate measurement apparatus, a drying rate measurement device and measurement instrumentation for temperature, pressure, power and humidity.

The apparatus allows to measure the amount of water removed from a moistened patch. The support holds the hairdryer perpendicularly to a plate carrying a circular moistened patch and allows the centre of the hairdryer nozzle to be aligned with the centre of patch with an accuracy of ±1.5 mm. The hairdryer used in these tests has an electric power of about 2000 W with an air flow rate of 50-60 m³/h at standard air conditions (\( T_{\text{air}} = 22 \ ^\circ\text{C}, R.H. = 60\% \)). The nozzle has a diameter of 46 mm and is placed at the distance of 130 mm from a thin wet porous patch of 279 mm of diameter, issuing the jet vertically downwards.
The air flow rate of the appliance is measured via a calibrated orifice in compliance with ISO norm 5167-2 [17]. The calibrated sharp-edged orifice has a diameter of 30 mm. A differential pressure transducer of 50 mbar f.s.v. (accuracy 0.5% f.s.v.) is mounted across the orifice. The accuracy of the gas flow rate measurement is better than 3%. At the same time, the electric power is measured by a pre-calibrated wattmeter with a maximum relative error lower than 4%. The dry and wet temperatures of the environmental air are measured by a dedicated probe (accuracy 0.15°C for the temperature at 0°C and 3% for the humidity). The absolute pressure of the environmental air is measured by a Druck PTX 610 transmitter (0 to 4 bar, accuracy 0.08% of full scale range). The temperature at the nozzle exit is measured with a T-Type thermocouple. The transient drying rate is measured with an electronic scale balance with a frequency of 0.2 Hz; compensation is performed to subtract the jet momentum.

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 mm².

(a) b) Figure 1 – a) Sketch of the experimental apparatus; b) fabric samples

The hairdryer input power was kept constant throughout each test. For each power level, the drying power 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 jet, and data were acquired every 5 seconds up to complete drying.

4. Fabric characterization
Figure 1-b shows the tested fabrics. All the fabrics have been experimentally characterized by measuring the drying kinetic parameters for hygroscopic materials. The moisture content \( X \) of a solid is expressed as the moisture by weight of bone-dry material in the solid. The saturation moisture content \( X_{sat} \) is defined as the maximum moisture content which can be hold by the fabric. The critical moisture content \( X_{crit} \) is 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 saturation humidity of the air. While $X_{sat}$ and $X_{crit}$ have been experimentally determined with an accuracy of 10%, $X^*$ has been calculated by the equation shown in [18]. The drying kinetic curves of all the materials are shown in figure 2 and the kinetic parameters are reported in table 2.

| Sample | Fabric type          | Dry weight [g] | $X_{crit}$ [gwater/gsolid] | $X_{sat}$ [gwater/gsolid] | $X^*$ [gwater/gsolid] | Experimental drying rate [g/s m²] | Theor. drying rate, 1D model [g/s m²] |
|--------|----------------------|----------------|-----------------------------|---------------------------|----------------------|----------------------------------|-------------------------------------|
| a      | Cotton / cellulose   | 13.3           | 3.2                         | 14.9                      | 0.042                | 1.74                             | 2.79                                |
| b      | Large pore cotton    | 20.6           | 1.75                        | 6.2                       | 0.042                | 2.18                             | 2.70                                |
| c      | Small pore cotton    | 22.4           | 2.16                        | 5.7                       | 0.111                | 1.64                             | 2.64                                |
| d      | Wool                 | 11.7           | 7.89                        | 9.5                       | 0.099                | 1.61                             | 2.76                                |

From the analysis of figure 2 and table 2 it is possible to see that all the tested fabrics show a hygroscopic behavior, but all the materials show a period where the drying rate is almost constant, except for “fabric d”. The constant rate regime is attained after about 100 s for all the fabrics. This period lasts from 630 s for fabric “b” up to about 1400 s for fabric “a”. For the fabrics “c” and “d”, the critical moisture detection is more complicated because the material gradually changes from a constant drying rate stage to a decreasing rate stage. For fabric “d” a constant drying rate is never really observed. The experimental drying rates of Table 2 are referred to the constant drying rate stage for all the materials, and compared with the theoretical value obtained with the 1-D model. Fabric “b” shows the lower prediction error (+20%) while fabric “d” exhibits the higher (+42%).

![Figure 2 – Kinetic drying curves for the tested samples.](image)

![Figure 3 - IR image of sample “b”, raw (left) and averaged (right), 80 s after the drying start.](image)
5. Measurement of local temperature distribution over the patch

In the experiments here described, infrared inspection has been used to measure the radial temperature distribution. The emissivity of each fabric has been estimated with several tests at cold condition. The temperature of the wet fabric has been measured by a thermocouple in different points and compared with that measured by the IR camera. Emissivities of 0.96 for fabric “b” and of 0.98 for fabric “d” have been measured. The effect of environment on the temperature map during the drying period has been estimated and corrected by continuously measuring the temperature of a copper plate, painted with a known emissivity painting (ε=1).

A typical IR image is shown in figure 3. The fabric surface has been divided into 20 concentric sectors, in which the average temperature has been calculated. The standard deviation of the experimental temperature is approximately 1.74% for the stagnation region and 2.5% for the wall jet region.

The transient radial temperature profile for fabric “b” and “d” are shown in figure 4 a) and b), respectively. For fabric “b”, after a period of 100 s, when constant drying rate is observed, the temperature keeps approximately constant over time; for r/D lower than 0.8 the temperature is nearly uniform, while it decreases with r for r/D ratios higher than 1. For fabric “d”, the temperature keeps varying with radius and time during the entire drying process.

![Figure 4](image)

**Figure 4**– Temperature profile along the radius at different times, for fabrics “b” and “d”

For fabric “a”, the theoretical 1-D model shows an acceptable qualitative agreement. The value of temperature match with the experimental ones in the wall jet region, but is lower than the experiment in the stagnation region, where the evaporation rate of the water is larger. Despite the calculated surface temperature is lower, the theoretical evaporation rate is higher than the experimental one. The reasons for this behavior are currently under investigation: some possible explanations are that the Lewis analogy is not valid in this region, due to additional mass transfer resistance in the fabric for high evaporation rate, or that the heat transfer correlations are not valid for a mixture of variable composition along r, like wet air. In the case of highly hygroscopic fabric (“d”) the discordance between the theoretical and the experimental profile is higher. In fact, at present, the theoretical model does not account at all of different fabric properties.

6. Conclusions

The paper deals with the experimental and theoretical evaluation of drying of hygroscopic fabric. The aim is testing the accuracy of the heat and mass transfer correlations in predicting the drying rate. In particular, attention has been focused on the first drying stage, when the drying rate is constant and the temperature at the evaporating surface should keep at the adiabatic saturation temperature. The kinetic drying curves and parameters of four different fabric samples have been experimentally detected. The temperature profile along the radius has been measured with an IR camera. A simple 1-D model has
been set up and compared with experimental data. Although the temperature profile is qualitatively matched, the experimental values of temperature resulted higher than the theoretical prediction. Furthermore, the model overpredicted the drying rate. The error prediction seems to be correlated with the hygroscopic behavior of the fabric: more hygroscopic fabrics show higher errors.

The encountered discrepancy between theoretical and experimental values may be explained by the fact that higroscopicity of the surface introduces additional physical mechanisms in the process. In particular, this may invalidate Lewis analogy and/or heat transfer correlations. However, a wider experimental activity must be performed before proposing corrections to the current correlations and models.

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