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Physical incorporation of particles in a porous media: a path to a smart wood*

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Abstract. The aim of this work is to develop a functional wood incorporating, in its surface, physical and chemical properties that meet society demand. For instance: fire resistance, magnetic electrical conduction (metal-wood particles), antibacterial reaction (copper-wood), anti-pollution (zeolite-wood), dry coloring, reflective effects (minerals-wood). As part of the research on wooden materials, the technique of "JAZOLTHOP[1]" driving micrometric particles before combining them and moving in supersonic speeds was used in the framework of enriching a wooden substrate. Various tests were conducted on two wooden materials (fir and ash tree) submitted to four typologies of particles (steel shot, garnet, corundum and glass beads). The surfaces of the test samples were machined beforehand for a use of conventional smooth quality, thus defining a reference surface before incorporation. The enriched samples were characterized by using two optical techniques; firstly a surface technique through macroscopy Leica 110X ZP, then a volume technique through tomography[2]. Subsequently, volume simulations (wood-inclusions) were implemented to study the thermal transfer. The obtained results showcase the existence of certain set conditions to reach the critical fluency of incorporation and to localize the enrichment on a parallel plan to the sample surface. The results show also the influence of particles concentration and the kind of the chosen wood on the final composite matrix/particle media.

1 Introduction

The surface treatment process by nitrogen jet is in the development sustainable environmental technologies. It is presented as clean treatment methods. The process consists of projecting on the and innovative process compared to other surface a stream of nitrogen from a high pressure reservoir (300–380 MPa) and low temperature (−150 °C), without generating additional waste by recycling of the inert gas in the atmosphere [1,2].

On leaving the spray nozzle, nitrogen becomes supersonic jet and gaseous. However, it undergoes many thermodynamic transformations during its passage through the atmosphere, which leads to changes in the nature and composition of the phases present. Thermo-physical data nitrogen with critical conditions $P_c = 3.3958$ MPa, $T_c = 126.192$ K and $\rho_c = 313.3$ Kg m^{-3} show that one can move from a position where the jet is made of a 100% dense phase (liquid or supercritical) to a position where the jet is multiphase and consisting of a mixture of phases (gas/liquid/solid particles) while passing through an extreme position or the jet is 100% gaseous (directly at the nozzle exit) [3].

Wood as a natural organic material has played a big role in human activity thanks to his unique properties like for example high strength weight ratio, strong mechanical properties, good formability and aesthetic texture [4,5]. It's a lightweight and healthy biopolymer that has been largely used in fields of decoration, buildings and other constantly lives [6,7]. Nonetheless, it also suffers from some disadvantages such as low dimensional stability, appearance variation and it's easy to be biologically attacked, etc. [8]. That's why many tries have been made in order to improve potential applications of wood [9,10]. Besides, lately, much effect has been committed to create sophisticated functional materials by mimicking biological structures and architectures that cause excellent functions and performance, such as adjusted mechanical properties [11], drag and turbulence reduction (shark skin) [12] and brilliant colors (butterfly effect) [13]. Understanding and trying to apply the basic principles of engineered materials

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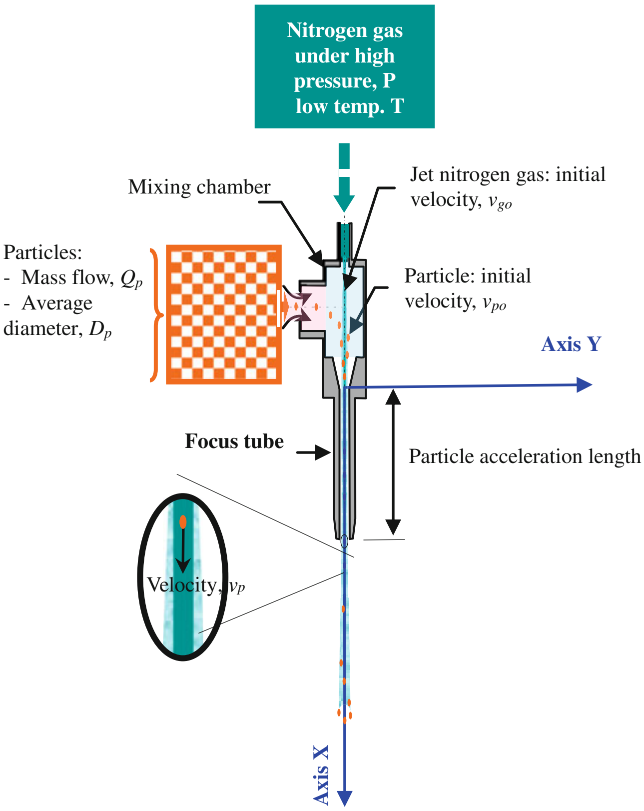


Fig. 1. Schematic diagram of the mixture model and particles acceleration in a gas stream.

can lead materials science towards renewable, sustainable and smart materials. For example, recently, a study was made about fabrication of smart coatings based on wood substrates with photo-responsive behavior and hydrophobic performance [14].

The objective of the study is to verify the technological feasibility of the research dealing with the enrichment or the incorporation of particles in a wood substrate with a nitrogen jet. To achieve this goal, we will show in the following sections, by experiments carried out on a non-optimized test bed specially designed to scale laboratories, how different types of particles may be added to a nitrogen jet supercritical fluid to form a complex mixture, how these particles can be accelerated without hot thermal excitation and incorporated in a wood sample. The different experimental conditions were chosen to highlight the phenomena characteristic of a process of incorporation.

2 Simplified model for evaluating the particle speed

In a two-phase flow gas-particles in a cylindrical pipe called focus tube, the particle assumed isolated m_p mass, mass flow rate Q_p and the average diameter D_p reaches the velocity v_p to the distance x by the transfer of momentum of the gaseous fluid at the interface (Fig. 1).

Assuming constant along the focusing tube, the following physical magnitudes: temperature, pressure, density of the gaseous fluid, and neglecting the virtual ground forces, wall friction and gravity, the variation of the particle velocity v_p in function of the distance x, under the action of drag, is given by the following analytical equation [15]:

$$x = \frac{\frac{m_\mathrm{p}}{Q_\mathrm{p}^2}}{\frac{1}{4}K_\mathrm{d}\left(\frac{1}{Q_\mathrm{g}}+\frac{1}{Q_\mathrm{p}}\right)^2} \times \left(\ln\left|\frac{2Q_\mathrm{p}}{R}v_\mathrm{p} - \frac{2}{1+\frac{Q_\mathrm{g}}{Q_\mathrm{p}}}\right| - \frac{\frac{2}{1+\frac{Q_\mathrm{g}}{Q_\mathrm{p}}}}{\frac{2Q_\mathrm{p}}{R}v_\mathrm{p} - \frac{2}{1+\frac{Q_\mathrm{g}}{Q_\mathrm{p}}}} + 2C\right).$$

This analytical model is derived from the amount of movement of balance written by Drew [16] in a two-phase mixture flowing in a cylindrical conduit.

R is the pulse of nitrogen mixture-particles given by the following mathematical formula:

$$R = Q_\mathrm{p}v_\mathrm{po} + Q_\mathrm{e}v_\mathrm{eo} = Cste,$$

Q_e and Q_p the mass flow of particles and gas respectively v_po and v_eo the initial velocities in particle mixing chamber and nitrogen jet respectively K_d: the drag factor given by the following formula:

$$K_\mathrm{d} = \frac{3}{4}C_\mathrm{d}\frac{\rho_\mathrm{g}}{D_\mathrm{p}} = \frac{1}{2}\Omega_\mathrm{p}\rho_\mathrm{g}C_\mathrm{d},$$

C_d drag coefficient, Ω_p, the area of the master torque of a particle, ρ_g, the density of nitrogen gas, C, a constant determined by the initial conditions.

Equilibrium and velocity of the particle flow of propellant nitrogen gas is given by the following expression:

$$v_\mathrm{eq} = \frac{\dot{m}_\mathrm{p}\,v_\mathrm{po} + \dot{m}_\mathrm{g}\,v_\mathrm{go}}{\dot{m}_\mathrm{p} + \dot{m}_\mathrm{g}}.$$

The simplified model of accelerated particles proposed in the first equation. It gives the particle velocity v_p in the focusing tube for dynamic pressure of the gas $P = 2500$ bar, the average diameter of the particle $d_\mathrm{p} = 50$ microns, particle mass flow rate $Q_\mathrm{p} = 8.33$ g/s (30 kg/h), volume flow rate of liquid nitrogen, Q_g (liq.) $= 8$ E^{-5} m^3/s (4.8 L/min). Forecast curves show that the particle quickly accelerates to approach asymptotically the equilibrium speed $V_\mathrm{ss} = 633.49$ m/s.

The particle was mechanically excited (dynamic pressure nitrogen gas) and without heat it can reach supersonic speeds (500–600 m/s) of the same order of magnitude as those achieved by similar particles, but excited heat in the cold spray [17,18].

This finding is of paramount importance for further research. It leads us to conjecture the existence of a critical rate of incorporation of the particle in a porous material like wood. The first major result from the theoretical point of view is experimentally confirmed by the observation of particles embedded in perfect mechanical balance in a solid wood.

Table 1. Some properties of the chosen species.

Wood	Density	Monnin hardness	Tensile strength in static bending (MPa)	Longitudinal elastic modulus (MPa)
Fir	0.49	2.5	80	14 300
Ash	0.71	4.2	111	15 300

3 The test samples

We chose two common species: a fir tree and an ash tree. These are some properties of the chosen species of wood in Table 1.

The samples were machined wedge-shaped in order to maximize the number of tests by the geometric change of the shooting distance during the scanning of the jet. The other characteristic of the samples is to obtain a constant reference surface quality using the same machining parameters (Fig. 2).

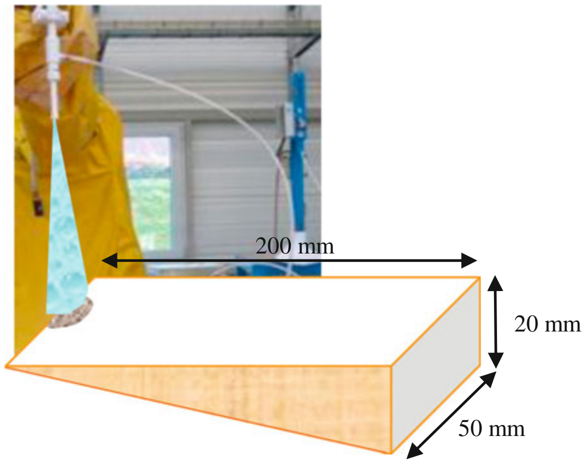


Fig. 2. Geometric shape and dimensions of a wood sample, machined face receiving the jet.

4 Particles used

In Table 2 below are the particles that have been used for this experimentation, metallic granulate, white corundum and garnet barton and some of their properties.

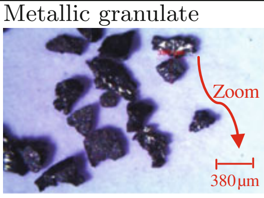
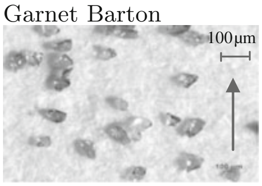
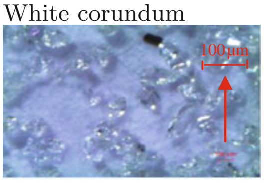
5 Results and discussion

During the incorporation tests, we arranged two by two samples, on a horizontal plan, fir and ash to treat both species simultaneously for given conditions of work settings. This arrangement causes the variation of the shooting range where the jet moves horizontally on the samples (Fig. 3).

5.1 Results of optical observations on the surface

First, pictures at the macroscopic optical Leica X110 ZP (X4.5 zoom) machined surfaces of samples fir and ash (photographs 1 and 2) are taken before incorporation of particles trials. This manipulation was performed to compare the surfaces before and after incorporation and measured, macroscopically, transformations/enrichments recorded.

Table 2. Particles properties.

Particles	Grain size geometry	Chemistry	Hardness
Metallic granulate 	125–425 microns Angular	C (0.80%), Mn (0.60–1.20%), Si (0.40%)	Rockwell 64–68 HRC
Garnet Barton 	50–70 microns Angular	Fe_3 $Al_2(SiO_4)3$	Mohs hardness 7.5–8
White corundum 	106–150 microns round	Al_2O_3 (alumina)	Mohs hardness 9

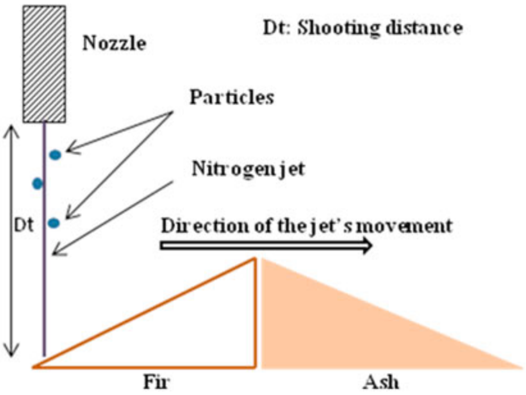


Fig. 3. Placing samples in pairs (fir, ash) while scanning the shooting distance *Dt*.

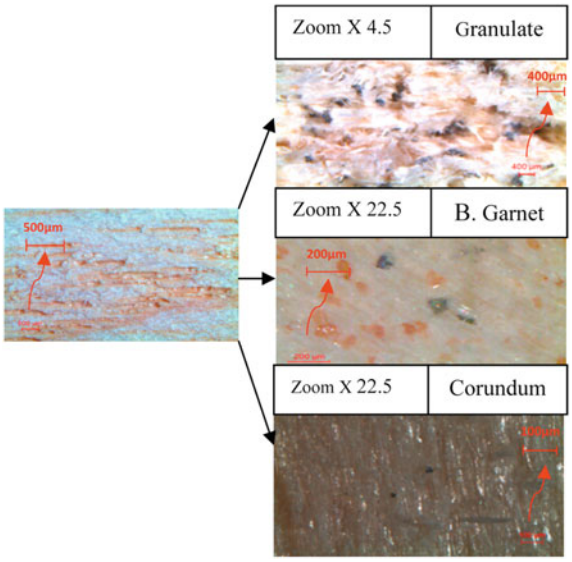


Fig. 4. Fir before and after incorporation.

Below are some pictures of optical observations on the surface of Fir before and after incorporation of granulate, barton garnet and white corundum (Fig. 4).

This second figure is the results for the ash tests before and after incorporation with the three types of particles (Fig. 5).

We can see a "highly localized" transformation on the surface of the wood, the mechanism appears to be limited to the surface material. In fact, the particle is doped in the material by deforming or locally by pushing the fibers, giving the surface a new microstructure.

This result was more pronounced in the case of fir than in the ash and this leads the say that the softest wood is best suited for the incorporation. The angular particles have given a better result than round ones however another experimental trial will be done to test many sizes and compare the different impacts. This deformation does not induce changes in mechanical properties across the sample structure but conventional mechanical characterization tests will be performed to confirm or disprove this result.

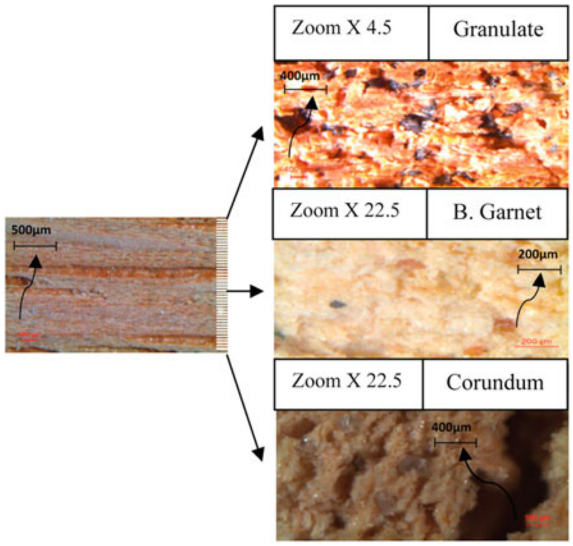
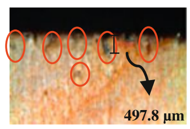
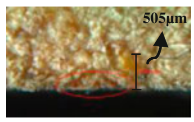
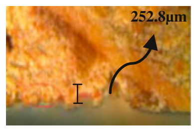


Fig. 5. Ash before and after incorporation.

Table 3. Results of optical observations in depth.

Wood/particle	Picture	Depth (μm)
Fir/granulate		500–600
Ash/granulate		450–600
Fir/Garnet Barton		100–600
Ash/Garnet Barton		200–250

In the images of "wood and white corundum", the bright areas are assigned to the white corundum particles due to reflected light from the macroscope.

5.2 Results of optical observations in depth

Optical observations show macroscopically visible presence of particles of settlements on the sample surface impacted upon incorporation. This process starts, however, identified three phenomena that seem beings characteristics (Tab. 3).

A test sample (Fir) was analyzed by tomography in ENS-Cachan and it gaves the following result, below, showing that in the three surfaces of the sample we can see the incorporation of the particles in the wood (Fig. 6).

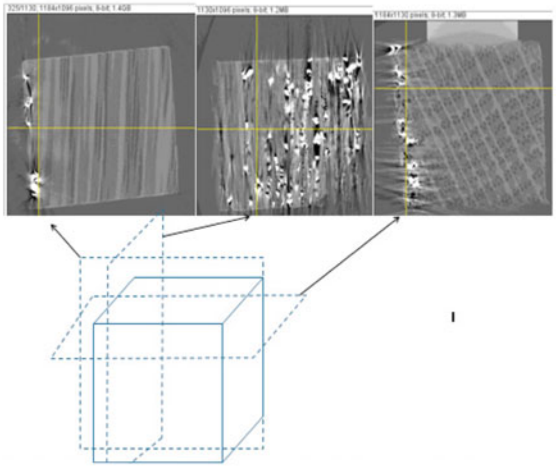


Fig. 6. Tomography analysis result.

6 Conclusions

Following these initial tests and observations, it was possible to obtain particles embedded in the wood at different depths depending on the species and the selected particles. The more we master this method the more we can later act on the material to be functionalized.

The interaction between the nitrogen jet projected through the injection nozzle and the material to be treated involves three types of parameters:

- The operating parameters which relate to the geometry of the nozzle, the upstream pressure, the working temperature and the firing distance;
- The thermo-mechanical properties of the target which is the material to be treated;
- Parameters related to nitrogen jet concerning its formation, the flare, the nature and composition of its phases, and its physical properties.

The effects of the temperature and the analysis of the hardness tests before and after the incorporation of the particles in the wood will be programmed into the next test campaign.

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