A Novel Economic Large-scale Production Technology for High-quality Thermally Modified Wood

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ABSTRACT

A modified and expanded version of Burmester's technique for thermal treatment of wood in a pressure autoclave is presented here. Using a simple and accurate control strategy, the wood is kept near hygroscopic equilibrium with its surroundings during the entire treatment cycle. Treatment-induced internal wood stresses and associated wood degrade are thus minimized. The autoclave is completely closed during the treatment cycle and is by definition devoid of emissions of volatile organic substances. Consequently, reactive volatiles stay available for re-incorporation into the wood matrix, for the purpose of optimizing both strength properties and biological durability, achieved at moderately high temperatures between 160 and 190 °C. The technique is suitable for economic large-scale industrial production of high-quality thermally modified timber. The first plant using this technology has commenced operation in the Netherlands.

INTRODUCTION

The effects of heat treatment on wood are known for almost a century, but their large scale industrial application has waited until the emergence of interest in environmentally benign means of wood preservation, two decades ago. Thermally modified timber was envisioned to become an important alternative for CCA-treated wood and very durable natural wood species, but is today mainly found in lesser demanding applications, utilising its appealing appearance (darkened colour) and reduced moisture swelling property, with a limited degree of biological durability enhancement. Judged from the scope of technical possibilities with thermal modification and its environmental profile, the present market size might be expected to be much larger than it actually is. The inhibiting factors for substantial market growth are analysed in the next section. Then, a novel production technique is presented which is specifically designed to diminish these inhibitors.

COMMERCIAL CONSIDERATIONS

Wood modification treatments upgrade wood as a raw material into a new raw material with one or more improved properties. The added value of this transformation must outweigh the costs to create it. The business case for thermally modified wood has to cope with a number of difficulties, imposed by the high quality requirements on the input material, the competition by alternative raw materials and the high production, development and marketing costs. High-value markets, *e.g.* the wall cladding market, have been found for heat treated high-quality natural wood species, providing the basis for a growing wood heat treatment industry. Beneath these niche markets, there are huge volume markets, wherein thermally modified timber could compete technically, but not yet economically. A choice for adding extra value by adjacent conversion of relatively too expensive thermally modified timber into finished products would not fundamentally improve the business case for the heat treatment. For a more sound approach to open new markets for thermally modified timber, one might try taking a route via a process improvement requiring input material of a less stringent quality. Such an attempt is undertaken and described in the next section.

TECHNOLOGICAL CONSIDERATIONS

Wood moisture content

The presence of moisture in wood presents great difficulties in heat treatment. During the heat treatment cycle, steam pressure and moisture gradients in wet wood can cause severe structural damage. The usual way to reduce this problem is to carefully dry the wood to a low moisture content at a sufficiently low temperature before exposing it to the high-temperature regimes in the heat treatment cycle (Johansson 2006, Boonstra *et al.* 2006). In all heat treatment processes known to the author, wood will eventually reach a high temperature oven dry state, where shrinkage stresses due to the structural anisotropy and inhomogeneity of wood reach a maximum (Cheng *et al.* 2007). Conversely, if the oven dry state could be avoided in the heat treatment cycle, a lower threshold on input timber quality can be used – with an important economic advantage. Following this premise, a novel heat treatment technology is introduced.

Hygroscopic equilibrium

Using the principles of kiln drying, wood can be brought in a hygroscopic equilibrium with its environment: for any given wood species at a given temperature there is a water vapour pressure in equilibrium with its moisture content, i.e. which avoids drying. In the temperature range for pre-dried (*ca.* 12% MC) wood modification the required water vapour pressures for hygroscopic equilibrium are well above atmospheric pressure and must be contained in a pressure autoclave.

Thermal modification

The system of pre-dried wood, interacting with pressurized superheated steam, has been shown (Burmester 1973) to produce chemical reactions in carbohydrates and lignin, giving the characteristic properties of thermally modified timber. Moreover, the typically used temperatures in pressurized steam environments, 160-190 °C (Tjeerdsma *et al.* 1998), are about 50 °C lower than with dry heating (Weiland & Guyonnet 2003) at the same level of modification. The pressurized steam offers therefore the possibility of multiple simultaneous functions: to establish a hygroscopic equilibrium, to lower the treatment temperature and/or to shorten the production time. These three functions all contribute to the economy of the process, but are mutually dependent and must be optimized for each treatment schedule dedicated for a particular wood species.

Closed system

Keeping the system gas-tight during the heat treatment has the advantage of having no volatile organic emissions during production time and keeping reactive volatiles available for repolymerization reactions.

Process Reactor

First, consider a 2.0 m diameter fast-opening door jacketed pressure autoclave, heated with temperature controlled oil circulating through the heating jacket. The timber (a 20 mm stickered timber stack 1.20m x 1.20m x 6m) and a suitable quantity of liquid water are put in the inner pressure compartment, which is evacuated to about 0.1 bar (abs). Then it is slowly heated allowing equilibration between the wood moisture content, the water and the vapour. This setup is an enlarged version of Burmester's classical experiment. It has several limitations on this large scale, like a very slow heating and equilibration rate, a lacking active water vapour pressure control, and virtually no means of keeping equilibrium during the evolution of the modification reactions as well as during the heating and cooling trajectories. Nevertheless, early experiments at a temperature of 180 ºC using this simple setup showed very promising biological durability EN113 and ENV807 test results on European wood species fir, spruce, pine, beech, ash and oak, but with poor (casehardened) structural properties (Ohnesorge *et al.* 2008) as a result of uncontrolled excursions from hygroscopic equilibrium during the treatment cycle.

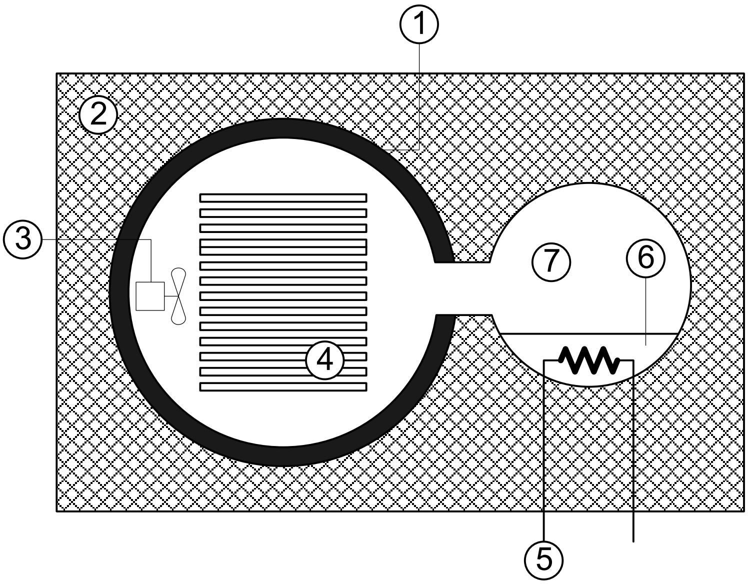

Figure 1: Schematic drawing of the Firmolin® technique. 1=heating jacket of pressure autoclave, 2=thermal insulation, 3=fan, 4=timber stack, 5=heating element, 6=water reservoir, 7=water vapour.

The next generation setup (Figure 1) consists of two connected pressure compartments (Willems 2008) and has recently been built and tested in the Netherlands. The left wing compartment is the just described jacketed autoclave with the same cross-sectional dimensions, extended to 13.5 m length and equipped with a heavy duty fan for vapour circulation. The right wing compartment is a temperature controlled, directly heated water reservoir. This setup provides a fast and accurate control of both vapour temperature T_{vap} and water vapour pressure, via the heating jacket temperature and the water reservoir temperature T_{res} respectively. From the (T_{vap}, T_{res}) set of temperatures the relative humidity (RH) of the vapour can be calculated (Eqn. 1).

$$RH(\%) = (P_{sat}(T_{res}) / P_{sat}(T_{vap})) \times 100 \qquad (1)$$

where RH is the relative humidity and $P_{sat}(T)$ is the saturated water vapour pressure at a given temperature T. In the 2-compartment setup heat treatments can be performed under fully controlled climatic (T_{vap}, RH) conditions. This heat treatment technology has been patented and given the name Firmolin®, the contraction between the Latin words *firmo-* (strong, durable) and *–lin,* abbreviated from *lignum* (wood).

DISCUSSION

During the heat treatment several physical and chemical transformations are taking place in wood, which have an effect on its hygroscopicity as well as the moisture content (MC). Both changes cannot be quantitatively captured *on-line*, which makes the control of MC unfeasible. Instead, the measured wood temperature and the RH of the surrounding vapour are controlled via the process temperatures (T_{vap}, T_{res}), whilst the MC is allowed to self-adapt to the shifting hygroscopic equilibrium. Since the initial MC is ca. 12% and the hygroscopic equilibrium changes smoothly, both the magnitude and the rate of MC-changes remain acceptably low.

By performing the thermal modification of wood at a suitable MC in hygroscopic equilibrium, continued drying to the oven dry state is evidently avoided. The question that must be addressed here is whether it *should* be avoided, apart from the prospect that it diminishes wood degrade losses. Concerns might be risen whether certain chemical reactions in the later stages of the modification process, the dehydration and cross-linking reactions, will sufficiently develop. To shift the reaction equilibria towards the dehydration and condensation products, the removal of water (a co-product) might be required. On the other hand, in batch reactors for the production of furfural (a dehydration product) from xylan hemicellulose, condensation type loss reactions occur in a saturated steam environment up to 200°C (Zeitsch 2000). In steam treated lignin at 185 to 220 °C depolymerization and repolymerization reactions are taking place simultaneously (Li *et al.* 2007). They show that the repolymerization reactions eventually prevail, producing stable carbon-carbon cross-links between lignin units, again in a saturated steam environment. These results indicate that there is no necessity to perform heat treatments in the oven dry state.

Although process optimization efforts are ongoing, some statements about economy of the Fimolin®-technology can already be made. The pressure equipment needed for this technology requires a slightly larger capital investment (treatment volume based) in comparison to dry heating thermal modification kilns. During the treatment cycle wood releases water as well as some polluting organic substances, which are added to the water reservoir. After each treatment cycle excess water must be decanted and properly disposed of, which is a cost component. Against the extra costs there are decisive cost-reducing factors: shorter treatment time, lower treatment temperature, less wood degrade, lower quality requirements on input material.

CONCLUSIONS

It is beneficial to perform thermal modification treatments on pre-dried wood in hygroscopic equilibrium with superheated steam by using a dedicated pressure autoclave. Such a process is less dependent on timber of the best available quality. The presented Firmolin®-technology offers a fast and accurately controlled process to perform this type of heat treatments. Its economic figure promises opportunities in new markets, beyond the commercial scope of thermally modified timber produced from costly defect-free timber.

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