Department of Forest Products Technology

Feasibility of wood peeling assisted by infrared heating

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written by Anna Dupleix

Aalto University

DOCTORAL DISSERTATIONS

Aalto University publication series
DOCTORAL DISSERTATIONS 200/2013

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A doctoral dissertation completed for the degree of Doctor of Science (Technology) (Doctor of Philosophy) to be defended, with the permission of the Aalto University School of Chemistry, at a public examination held at the lecture hall 3 of the school Arts et Metiers ParisTech, rue Porte de Paris, 71250 Cluny, France on 13 December 2013 at 2 PM and broadcasted live in Kuitu Puu1 at the Aalto University School of Chemical Technology (Espoo, Finland)

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2013-ENAM-0044

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Aalto University publication series
DOCTORAL DISSERTATIONS 200/2013

ISBN 978-952-60-5464-3
ISBN 978-952-60-5465-0 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-60-5465-0

Unigrafia Oy
Helsinki 2013

Finland

Publication orders (printed book):
https://aaltodoc.aalto.fi/
http://pastel.archives-ouvertes.fr/

441 697
Printed matter

Aalto University

Abstract

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Author
Anna Dupleix

Name of the doctoral dissertation
Feasibility of wood peeling assisted by infrared heating

Publisher School of Chemical Technology

Unit Department of Forest Produtcs Tehnology

Series Aalto University publication series DOCTORAL DISSERTATIONS 200/2013

Field of research Wood Material Technology

Manuscript submitted 5 September 2013 **Date of the defence** 13 December 2013

Permission to publish granted (date) 8 October 2013 **Language** English

☐ **Monograph** ☒ **Article dissertation (summary + original articles)**

Abstract

'Peeling' is the process of converting a log into a continuous thin (from 0.6 to more than 3 mm) ribbon of green wood termed 'veneer' whose production plays an important role in the manufacture of light-weight packaging, plywood and Laminated Veneer Lumber (LVL) which are amongst the most widely used wood products. Prior to peeling, the round green-wood of most species needs to be heated to temperatures ranging from 30 to 90°C in order to soften the wood and ease cutting. Forming part of a broader programme to develop a system that could be embedded on a peeling lathe, the goal of this PhD thesis was to investigate the technological feasibility of using infrared (IR) to heat green logs and so circumvent many of the economic and environmental disadvantages arising from soaking. The main output of this study was to demonstrate that the penetration depth of IR into green wood is limited to several tens of micrometres and that heat transfers into green wood up to the cutting plane (located several millimetres underneath the surface) is by conduction, which is slow due to the insulating properties of wood. Heating green wood with IR radiation is therefore unsuitable for the high peeling rates currently in use in the industry.

Résumé

Le déroulage permet de transformer un billon en un ruban continu de bois vert (de 0.6 à plus de 3 mm d'épaisseur) appelé « placage » dont la production joue un rôle important car les placages servent de base à un grand nombre de produits industriels parmi les plus utilisés dans l'industrie du bois (Laminated Veneer Lumber (LVL), contreplaqués, emballages légers, etc.). Pour certaines essences, ce procédé exige un prétraitement, appelé « étuvage » qui consiste à chauffer au préalable le bois vert (saturé en eau) par immersion dans l'eau ou dans la vapeur d'eau chaude (de 30 à 90°C) afin de lui conférer une déformabilité remarquable et faciliter la coupe. Cette pratique présente cependant de nombreux inconvénients industriels et environnementaux. Cette étude vise à remplacer les pratiques d'étuvage par une technologie de chauffe par rayonnement infrarouge (IR) embarquée sur les machines de production. L'apport majeur de cette étude est d'avoir démontré que la pénétration des rayonnements IR dans le bois se limite à quelques dizaines de micromètres. La propagation de la chaleur jusqu'au plan de coupe situé à quelques millimètres sous la surface s'effectue donc par conduction, mode de transfert de chaleur lent dans le cas du bois aux propriétés isolantes remarquables. La chauffe embarquée faisant appel aux IR semble donc inadaptée face aux cadences de déroulage imposées par les industriels.

Keywords beech (bouleau) , birch (hêtre), Douglas-fir (douglas), green wood (bois vert), heating (chauffe), infrared (infrarouge), peeling (déroulage), spruce (épicéa)

ISBN (printed) 978-952-60-5464-3 **ISBN (pdf)** 978-952-60-5465-0

ISSN-L 1799-4934 **ISSN (printed)** 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year** 2013

Pages 132 **urn** http://urn.fi/URN:ISBN:978-952-60-5465-0

Préface

Ce document est le résumé d'un travail de recherche débuté en octobre 2010 sous la supervision de Mark Hughes, Rémy Marchal, Jean-Christophe Batsale et encadré par Louis-Etienne Denaud, Andrzej Kusiak et Fréderic Rossi.

Ils m'ont permis de conduire ce travail comme je l'entendais. Je les remercie chaleureusement.

Ce travail a été mené au sein des laboratoires de recherche du Department of Forest Products Technology - School of Chemical Technology de l'Université d'Aalto en Finlande et du LaBoMaP (Laboratoire Bourguignon des Matériaux et Procédés) à Cluny, dans le cadre d'une cotutelle de thèse entre l'Université d'Aalto et l'ENSAM (Ecole Nationale Supérieure d'Arts et Métiers) ainsi qu'au sein des laboratoires I2M (Institut de Mécanique et d'Ingénierie) de Bordeaux et CEMHTI (Conditions Extrêmes et Matériaux : Haute Température et Irradiation) d'Orléans.

Ces travaux de recherche ont été menés en vue des cinq articles qui composent cette thèse.

Ce projet est la réalisation collective de différentes équipes de recherche, et en particulier de:

Fabrice, Jean, Jean-Claude, Laurent, Louis, Michael, Rémy, Robert et Simon ;

Andrzej et Jean-Christophe ;

Domingos et Patrick.

Certains résultats présentés sont également issus du travail de :

Guillaume, Hannu, Olivier, Madeleine, Sid'Ahmed, Tiina et Timo.

Je souhaite remercier les membres des équipes administratives qui permettent la vie quotidienne au sein des laboratoires qui m'ont accueilli et notamment : Iina, Isabelle, Kati, Muriel, Nathalie, Sirje et Ulla, le personnel de l'ENSAM, de l'accueil, de la comptabilité et de la scolarité à Cluny.

Je remercie les écoles doctorales de l'Université d'Aalto et de l'ENSAM pour leur aide et leur compréhension, en particulier : Carole, Christian, Claude et Florence.

Je remercie les documentalistes de l'ENSAM: Christine, Françoise et Thomas.

Je remercie les élèves de l'IUT SGM (Sciences et Génie des Matériaux) de Châlon-sur-Saône, Luc, Sandrine et Sylvie.

Je remercie les collègues de l'équipe bois de l'Université d'Aalto: Albert, Anti, Atsushi, Ditta, Jonna, Jussi, Lauri, Katja, Kristiina, Olli, Pekka et de l'équipe pédagogique d'Aalto.

Ainsi que Mireille, les collègues de l'ENSAM de Cluny et du TREFLE (Transferts Écoulements Fluides Énergétique) de Bordeaux.

Enfin, je remercie les personnes et institutions qui ont soutenu financièrement ce projet me permettant de me déplacer et de travailler dans des conditions optimales: l'institut Carnot ARTS (Association de Recherche Technologie et Sciences), l'Académie Française (et sa fondation Jean-Walter Zellidja), l'Ambassade de France en Finlande (et le programme Kaksin), l'entreprise Fortum en Finlande, l'action COST FP0904, et l'école doctorale RYM-TO dont la bourse m'a permis de travailler au cours de l'année 2012 en Finlande.

Octobre 2010.

Assise sur les marches de l'école en face du cinéma de Cluny, je m'apprêtais à reprendre la route sans me présenter à l'ENSAM où l'on m'attendait pour y discuter d'un projet de thèse. Je remercie Lucas et Maman pour m'avoir persuadé au téléphone de me rendre à l'entretien.

Réaliser une thèse était alors un rêve et un défi qui clôturait un parcours entamé en classes préparatoires aux lycées Sainte-Geneviève, Faidherbe et Joffre, et poursuivi à l'école Centrale et à l'Université d'Aalto. Je remercie toutes les personnes qui ont facilité mon apprentissage lors de ces années d'études, et auparavant. Je remercie aussi les personnes qui, au cours de mes premières années de vie professionnelle, m'ont invité à faire de la recherche et à découvrir le matériau bois. En particulier, je pense à Jean-François, Matthieu, Patrick de l'AFTBM (Association Forêt Bois Trièves Matheysine) et Pierre de l'Université d'Auckland ainsi qu'à François et aux entreprises Baufritz et Bouygues.

J'envisageai la thèse comme une construction commune au sein de laquelle j'appréciai assembler les idées et expertises de chacun. C'est animée d'un sentiment d'urgence et rarement sereinement que j'ai mené ce travail. Aujourd'hui, il en serait sans doute tout autrement. Ces travaux de recherche auront donc été particulièrement enrichissants et constructifs - au-delà d'une meilleure compréhension des phénomènes physiques mis en jeu lors de la chauffe infrarouge du bois vert déroulé.

Bien des questions se sont posées au cours de ces trois dernières années sur le plan professionnel mais aussi et tout autant sur le plan personnel. La présence rassurante d'un certain nombre de personnes et la richesse de nos échanges m'ont beaucoup aidée et me permettent aujourd'hui de terminer ce travail. Je pense tout particulièrement à :

Bonne ;

Alexandra, Alp, Annaig, Anne, Antoine, Ariane, Betty, Camille, Catherine, Cécile, Céline, Christine, Emmanuel, Erkki, Etty, Helena, Irma, les jardiniers de l'APSH 34, Jacquot, Jacqueline, Karin, Kristina, Liina, Lucas, Lucie, Maimouna, Maman, Manu, Marion, Michel, Michelle, Minna, Mireille, Monique, Myriam, Nolwenn, Olivier, Outi, Papa, Pascale, Patrick, Pauline, Pierre, Rém, Renaud, Sampsa, Seija, Stéphanie, Stevan, Suvi, Sylvie, Tan, Timo, Tom, Véronique, Viet-Anh et Yannick.

et aux personnes croisées ici et là, récemment et il y a plus longtemps.

J’aimerais pouvoir partager les fruits de ce travail avec chacun.

Novembre 2013.

Preface

The following document sums up research work that started in October 2010 under the supervision of Mark Hughes, Rémy Marchal, Jean-Christophe Batsale and lead by Louis-Etienne Denaud, Andrzej Kusiak and Fréderic Rossi.

They enabled me to conduct this research the way I intended. A warm thank you goes to each and all of them.

This thesis took place at the research labs of the Department of Forest Products Technology - School of Chemical Technology of Aalto University in Finland and LaBoMaP (Laboratoire Bourguignon des Matériaux et Procédés) in Cluny, France, and is a cotutelle between Aalto University and ENSAM (Ecole Nationale Supérieure d'Arts et Métiers). Also, parts of the research work took place at the I2M (Institut de Mécanique et d'Ingénierie) labs in Bordeaux, France and at the CEMHTI (Conditions Extrêmes et Matériaux : Haute Température et Irradiation) labs in Orléans, France.

This research work has been conducted in view of the five publications of which composed this thesis.

The overall project is the result of a collective effort from various research teams and I would like to thank the following people in that respect:

Fabrice, Jean, Jean-Claude, Laurent, Louis, Michael, Rémy, Robert and Simon;

Andrzej and Jean-Christophe;

Domingos and Patrick.

Some of the results and obervations presented here are based on the work of:

Guillaume, Hannu, Olivier, Madeleine, Sid'Ahmed, Tiina and Timo.

I wish to thank also:

-the administrative teams who ensure the smooth running of the labs where I conducted research, namely: Iina, Isabelle, Kati, Muriel, Nathalie, Sirje and Ulla, the ENSAM staff, reception, accounting and student help staff in Cluny.

-for their help and attention, the schools for doctoral studies of Aalto University and ENSAM, namely: Carole, Christian, Claude and Florence.

-the librarians within ENSAM: Christine, Françoise and Thomas.

-students from the IUT SGM (Sciences et Génie des Matériaux) of Châlon-sur-Saône, Luc, Sandrine and Sylvie.

-my colleagues from the wood research team at Aalto University, namely Albert, Anti, Atsushi, Ditta, Jonna, Jussi, Lauri, Katja, Kristiina, Olli, Pekka and the education team.

-Mireille and my fellow researchers at ENSAM in Cluny and at TREFLE (Transferts Écoulements Fluides Énergétique) in Bordeaux.

Lastly, I wish to thank the people and institutions who have brought financial support to the project, with which I was able to travel and work in the best possible conditions: the Institut Carnot ARTS (Association de Recherche Technologie et Sciences), the Académie Française (within which the Jean-Walter Zellidja foundation), the French Embassy in Finland (and its Kaksin program), the Fortum company in Finland, the COST Action FP0904, and the school for doctoral studies RYM-TO, with the grant of which I was able to work in Finland during 2012.

October 2010

I was then sitting on the school steps facing the movie theater in Cluny, questioning whether or not to attend a meeting in ENSAM concerning a project of doctoral thesis. I wish to thank Mum and Lucas for talking me over the phone into attending the first interview.

At that time, doing a doctorate was a dream for me and a challenge which concludes an education started in preparatory classes in Sainte-Geneviève, Faidherbe and Joffre high schools, and continued in Ecole Centrale and Aalto University. I wish to thank all the people who were directly or indirectly involved in my apprenticeship during these school years and before. I also wish to thank the people and companies who invited me to take part in research and made me discover wood material, namely Jean-François, Matthieu, Patrick from the AFTBM (Association Forêt Bois Trièves Matheysine), Pierre from Auckland University in New Zealand as well as François and Baufritz and Bouygues companies.

I considered this thesis to be a joint construction in which I liked to organise everyone's ideas and expertise. It is with a sense of emergency and rarely with serenity that I conducted this study. Today, it would no doubt be different. This thesis has been a very rewarding and constructive time - beyond the better understanding of the physical phenomena at stake during infrared heating of green wood achieved through this research,

Many questions were raised during those three years, professionally as well as personally. The reassuring presence of many people and the fruitful interactions we have had empowered me to complete the present body of work. Namely:

Bonne ;

Alexandra, Alp, Annaig, Anne, Antoine, Ariane, Betty, Camille, Catherine, Cécile, Céline, Christine, Emmanuel, Erkki, Etty, Helena, Irma, les jardiniers de l'APSH 34, Jacquot, Jacqueline, Karin, Kristina, Liina, Lucas, Lucie, Maimouna, Maman, Manu, Marion, Michel, Michelle, Minna, Mireille, Monique, Myriam, Nolwenn, Olivier, Outi, Papa, Pascale, Patrick, Pauline, Pierre, Rém, Renaud, Sampsa, Seija, Stéphanie, Stevan, Suvi, Sylvie, Tan, Timo, Tom, Véronique, Viet-Anh et Yannick.

and the people met here and there, recently or a longer time ago.

I would like to share the result of this work among all the people mentioned above.

November 2013.

List of publications

This thesis consists of an overview of the following five publications, which from here on are referred to as Roman numerals in the text:

I Dupleix A., Denaud L., Bléron L., Marchal R., Hughes M. (2013) The effect of log heating temperature on the peeling process and veneer quality: beech, birch and spruce case studies. *Eur J Wood Prod* ***71(2)***, 163-171, DOI 10.1007/s00107-012-0656-1.

II Dupleix A., De Sousa Meneses D., Hughes M., Marchal R. (2012) Mid infrared absorption properties of green wood. *Wood Sci Technol* ***47(6)***, 1231-1241, DOI 10.1007/s00226-013-0572-5.

III Dupleix A., Kusiak A., Hughes M., Rossi F. (2012) Measuring the thermal properties of green wood by the transient plane source (TPS) technique. *Holzforschung* ***67(4)***, 437-445, DOI 10.1515/hf-2012-0125.

IV Dupleix A., Ould Ahmedou S.-A., Bléron L., Rossi F., Hughes M. (2012) Rational production of veneer by IR-heating of green wood during peeling: Modeling experiments. *Holzforschung* ***67(1)***, 53-58, DOI 10.1515/hf-2012-0005.

V Dupleix A., Batsale J.C., Kusiak A., Hughes M., Denaud L. (2013) Experimental validation of green wood peeling assisted by IR heating – some analytical considerations for system design. Submitted.

Author's contribution

I AD carried out the literature review, executed the experimental plan and wrote the whole manuscript with comments from the co-authors. The design of the experimental plan and interpretation of the results was carried out in collaboration with Rémy Marchal, Louis Denaud and Laurent Bléron.

II AD carried out the literature review, processed the samples and designed the experimental plan with Rémy Marchal, carried out the experiments with the technical help of Domingos De Sousa Meneses, analysed the results with Domingos De Sousa Meneses and wrote the whole manuscript with the careful review of all co-authors. Figures were designed in collaboration with Domingos De Sousa Meneses.

III AD was responsible of manufacturing and testing the samples investigated, and writing the manuscript. Interpreting the results was done in collaboration with Andrzej Kusiak.

IV AD was responsible for running the numerical simulation according to the research needs and interpreting the results with the co-authors. The article manuscript was written in collaboration with Sid'Ahmed Ould'Ahmedou, who designed the numerical model.

V AD processed the samples, designed the experimental plan with Mark Hughes, wrote the manuscript and interpreted the results with Andrzej Kusiak and Jean-Christophe Batsale.

List of abbreviations and symbols

A	absorptivity
Ac	additional coefficient to take the energy lost during the wetting of the cell wall into account
Amb	ambient spectra
Bp	pressure bar
c	specific heat
c_{water}	specific heat of water
C	heat capacity
CD_i	checking depth of check i
CF	checking frequency
CI	Checking Index
CIn_i	checking interval between checks i and i+1
COV	Coefficient Of Variation
CR	radial heat capacity
CR_i	Checking Ratio for check i
CT	tangential heat capacity
d	depth
D	bolt diameter
e_{nom}	nominal veneer thickness
erfc	complementary error function
E_R	reflected flux

E_T	transmitted flux
f.s.p	fibre saturation point
h	heat transfer coefficient
H	Heaviside function
IR	infrared
L	wavelength
LVL	Laminated Veneer Lumber
m_f	mass of the sample after heating
m_i	mass of the sample before heating
m_{od}	mass of the oven-dried sample
M	reference spectra
MC	moisture content
MC_f	moisture content after heating
MC_i	moisture content before heating
n	vector normal to the boundary
q	IR source heat flux
q_{est}	estimated heat flux
q_{mes}	measured heat flux
R	reflectance
R^2	coefficient of determination
t	time
t_h	heating time
s	peeling speed
SMOF	Système de Mesure de l’Ouverture des Fissures
t	time
t_h	heating time
T	bolt temperature

T_d	temperature attained at depth d
T_{ext}	IR source temperature
Tg	glass transition temperature
T_{init}	initial bolt temperature
Tr	transmittance
T_{surf}	surface temperature
THS	Transient Hot Strip
THW	Transient Hot Wire
TPS	Transient Plane Source
x	arc surface of the log subjected to external infrared heating
x_i	position of the lathe check along the veneer length
Xk	vertical effort applied on the cutting knife
Yk	horizontal effort applied on the cutting knife

α_{surf}^{anal}	analytical values of slopes
α_{surf}^{simul}	numerical values of slopes
ΔMC	difference of MC before and after heating
ε	emissivity of the wood surface
κ	thermal diffusivity
κR	radial thermal diffusivity
κT	tangential thermal diffusivity
λ	thermal conductivity
λ_{air}	thermal conductivity of air
λR	radial thermal conductivity
λT	tangential thermal conductivity
λ_{water}	thermal conductivity of water

ρ	wood density
σ	wavenumber

Table of contents

1. Introduction

In the wood-products industry, ‘peeling’ is the process of converting a log into a continuous thin ribbon of green wood termed veneer. In this process, the log, or ‘bolt’, rotates about its longitudinal axis on a lathe, whilst the peeling knife and pressure bar are driven forward and placed in tangential contact with the bolt surface (Fig. 1). The rotation speed of the bolt increases continuously with decreasing bolt radius so as to generate veneer at a constant linear speed at the output of the peeling lathe. Industrial peeling speeds, s, range from 1 to 5 m.s^{-1}.

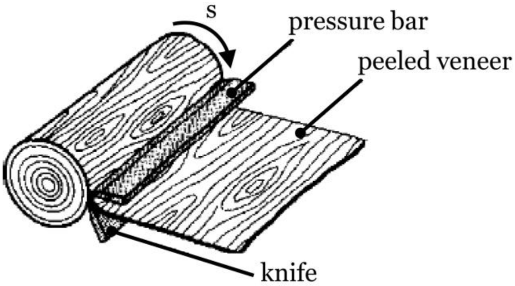

Figure 1 Principle of a rotary peeling lathe

The production of veneer plays an important role in the wood-products industry because plywood and Laminated Veneer Lumber (LVL), which are two of the most widely used Engineered Wood Products, are manufactured from veneers glued and pressed together, with the adjacent plies having their wood grain either crossed at right angles, as in the case of plywood or parallel, as in the case of LVL. Peeling is also widely used to produce material for light weight packaging. Peeling is one of the first steps in the plywood or LVL manufacturing chain, preceded by soaking, debarking and cut-off sawing, and followed by veneer drying, glue spreading, cross-cutting and pressing (Fig. 4a). In the case of almost all hardwood and softwood species it is necessary to heat the green wood prior to peeling in order to ‘soften’ the wood material for successful veneer production. The purposes of heating and the physical mechanisms behind it will be reviewed in Section 2.1.1. Industrially, the heating of green wood prior to peeling has traditionally been accomplished by soaking - immersing the whole logs in hot water basins - or by steaming them in vats. In both processes, water, as an integral part of wood, makes an ideal medium for heat transfer into green wood. In the preparation of wood prior to peeling, most of the positive effects resulting from soaking (expressed with ⊕ signs in Fig. 2) come from the action of heating it whilst the utilisation of hot water is a major source of negative effects (expressed with ⊖ signs in Fig. 2).

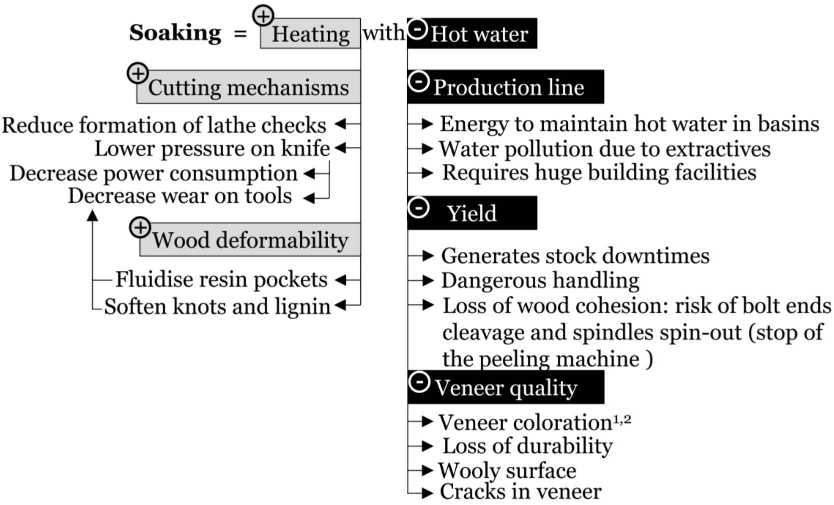

Figure 2 The pros and cons of soaking

The positive and negative effects of soaking detailed below are classified according to their impacts on (1) the production line, (2) yield and (3) veneer quality.

(1) Soaking increases complexity in the production line for three main reasons. Firstly, soaking is energetically demanding: the energy costs of soaking are high because immersing the whole bolt in hot water for long enough to ensure heat penetration into wood involves significant amounts of water and energy.

In addition, soaking basins are responsible for considerable energy losses because they are generally located outside and are badly insulated (often with just a tarpaulin to cover them), they can be sources of water leakages

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[1] Veneer coloration can also be a sought after effect for certain wood species as explained later in this section.

[2] Both heat and the use of hot water are responsible for veneer coloration.

and they are made out of concrete which is a resistant, but poor, insulating material (Fig. 3). Secondly, soaking generates water pollution: during soaking, wood liberates large amounts of phenolic extractives responsible for water pollution. This is particularly true for certain wood species such as oak (Svoradova et al. 2004). In most European countries, ever tighter regulation requires that treatment plants are usually necessary to clean up contaminated water. These expensive water treatment procedures in the post-production phase add extra cost to the soaking process. In Australia, the government, facing severe water supply and water pollution problems, has forbidden the use of water for log soaking, preferring the use of steaming which does not necessitate any post-treatment of water (personal communication). Thirdly, soaking requires substantial building facilities: large-scale soaking basins need a large footprint, which is costly.

Figure 3 Large-scale soaking basins sources of leakage in Bois Déroulés de l'Auxois, France

(2) Soaking impacts negatively on yield for three main reasons. Firstly, soaking generates stock downtimes: being a good insulating material, wood requires a long time (several hours or days) to ensure heat transfer through to the core. This, added to the time necessary for heating-up the soaking water to the required temperature, causes costly stock downtimes and makes the logistics more complex. Consequently, soaking (compared to the high production rates of the peeling machines) is a bottleneck when the producer has to be able to react quickly to respond to specific clients' needs. In order to speed up the soaking process, manufacturers frequently increase the soaking water temperature. However, this practice can lead to the heterogeneous heating of the different parts of wood, creating temperature gradients within the bolt that can, as will be explained below, be detrimental to veneer quality. Secondly, soaking necessitates sophisticated handling: handling the bolts out of the soaking basin to the peeling machine is dangerous for the operators. Thirdly, soaking lowers wood cohesion: with the whole bolt being immersed, the bolt ends are also affected by heat and water. Being 'softened', the bolt ends can cleave on

contact with the spindles of the peeling lathe leading to the fracture of the bolt and finally to the stoppage of the peeling process.

(3) Soaking could impact negatively on veneer quality for three reasons. Firstly, soaking can lead to colour change in the veneer in both a positive way (soaking turns birch veneers lighter and more valuable) as well as in a negative way (soaking results in a non-uniform pink colour in beech veneers whereas its light natural colour is valuable). Secondly, in certain wood species such as oak and chestnut, which have a high extractive content, soaking could lead to a loss in durability. By removing wood extractives, soaking can produce veneers with reduced durability off-setting the efforts of foresters and the forest industry to select, improve and harvest naturally durable species with high amounts of extractives (Svoradova et al. 2004). Thirdly, certain species such as Douglas-fir have rather heterogeneous structures and in these, soaking heats the wood non-uniformly. As a result of differences in density and moisture content (MC) (Mothe et al. 2000), different parts of the log have different thermal properties and as such heat at different rates. In such species, soaking leads to different temperatures in the different parts of the log and it means that the log is peeled at different temperatures - the sapwood is overheated and the heartwood is under-heated in the same peeling log - which causes problems. Overheating the sapwood increases surface roughness, creating a 'woolly' surface, whilst under-heating the heartwood results in the generation of significant lathe checking and tearing of the fibres. This problem of non-uniform heating is emphasised all the more in industrial practices which tend to increase soaking water temperature to speed up the soaking process but which can create temperature gradients within the log. For these species, it is necessary to find techniques to heat the wood more homogeneously. Fourthly, soaking can create cracks in the veneers: by releasing growth strains in wood due to hygrothermal recovery, soaking creates irreversible heart-checks in bolts which are responsible for cracks in the veneer (Thibaut et al. 1995, Gril et al. 1993). Commercially, these cracked veneers are rejected.

1.1. Background

In addition to the numerous disadvantages of soaking, two other reasons have stimulated the search for an alternative solution to heating green wood prior to peeling it. Firstly, in the case of Douglas-fir at least, it is inappropriate to soak it. The MC of green Douglas-fir heartwood is around Fiber Saturation Point (f.s.p) with no free water available to serve as a heat transfer medium and since Douglas-fir is difficult to impregnate, it necessitates long soaking times (Mothe et al. 2000). Secondly, the contention, supported by many manufacturers, that soaking is a ‘cooking’ process which requires a long time for the wood to soften (Lutz 1960) has recently been challenged by researchers in the wood micromechanics community with the results from experiments on the electric ohmic heating of wood. In forcing an electric current through the whole bolt which, acting like a resistor heats up (the Joule effect), researchers have demonstrated that the sought ‘softening' of green wood does not depend on the heating duration but only on the cell wall temperature (Gaudillière 2003). The understanding that veneer quality might be the same at heating rates significantly higher than those that could be obtained by soaking, pointed towards the feasibility of a more rapid method of log heating which might be directly embedded onto the peeling lathe. Feasibly, this alternative to soaking might be achieved by using radiation instead of conduction to transfer heat within wood. The first trials employed microwave heating which could heat up the whole volume of the log at a heating rate of 2°C.s^{-1} and confirmed that the ‘softening’ effect does not depend on the heating time (Torgovnikov and Vinden 2010, Coste and De Bevy 2005). However, microwave technology necessitating covered waveguides makes it relatively complex to embed within the peeling process. Moreover, in order to speed up heating, another debate began concerning whether it was necessary to bring the whole volume of the bolt to the required heating temperature. Theoretically, a promising solution would be to locally heat the bolt’s surface just ahead of the knife and to the depth of the cutting plane - to a depth equal to that of the thickness of the veneer produced (Marchal and Collet 2000). Such surface heating would be beneficial for two main reasons: (1) surface heating avoids the risk of heart-checks which appear in volume heating due to hygrothermal recovery, (2) surface heating can be appropriately dosed and only activated when peeling heartwood: this enables the saving of energy and avoids the unnecessary heating of sapwood (whose MC already confers an acceptable level of deformability) and the core of the wood (which remains unpeeled) and, at the same time, limiting the occurrence of spin-out. An Infrared (IR) heating system may be the most suitable technology in terms of rapid heating rates and such a system might be easy to install on the peeling lathe (Coste and De Bevy 2005). It has been established that IR radiation is characterised by a penetration depth of a few cells rows and, feasibly, is suitable for heating green wood surfaces up to a depth of several millimeters (Gaudillière 2003). From this perspective, the following modification to the plywood manufacturing chain could be considered (Fig. 4b). Embedding a heating system directly onto the peeling lathe would bring ‘unity’ to the process

(Fig. 4a) and negate the numerous adverse effects of the soaking step in veneer production (Fig. 2). From an economical point of view, it might be expected that simplification of the manufacturing chain resulting from the reduction of two operations - soaking and peeling - to one would lower production costs (by deleting the dangerous, polluting and energetically demanding soaking step) and favour the solution of IR heating.

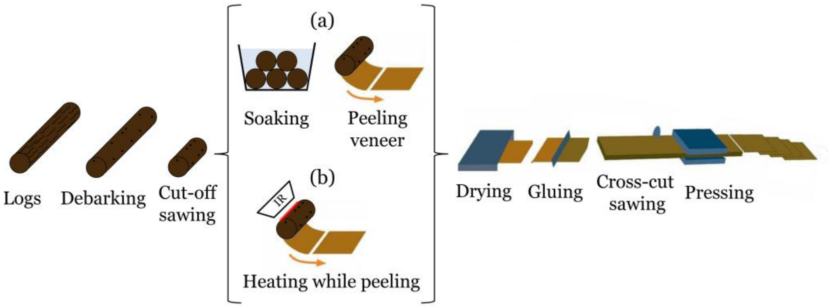

Figure 4 (a) Traditional manufacturing chain of plywood (b) modified by replacing the soaking step by IR heating

1.2. Aims of study

The aim of this study was to investigate the potential of IR radiation to heat a green log rotating on a peeling lathe. Because the study was carried out with the development of veneer production in mind, the parameters studied (heating depth, heating temperature and peeling speed) were chosen accordingly to industrial practices. The heating depths were defined by the cutting plane located from 1 to 3 mm beneath the surface. The heating temperatures were redefined to optimise the effect on cutting effort and veneer quality (Section 4.1). The peeling speed was chosen for the high production capacity of industrial peeling lathes, but was not considered as a limiting factor for the feasibility of IR heating. Indeed, lower peeling speeds could balance the disparities between peeling and drying rates and could benefit the whole veneer production process because : (1) the inability of driers to cater for the high peeling rates demanded generate buffer stocks in the production line so that lower peeling speeds would necessitate a rearrangement of the production into several shifts but would not decrease the veneer production (2) heat storage and loss of MC in veneers during IR heating would reduce drying times.

A series of distinct and practical questions were raised which form the basis of the papers that make up this thesis.

Paper I. What benefits are desired when heating wood prior to peeling it? What are the 'minimum-optimum' heating temperatures required for adequate veneer quality?

Paper II. How does IR radiation interact with green wood?

Paper III. How do MC and anisotropy modify heat transfer in wood?

Papers IV. and V. What heating rates can be achieved in green wood under an external IR heating?

These are the key-questions that have to be assessed even before considering the economic feasibility and feasibility at pilot scale. Chapter 2 provides an overview of the answers to these key-questions found in the literature. Chapter 3 describes the materials and methods used in the different research works performed in this study. Within Chapter 3, Section 3.2 is particularly helpful in clarifying the research needs and in understanding the research plan executed in order to answer them. Chapter 4 presents the results obtained from each of the research works and discusses them. Points for further work are discussed in the last chapter (Chapter 5).

2. Literature review

2.1. Heating green wood prior to peeling

2.1.1. The benefits of heating wood prior to peeling it

Both mechanical and chemical perspectives are necessary to understand the desired effects of heating green wood prior to peeling it. The basic idea is that by heating wood it 'softens' which facilitates cutting.

From a mechanical point of view, Baldwin (1975) stated that heating logs to increase the mechanical deformability of green wood under the cutting knife is a key stage in industrial veneer production. Using an energy approach to study the properties of wood surfaces and the fracture behaviour of wood, it has been demonstrated that the ratio of fracture energy (to create a new unit surface) to shearing (or compression) energy increases with heating (Thibaut and Beauchêne 2004). A diminution in the energy dissipated in the shearing of wood lowers the pressure applied by the bolt on the cutting knife, thereby decreasing the effort required in debarking - and therefore presumably in peeling (Bédard and Poulain 2000). This consequently results in reduced power consumption and cutting tool wear (Marchal et al. 2004). Secondly, the reduction in the fracture energy required to create a unit area of surface reduces the formation of checks and therefore improves veneer quality (Thibaut and Beauchêne 2004).

From a chemical point of view, the mechanical deformability of wood is increased by softening the lignin moiety (Baldwin 1975, Matsunaga and Minato 1998, Bardet et al. 2003, Yamauchi et al. 2005). For this purpose, the heating temperature should ideally exceed the glass transition temperature, Tg, of lignin at the MC of green wood. This temperature is lower than the Tg of cellulose and hemicelluloses (Engelund et al. 2013) and dominates the behaviour of the wood material. This statement remains true for wood polymeric constituents either isolated or embedded in the native hemicelluloses-lignin matrix (Navi and Sandberg 2012). Reaching the Tg of lignin would also fluidise resin and soften knots. The softening of knots also contributes to a reduction in cutting tool wear (Marchal et al. 2004).

2.2. Optical properties of green wood under IR radiation

The technical feasibility of IR heating as a means of warming wood prior to peeling necessitates that IR radiation can heat wood rapidly. This depends on the ability to 'deposit' IR energy deep into wood so that heat can transfer within wood more rapidly than by the slow process of conduction. This issue raises the following questions: how deep can IR radiation penetrate wood? What proportion of the incident radiation is absorbed by the wood? Can the physical parameters of wood (such as density, surface roughness and MC) significantly impact on IR absorption to enhance it? The following state of knowledge reviews the latest findings on the interaction between wood material and IR radiation to understand better which of these issues have already been addressed, so as to determine precisely the research needs. However, some basic laws regarding IR radiation are first reviewed in Section 2.2.1.

2.2.1. Basic laws of IR radiation

IR are electromagnetic waves which propagate at wavelengths, L, ranging from 0.78 to 1000 μm (i.e. wavenumbers σ ranging from 12 820 to 10 cm^{-1} with $\sigma = 1/L$) in the form of photons. Depending on the wavelength, IR radiation can be classified into 3 or 4 spectral bands: near-infrared (NIR), mid-infrared (MIR), far-infrared (FIR) and even extreme infrared (EIR).

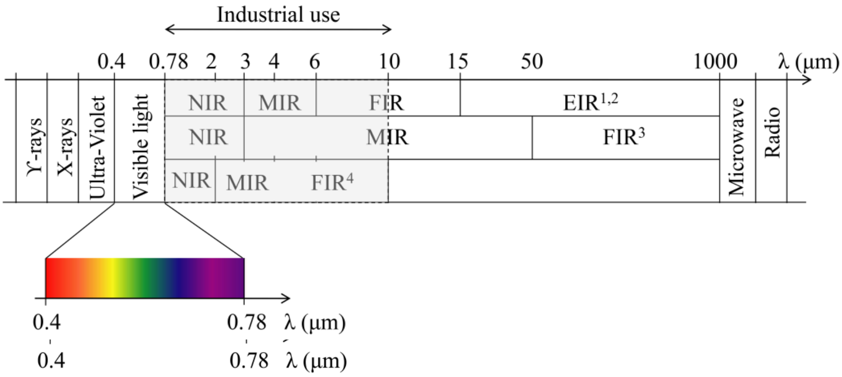

Figure 5 IR classification according to ISO (2007)[1], Flir Systems(2004)[2], Meola and Giovanni (2004)[3], Dory et al. (1999)[4]

These subdivisions are arbitrarily chosen by authors, which can be confusing (Fig. 5). However, the classification can be summed up in the following way: NIR features wavelengths and properties close to visible light while MIR and FIR exhibit far different characteristics.

IR spectroscopy used in wood studies, utilises the interaction between IR radiation and wood's molecular components - which vibrate at specific IR wavelengths - to determine its chemical composition. Usual IR spectroscopy focuses on the region from 2.5 to 25 µm (4000 to 400 cm^{-1}) i.e. in the MIR region where most of the fundamental vibrational modes of molecular chains occur (ASM International Handbook Committee 1986). However, wood components are also excited by IR radiation of shorter wavelengths, that is in the NIR range - from 0.78 to 2.5 µm - but the vibrations are less numerous (Berthold et al. 1998, Kelley et al. 2004). Heating wood with IR consists in exciting wood molecules with IR radiation in order to heat the wood material. In the case of green wood, the aim of IR heating is to directly heat the wood cell wall material and so avoid the unnecessary, and energy consuming, heating of water. For this purpose, it would be necessary to irradiate the wood with IR wavelengths specific to the wood molecular components in order to excite them and not the water molecules present in wood (either free or bound to the cell wall). In particular, since lignin has the lowest Tg at high MC (Section 2.1.1), exciting lignin molecules could be sufficient to soften green wood and its knots (since lignin is a major component of knots) and so aid the peeling process. The first step in the study is therefore to gain an understanding of IR penetration depth and IR absorption by green wood. For this reason, using a broad IR band that encompasses a spectrum of wavelengths larger than the specific wavelengths of lignin is precise enough. In this perspective, the IR band from 550 to 5500 cm^{-1} used by the integrating sphere (Section 3.4) fits the purpose of the study. If the results were to be convincing, further study could try to select specific wavelengths to enhance the heating of green wood cell wall and avoid the heating of water.

2.2.2. IR penetration depth in wood

The notion of penetration of IR radiation into wood appears for the first time in the literature in 1983 when Grimhall and Hoel (1983) mentioned that IR is 'intensively' absorbed by the surface of oak. More recently, Potter and Andresen (2010) reported a similar qualitative observation that living trees are heated via IR radiation. Measuring the temperature profile deep within the wood as an indirect measure of the penetration depth of IR radiation, Makoviny and Zemiar (2004) suggested that in all probability the penetration depth of IR was less than 0.1 mm in oak at MCs of between 0 and 20%. However, with Makoviny and Zemiar's method it remains difficult to precisely evaluate the penetration depth of IR radiation absorbed by wood because the measurement technique is necessarily biased by heat transfer through conduction (Cserta et al. 2012). More precise estimates of IR penetration into wood have been achieved by recent developments in IR spectroscopy. The penetration depth has been calculated to be from 0.13 to 2.15 µm depending upon the wavelength (Zavarin et al. 1991) with a maximum depth of penetration of 37-138 µm recorded at 2242 cm^{-1} (Zavarin et al. 1990).

2.2.3. Influence of wood physical parameters on IR absorption

All authors agree that any modification of the wood surface quality will influence IR absorption by wood as clearly stated by Jones et al (2008). But there is some controversy about the effect of surface roughness on absorbance. Bennett and Porteus (1961) highlighted that the rougher the wood surface, the greater the reflection and the less absorption. This behaviour was confirmed by De Santo (2007) who noted that surface roughness increases light scattering and is proportional to surface reflectance but this was in contrast to previous studies who found the opposite to be the case (Zavarin et al. 1990, 1991). It has also been reported that the effect of surface roughness on absorbance differs according to wavelength (Tsuchikawa et al. 1996). There are fewer studies concerning the effect of wood density on energy absorption, however, Zavarin et al. (1990) noted that both wood density and fibre orientation are minor factors influencing energy absorption and the penetration depth in wood (Zavarin et al. 1990).

2.2.4. Influence of wood MC on IR absorption

However, all the above mentioned studies were carried out on dry wood or wood below the f.s.p and data on the penetration depth into green wood (wood above the f.s.p which has never been dried) are lacking. The only study on the effect of MC on the optical properties of wood is with regard to its emissivity. The emissivity, ε, of a surface is its ability to absorb (and emit) energy by radiation. The more absorbent a surface is, the higher its emissivity. Kollmann and Côté (1968) reported that wet wood absorbs more IR energy than dry wood and that ε increases with MC up to f.s.p, at which point the emissivity of wood is the same as that of water (ε = 0.93). Emissivity values provided by the manufacturers of IR thermography cameras (e.g. Flir System 2004) are given for all wavelengths of incident IR radiation, and the wood MC is referred to as either 'dry' or 'damp' which is not precise enough to obtain a clear picture of the dependence of optical properties on MC. Some experimental work has investigated the transmission and absorption of wet Douglas-fir, beech and oak veneers in the near- and mid-IR range using a flux meter located underneath exposed veneer (Marchal et al. 2004). From this work, it was concluded that veneers of between 0.5 and 2 mm absorb around 50% and transmit around 10% of the incident flux. These values were constant irrespective of the source wavelength and transmission was found to increase with increasing MC but decrease with sample thickness. However, it is believed that these results should be considered with care because the flux meter used may have been influenced by extraneous ambient light.

In view of the lack of accurate data concerning the ability of wood to absorb IR energy to a certain depth, the optical properties of green wood were investigated and the findings reported in Sections 3.4 (for the method) and 4.2 (for the results).

2.3. Thermal properties of green wood

Thermal conductivity (λ), heat capacity (C) or specific heat (c), and thermal diffusivity (κ) are the most important properties characterising the thermal behaviour of materials, including wood (Sonderegger et al. 2011, Suleiman et al. 1999). The characteristics of these properties are summarised in Table 1. The present review focuses on: (1) the influence of wood MC on wood thermal properties because the research needs concern the IR heating of wood in the green state, (2) the influence of anatomical orientation (radial or tangential) on wood thermal properties because they are the main directions of heat flow when heating wood in the transverse direction.

2.3.1. Influence of MC on thermal properties

At MCs between 0% and f.s.p, wood is considered to be a good insulating material with low λ, moderate C, and consequently low κ. The porosity of wood explains its low λ, because the λ of air filling the void spaces is lower (λ_{air} = 0.03 $W.m^{-1}.K^{-1}$ at 300 K, Rohsenow et al. 1973) than that of the wood cell wall (λ perpendicular to the grain = 0.42 $W.m^{-1}.K^{-1}$, Kollmann and Côté

1968). Heat flows preferentially through the wood cell walls, which act like heat bridges, whilst the air present in the lumens below f.s.p forms a barrier to heat flow (Kollmann and Côté 1968). The conductivity of water (λ_{water} = 0.613 W.m^{-1}.K^{-1} at 300K, Rohsenow et al. 1973) is higher than that of air. Accordingly, wood conductivity increases linearly with increasing MC (Sonderegger et al. 2011). Free water conducts more heat than bound water, thus the incremental increase in λ with MC above f.s.p is greater (Siau 1971).

Thermal properties	Unity	Definition
Thermal conductivity, λ	W.m^{-1}.K^{-1}	Rate or power (in W) at which heat is transferred through 1 m thickness of the sample material when subjected to a gradient of 1 K, measures the ability to transfer heat flux.
Heat capacity, C	J.m^{-3}.K^{-1}	Amount of heat (or energy, in J) needed to increase 1 m^3 of material of 1 K, measures the thermal inertia.
Specific heat, c	J.kg^{-1}.K^{-1}	Amount of heat (or energy, in J) needed to increase 1 kg of material of 1 K, defined by $C = \rho \cdot c$ with ρ is material density, measures the thermal inertia.
Thermal diffusivity, κ	m^2.s^{-1}	Speed at which heat transfers within the material, defined by λ/C, measures the transient thermal behaviour.

Table 1 Definitions of thermal conductivity, λ, heat capacity, C, specific heat, c, and thermal diffusivity, κ

The presence of water strongly affects the heat capacity (C) of wood because of the high C of water; the specific heat capacity of water, c_{water}, is 4.18 kJ.kg^{-1}.K^{-1} at 300 K (Rohsenow et al. 1973). As a first approximation, the specific heat, c, of wet wood can be calculated by a simple rule of mixtures by adding the specific heats of water, c_{water}, and of oven-dry wood, c_o, in their relative proportions (equations detailed in Paper III). But considering wet wood to be a mixture of two independent materials may be an oversimplification and some authors have suggested that this relationship only holds true when the MC is greater than 5% (Sonderegger et al. 2011, Jia et al. 2010). Some authors propose an additional coefficient, Ac (Table 1 in Paper III), to take into account the energy lost during the wetting of the cell wall due to the creation of H-bonds between the hydroxyl groups of cellulose and water (Sonderegger et al. 2011, Simpson and TenWolde 1999). However, Ac values vary among authors and are only valid below f.s.p. Other authors modify the coefficients in the rule of mixtures as a function of MC (Siau 1995, Koumoutsakos et al. 2001). Studies focusing on the heat diffusion, κ, of wet and dry wood are scarce. According to Kollmann and Côté (1968), κ decreases slightly with MC.

2.3.2. Influence of wood anisotropy R-T on thermal properties

The effect of wood anisotropy radial-tangential (R-T) on transverse conductivity is somewhat controversial. Some authors report the same λ values in the radial (λR) and tangential (λT) directions (Siau 1971, Simpson and TenWolde 1999, Suleiman et al. 1999), whereas others claim that transverse conductivity is higher in the R than in the T direction. The ratio of λR and λT is thought to be governed by the volume of ray cells in hardwoods, and the volume of latewood in softwoods (Steinhagen 1977). Similar λR and λT data were obtained for hardwood species with rather uniform wood structure or a low amount of latewood, such as in young softwoods (Suleiman et al. 1999). However, studies on beech and spruce support the concept that λR predominates (Sonderegger et al. 2011). Logically, there is no influence of orientation on specific heat, c, as this property is mainly dependent upon the cell wall material itself. The specific heat of oven-dry wood at 20°C is generally regarded to be constant with not much variation from one specie to another (Jia et al. 2010) and hardly any influence of density (Sonderegger et al. 2011). Since κ is proportional to λ, it is logical that diffusivity is also anisotropic since both ρ and c are isotropic properties (Steinhagen 1977). Therefore, the κR should be higher than κT because of the lower tangential λT (Kollmann and Côté 1968). However, as with λ, some findings do not corroborate the anisotropic nature of κ (Suleiman et al. 1999).

It was decided to clarify the influences of MC and wood anisotropy on thermal properties by the experimental measurements presented in Sections 3.5 (for the methods) and 4.3 (for the results).

2.4. Heating rates of green wood under external IR source

The investigation reported herein question the existence in the past of experimental or simulation trials to heat green wood with IR radiation. Potter and Andresen (2010) have demonstrated, using a finite-difference method, that living trees are heated via IR radiation. However, the promising results on IR induced heating rates of these authors have not been extended to conditions of dynamic rotational movement of the log. From an experimental perspective, the ability of IR radiation to raise both the surface temperature and the temperature below the surface in green wood has been positively confirmed for both the purpose of heating the wood (Bédard and Laganière 2009) and for drying it (Cserta et al. 2012). With heating source flux densities of 126 kW.m^{-2}, it has been shown that it is possible to achieve surface temperatures of 50°C in green logs of beech, Douglas-fir and okoumé rotating at speeds corresponding to peeling speeds of 0.25-0.5 m.s^{-1} with source power densities of 126 kW.m^{-2} (Coste and De Bevy 2005). Similar results have been obtained in spruce logs rotating at 0.1 m.s^{-1} using relatively low IR flux densities of 4-20 kW.m^{-2} for the purpose of thawing logs (Bédard and Poulain 2000). Several studies have been conducted to evaluate the time taken to achieve a peeling temperature of 50°C at different depths (0.5 mm, 1 mm, 2 mm and 5 mm) in samples of beech, Douglas-fir and oak as a function of the input power of the IR source (Gaudillière 2003, Marchal et al. 2004, Chave and Vial 2003, Makoviny and Zemiar 2004). As might be expected, the greater the input power of the IR source, the faster the target temperature of 50°C is achieved at a particular depth. However, for the purpose of heating the wood surface prior to peeling, the input power of the IR source should be adjusted in order to avoid overheating and eventual burning of the surface.

The multiplicity of experimental results generated by the diversity of experimental situations (due to different wood species, wood MCs, IR power densities, etc.) has highlighted the need for building a numerical model which could simulate the heating rates of green wood under IR radiation as a function of the different parameters cited above (Section 3.6 for the methods and Section 4.4 for the results). The accuracy of the model has then been tested by comparison with simplified solutions of analytical equations and with some experimental data (Section 3.7 for the methods and Section 4.4 for the results).

3. Materials and methods

3.1. Wood material

Four wood species were used in this study: two hardwoods - beech (*Fagus sylvatica* (L.)) and birch (*Betula pendula* (Roth)) and two softwoods - Douglas-fir (*Pseudotsuga menziesii* (Mull) Franco) and spruce (*Picea albies* (L.) Karst). This choice was guided by the industrial needs of veneer production in the two countries involved in this co-tutelle PhD - France and Finland. Birch and spruce are the most significant wood species harvested in Finland to produce veneers, whilst beech is the most important species for the production of veneer in France. Douglas-fir was studied as a potential resource for veneer production in order to take advantage of the plantations from the 1950s, which are nowadays reaching harvestable age. These four species were chosen because they all require soaking to ensure successful peeling. Moreover, the application of IR heating would likely be beneficial in the case of Douglas-fir which is not well suited to soaking because of its heterogeneous structure, arising from differences in the densities of earlywood and latewood, the presence of knots and heartwood dryness. The beech and Douglas-fir logs used for this study were obtained from forests near Cluny, France whilst the birch and spruce logs were harvested in Finland.

This wood material was processed into samples different of differing dimensions and form (Fig. 5), to fit the requirements of the various experimental tests carried out, as follows:

- Bolts of 400 mm diameter were cut to a length of 600 mm to fit the dimensions of the industrial peeling lathe available at Arts et Metiers ParisTech Cluny, France and to maximise the number of bolts and tests per log. For each species, all the bolts tested originated from the same log and each bolt was tested at one soaking temperature. The nominal veneer thickness (e_{nom}) was 3 mm; however, this differed from the actual measured thickness due to the wood structure. In order to evaluate only the influence of heating temperatures on the peeling process and veneer surface quality, the peeling speed, s, and the compression rate of the pressure bar, Bp, were kept constant (s = 1 m.s^{-1}; Bp = 5 %; vertical gap = 1 mm). This low Bp value compared to the 15-20 % pressure bar values usually used in industry was chosen to highlight that the checking phenomenon occurs with the slightest influence of the pressure bar. To assess veneer quality using the 'fuitometer' for an indirect measure of veneer roughness (explained in Section 3.3.1) and the 'SMOF' for lathe checking (described in Section 3.3.2), bands of veneer, 600 mm in length, were peeled from initially green bolts (① in Fig. 6);

- Discs, 30 mm diameter (② in Fig. 6), were cut with a circular cutter from different thicknesses of the aforementioned green veneer to characterise optical properties using the integrating sphere detailed in Section 3.4;

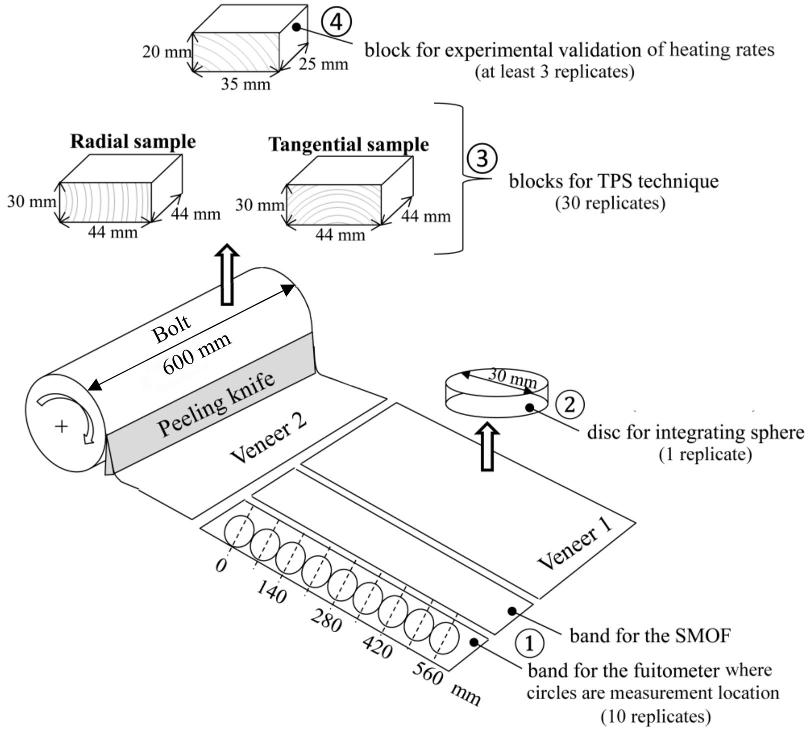

Figure 6. The different samples sizes and forms into which the wood material was processed for the experimental test (with the number of replicates in brackets[3])

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[3] The measure with the integrating sphere is done on a wide surface so that it is possible to consider that one replicate is already representative of the mean value for the surface being characterised ('representative surface').

- To characterise thermal properties using the TPS technique introduced in Section 3.5, knot free blocks having dimensions of $44\times44\times30mm^3$ were sawn from freshly cut trees in the tangential and radial directions with respect to grain orientation (③ in Fig. 6);

-Knot free blocks with dimensions of $44\times35\times20mm^3$ were sawn from freshly cut trees (④ in Fig. 6, Section 3.7) and were used to experimentally validate heating rates.

3.2. Research plan

The research plan was organised so as to render possible an estimation of the heating temperatures achievable within a green log rotating under IR radiation (Fig. 7). This estimation was based on a numerical simulation presented in Paper IV and validated by experiments (Paper V). For this purpose, it was necessary to know the 'minimum-optimum' target heating temperatures (Paper I), to feed the model with accurate thermal property data (Paper III) and to know whether the equations predicting the heating of wood layers beneath the surface by an external IR source should take into account the volumetric absorption of IR energy within wood and not only the transfer of the heat absorbed by the surface layers by conduction to the inside layers (Paper II).

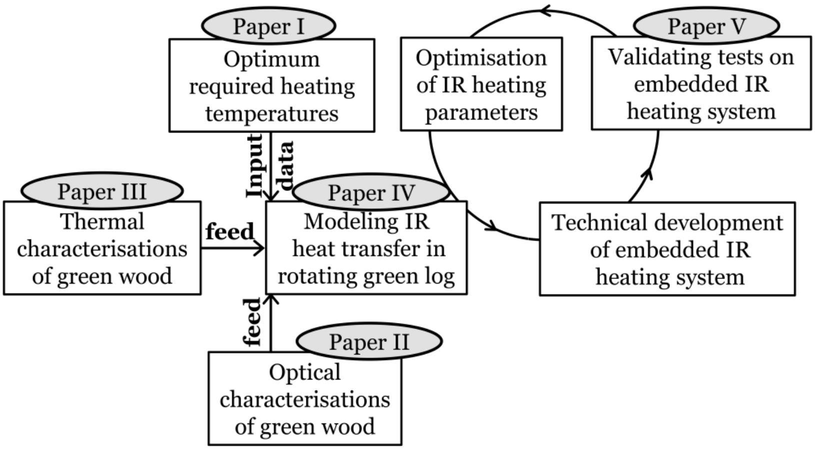

Figure 7. Schematic representation of the research plan carried out

3.3. Assessing veneer quality: the fuitometer and the SMOF (Système de Mesure de l’Ouverture des Fissures)

Veneer quality can be assessed by three factors: (1) veneer surface topography (including roughness and waving), (2) thickness variation and (3) lathe checking. It is well known that heating temperature in particularly influences the latter factor, which can be described by two parameters: checking interval (CIn) and checking depth (CD). This section presents the materials used to evaluate veneer quality as a function of soaking temperature in order to investigate ‘minimum-optimum’ heating temperatures (by soaking), with a view to assessing the possibility of reducing log heating temperatures compared to the temperatures currently in-use in the industry (research question raised in Paper I). Given the lack of a standard for veneer surface quality evaluation, it was decided to assess it by measuring: (1) air leakage on the veneer surface (as an indirect measure of veneer roughness) using a pneumatic rugosimeter - also referred to as a ‘fuitometer’, (2) thickness variation and (3) lathe checking with the SMOF (Système de Mesure de l’Ouverture des Fissures) device (Palubicki et al. 2010). Further details on the experimental procedures can be found in Paper I.

3.3.1. Measuring veneer air leakage: the fuitometer

The principle of the fuitometer is simple (Pouzeau and Pradal 1957). It is based on pressure loss when air flows through an annular-shaped pipe impinging on the uneven veneer surface (Fig. 8a). In the case of an uneven surface, air leaks through the pipe: the pressure at the output of the pipe decreases leading to a pressure loss indicated by the water column whose level gets higher. The difference between input and output pressure readings on a water column is a function of veneer air permeability. The fuitometer also gives the Checking Index (CI) which is calculated from the difference in air leakage between the ‘tight’ and ‘loose’ sides of the veneer (El Haouzali 2009) (Eq. 1, Fig. 8a).

$$\mathrm{CI\ (in\ mm\ of\ water)} = \mathrm{water\ level}_{\mathrm{on\ tight\ side}} - \mathrm{water\ level}_{\mathrm{on\ loose\ side}} \quad (1)$$

CI measures air leakage through the veneer which is influenced by lathe check formation (Palubicki et al. 2010): the more lathe checks there are, the greater the tearing of the fibers and the more uneven the surface. This results in greater air leakage and a higher water level and consequently a lower column reading.

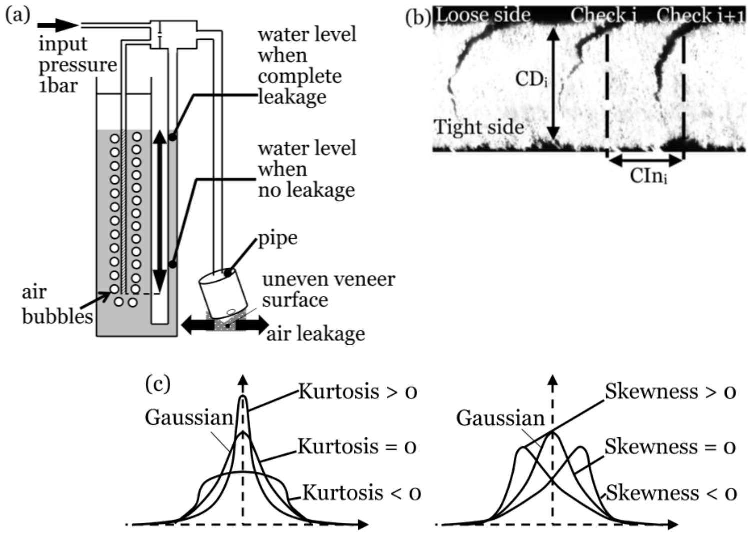

Figure 8. Schematic showing the principle of the fuitometer (a), SMOF output image with checking depth CD_i and checking interval CIn_i (b), definitions of kurtosis and skewness for a distribution of data (c) (Paper I)

3.3.2. Measuring veneer lathe checking : the SMOF

The purpose of the SMOF device is to detect the lathe checks which form on the 'loose' side of the veneer in contact with the knife (Fig. 8b, Palubicki et al. 2010). Lathe checking is brought about by a sudden tearing of wood fibers under the cutting knife due to an increase in the energy dissipated by wood shearing (Thibaut and Beauchêne 2004). The mechanisms behind the formation of lathe checking are influenced by the deformability of the wood and so, in turn, depend upon the peeling temperature. The principle of the SMOF involves bending a band, or ribbon, of veneer over a pulley in such a way as to open-up the checks that are then illuminated by a laser. A camera automatically takes images of the veneer edge that enables a continuous recording of the veneer cross-section to be made. The images obtained from the SMOF (Fig. 8b) enable the interval between two checks (CIn_i) and checking depth (CD_i) for each check to be calculated. For each check, i, the checking ratio, CR_i, is given by Eq. 2.

$$CR_i = \frac{CIn_i}{CD_i} \qquad (2)$$

The distributions of CIn_i and CD_i are then displayed in the form of histograms (Section 4.1.3): for each log heating temperature, the number of lathe checks (in terms of percentages of total number of lathe checks on the measured veneer) is represented for each range of CIn_i and CD_i displayed on the X-axis. In some cases the distributions are spread widely so that determining the most frequent values is not a statistically relevant way to characterise the checking distribution along the veneer length. For this reason a statistical analysis was chosen based on an evaluation of the coefficients of skewness and kurtosis illustrated in diagrams presented in Fig. 8c. Skewness is a measure of the asymmetry of the distribution while kurtosis is a measure of its peakedness.

3.4. Characterising green wood optical properties: the integrating sphere

The objective of using the integrating sphere was to determine the optical properties of green wood under IR radiation. The characterisation involved the experimental measurement of diffuse reflectance and transmittance IR spectra and is fully detailed in Paper II. Using this approach, it was possible to estimate the amount of energy absorbed by the wood and the penetration depth of the IR radiation into the wood (addressing the research questions raised in Paper II).

The integrating sphere device, consisting of a Bruker Vertex 70 spectrometer equipped with a 6 inch integrating sphere (Hoffman SphereOptics) with a diffuse reflective gold coating, provided reflectance (R) and transmittance (Tr) calculated from different spectra (Eqs. 3 and 4). For each wavelength of the incident radiation, R gives the amount of energy which leaves the incident sample surface without being absorbed because of reflectivity at the air-material interface or back-scattering by the wood fibres. For each wavelength of the incident radiation, Tr gives the amount of energy transmitted through the sample. In order to suppress any parasitic contribution appearing in reflectance mode, the reflectance spectra, R, were background corrected with a measure of the ambient spectra (spectra Amb in Fig. 9a). Reference spectra (M) were acquired with a mirror used as a gold diffuse reference (Fig. 9b). Spectra of the flux reflected by the sample surface, E_R, and spectra of the flux transmitted through the sample surface, E_T, were obtained by using the adequate integrating sphere configurations shown in Fig. 9c and Fig. 9d respectively (Labsphere). A simple energy balance shows that the absorptivity, A, the amount of energy absorbed by the material is given by Eq. 5 (Palmer et al. 1995).

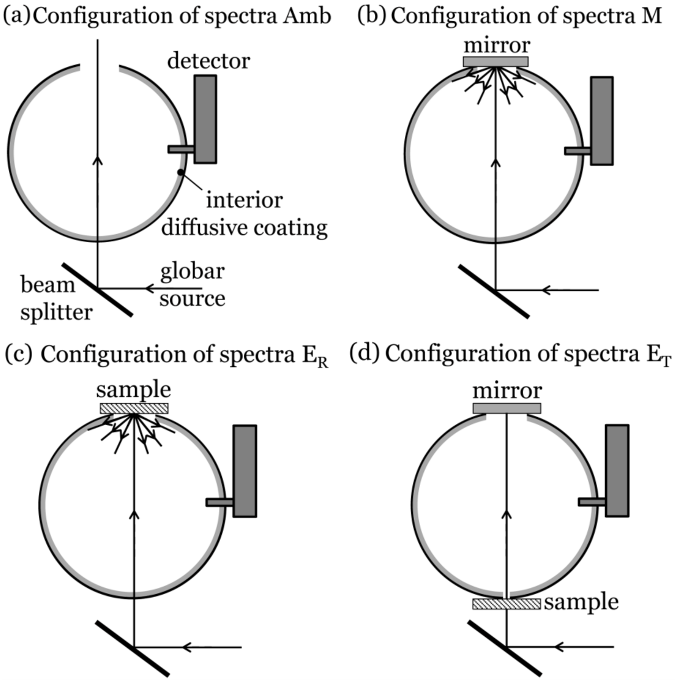

Figure 9. Scheme of the different configurations of the integrating sphere to obtain (a) ambient spectra Amb, (b) reference spectra M, (c) spectra of reflected flux E_R and (d) spectra of transmitted flux E_T (adapted from Paper II)

$$R = \frac{E_R - Amb}{M - Amb} \tag{3}$$

$$Tr = \frac{E_T}{M} \tag{4}$$

$$A = 1 - R - Tr \tag{5}$$

Due to its heterogeneous structure (porosity, fibres, etc.), light scattering is strong inside wood and so the penetration depths of these samples cannot be simply defined by the inverse of the absorption coefficient. Rather, a qualitative penetration depth is estimated by testing samples of decreasing thicknesses. As long as transmission is nearly equal to zero – meaning that all incident radiation is absorbed or reflected by the sample – the penetration depth is known to be less than the sample thickness. Table 2 shows the different thicknesses of all samples: increments of 0.1 mm could not be obtained because of the difficulty of peeling to such tight tolerances. The penetration depth reported in this study (Section 4.2) is thus given by default by the thinnest veneer section which gives a non-zero value for transmission.

Species	Sample thicknesses (mm)
Beech	0.2; 0.3; 0.5; 1.2; 2.0; 2.2; 3.1; 3.2
Birch	0.6; 0.9; 1.0; 1.1; 2.1; 2.3; 3.0; 3.2
Douglas-fir	0.5; 0.6; 0.7; 1.1; 2.1; 2.3; 3.2
Spruce	0.6; 1.1; 1.2; 2.1; 2.3; 3.2

Table 2 Thicknesses of the samples tested for the integrating sphere

3.5. Characterising green wood thermal properties: the TPS (Transient Plane Source) technique

The lack of data in the literature on the thermal properties of green wood provided the impetus for investigating the transverse (radial and tangential) thermal conductivity (λ), heat capacity (C) and thermal diffusivity (κ) of green wood at MC above f.s.p (Paper III) using the TPS technique. The TPS technique was chosen over the guarded hot plate and transient techniques such as the Transient Hot Wire (THW), the Transient Hot Strip (THS) and the flash method, which are other commonly used methods of thermal characterisation for the reasons summarised in Paper III. The general theory of TPS has been comprehensively described by Gustafsson (1991) and is detailed in Paper III. The TPS technique entails recording the resistance change as a function of time of the heat source, in the form of a disk, which serves as the measuring sensor. The TPS element is sandwiched between two specimens whilst an electrical current is passed through it with sufficient power to slightly increase its temperature (by between 1 and 2 K) (Fig. 10). The TPS technique consists of measuring λ and κ while C is calculated from the relationship $\kappa = \lambda / C$. Fitting the TPS experimental results with the analytical models presented by Gustafsson (1991) leads to values for λ and κ.

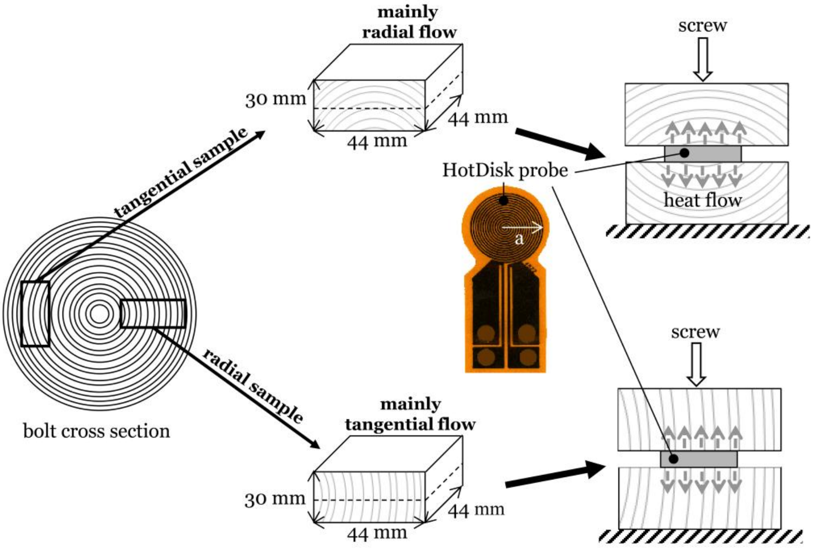

Figure 10. Sampling identical samples and TPS measurement configuration (adapted from Paper III)

3.6. Numerical modelling

The simulation consisted of numerically modelling the heating of green wood logs by an external IR radiation source during peeling in order to estimate the heating kinetics of a green wood cylinder rotating with decreasing radius (more details about the model can be found in Paper IV). Comsol Multiphysics (Comsol Inc., Burlington, MA, USA) software was used to solve the partial differential equations based on the finite element (FE) method with the overall procedure implemented under the flexible MatLab (MathWorks Inc., Natick, MA, USA) environment. The model meshes the log cross-section with 2D finite elements (in the radial and tangential directions) whilst the bolt length (the longitudinal direction) is not considered since heat transfer in the longitudinal direction can be neglected. To predict heat transfer accurately in the vicinity of the bolt surface, the mesh, which consisted of Lagrange-quadratic elements with triangular shapes as the basic functions, was refined close to the bolt surface and the cutting plane (Fig. 11b).

The cross-section of the bolt was divided into subdomains with specific initial settings in terms of physical properties (wood density, ρ) and thermal properties (C, λ). All the parameters needed to describe the bolt structure – such as bolt diameter, annual ring width (earlywood/latewood), heartwood/sapwood width, pith eccentricity – were defined by modifiable input values, since it is likely that structural properties influence heat transfer into wood because of the variations in densities and therefore in thermal characteristics. According to Kollmann and Côté (1968), the effect of MC is greater than the effect of density on the thermal characteristics of wood, both below and above f.s.p. This assumption is supported by the results presented in Fig. 22. Therefore, the variation of wood's thermal characteristics with wood density were not taken into account and only the influence of MC on wood thermal properties (C, λ) was considered in this study. For geometric convenience, the real situation was modelled by supposing an immobile bolt with an IR heat source turning around it; this is a valid simplification since only the movement of the IR source relative to the wood is important. The bolt surface was divided into 20 sections with uniform boundary settings. Only the IR source's external input heat flux q (in $W.m^{-2}$) was successively activated with a Boolean operator for each section of the bolt arc surface being radiated. The boundary conditions at the bolt surface were defined by Eqs. 6a and 6b with, n, the vector normal to the boundary.

- on the arc surface (radiated) x: $-n.(-\lambda\nabla T) = \varepsilon.Q.H(x)$ (6a)
- on the unradiated rest of the surface: $-n.(-\lambda\nabla T) = h\,(T - T_{ext})$ (6b)

where H is the Heaviside function (Fig. 11), ε the emissivity of the wood surface, T_{ext}, the external temperature (in K), q, the heat flux (in $W.m^{-2}$) and, h, the heat transfer coefficient fixed at 5 $W.m^{-2}.K^{-1}$ (Quéméner et al. 2003). The mean value $\varepsilon = 0.85$ was chosen because the emissivity of un-planed wood is said to vary from 0.70 to 0.98 for temperatures ranging from 17 to 70°C (Flir Systems 2004). Wood emissivity here is independent of the IR wavelength (total emissivity) because the whole emission spectrum of the IR source (independently of the wavelength) is taken into account.

Eq. 7 is the thermal equation solved by Comsol Multiphysics to predict the heating of wood surface and of the layers beneath the surface by an external IR source. It is derived from Fourier's law and only takes into account the transient transfer of the heat absorbed by the surface layers by conduction to the inside layers without integrating any volumetric absorption of IR into wood. This assumption was confirmed by the results obtained on optical properties of green wood (section 4.2.4).

$$\rho c \frac{\partial T}{\partial t} = \nabla(\lambda \nabla T) \qquad (7)$$

The continuous removal of the wood surface layer by peeling was modelled by turning the physical properties of each cut segment from that of wood into air. In Fig. 11b segments in blue, having a density of 1.2 kg.m^{-3} represent air, i.e. segments that have been cut from the bolt. In this case, the subdomain settings are functions of time and are automatically modified with Boolean functions. At each angular step, each element of the angular section reaches a new temperature resulting from the input of the external IR source and is calculated with Eqs. 6a and 6b. After each angular step, the IR is moved (by modifying the boundary settings) and the last heated section is removed (by turning its density to that of air). After each turn, the final calculated temperature of each element is used as the initial temperature of the new meshing element at the bolt surface.

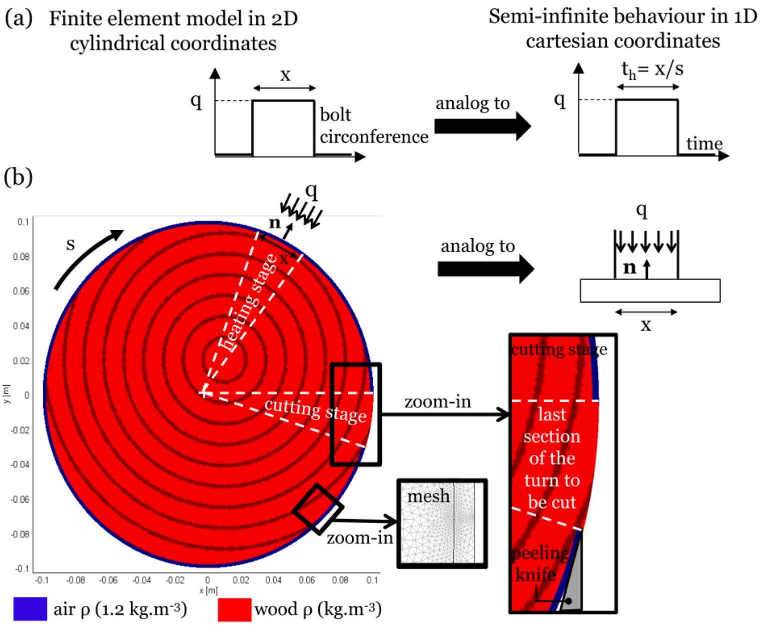

Figure 11. (adapted from Papers IV and V + additional data) (a) Analogy with semi-infinite behaviour in 1D Cartesian coordinates of (b) the modelling in 2D cylindrical coordinates of a bolt meshed with Finite Elements and heated with IR

3.7. Experimental and analytical validations of the numerical simulation of heating rates

In order to check its reliability in predicting the heating of a green log rotating under an IR heating source, this 2D numerical model in cylindrical coordinates was validated by experimental measurements. For this purpose, simplified analytical solutions of thermal transfer in a semi-infinite body in 1D Cartesian coordinates - proven to describe accurately this experimental situation (Section 4.4) - were necessary to estimate the effective flux density, q (Fig. 12), received by the sample by the inverse method of deconvolution proposed by Beck et al. (1985) (Paper V).

3.7.1. Experimental setting

The physical experiments consisted of conveying samples of green wood at a speed, s, of 0.0032 m.s^{-1} under an electric IR lamp composed of a quartz tube delivering a heat flux, q (in W.m^{-2}), onto a surface approximately 0.03 m wide (the gridded surface shown in Fig. 12). The samples were shaped in the form of rectangular prisms because (1) it is easier to record internal temperature rises in a block in motion than in a rotating cylinder, (2) the numerical simulation mentioned below has demonstrated that, with characteristics of the IR source used in the model, blocks behave in a similar manner to cylinders. The increase in surface temperature over time was recorded using a surface thermocouple, tightly stapled to the surface in order to minimize thermal contact resistance. Holes were drilled into the samples to insert the thermocouples which were used to measure the temperatures within the block. The holes were drilled at a depth of 3 mm millimeters beneath the exposed tangential surface (Fig. 12).

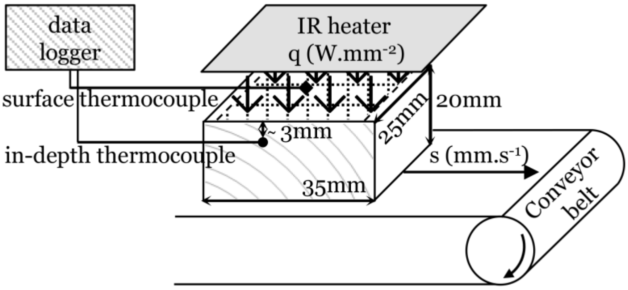

Figure 12. The experimental set-up for measuring the sample surface temperature under IR heating

A tight fit and filling the drilled holes with wood dust after inserting the thermocouples ensured minimal heat losses and thermal contact resistance. The thermocouples were connected to a data acquisition system which recorded the temperature every second. The samples were initially in the green state and at least 3 replicate tests were carried out on each species (in both sapwood and heartwood).

3.7.2. Simplified analytical solutions

Firstly, given the large dimension of the bolt diameter, D, compared to x, the arc surface of the green log subjected to external IR heating (x = D/20), it is possible to reduce the situation to one dimension in Cartesian coordinates (Fig. 11a). Secondly, in view of the very low thermal diffusivity of green wood of green wood (Paper III), the behaviour can be assumed to be that of a semi-infinite body with a spatially uniform step heat flux diffusing normally to the surface, x, applied during a heating time, t_h, where $t_h = x/s$ and s is the peeling speed (i.e. the constant linear speed at which veneer is generated at the output of the peeling lathe). The problem therefore becomes analogous to a 1D-transient problem where the spatial variable, x, is replaced by the temporal variable t_h. With these assumptions, the evolution of the sample surface temperature, T_{surf}, with the square root of time is linear according to Eq. 8 (Taler and Duda 2006).

$$T_{surf} = \frac{2q}{\sqrt{\pi}\sqrt{\lambda\rho c}}\sqrt{\frac{x}{s}} \quad \text{or} \quad T_{surf} = \frac{2q}{\sqrt{\pi}\sqrt{\lambda\rho c}}\sqrt{t} \tag{8}$$

The exact solution of the temperature, T_d, attained at depth, d, within the sample is then given by Eq. 9 with the diffusivity of wood, $\kappa = \lambda/(\rho c)$ (Taler and Duda 2006).

$$T_d = \frac{2q}{\sqrt{\pi}\sqrt{\lambda\rho c}} e^{-d^2/4\kappa t} - \frac{d}{\lambda} q \,\mathrm{erfc} \frac{d}{2\sqrt{\kappa t}} \tag{9}$$

where erfc is the complementary error function which tends to 1 when time tends to infinity. Therefore, the long-term behaviour of T_d is given by the asymptotic solution obtained when time tends to infinity (Eq. 10). It can be seen that at extended heating times the temperature at depth, d, also evolves at a rate proportional to the square root of time.

$$T_d = \frac{2q}{\sqrt{\pi}\sqrt{\lambda\rho c}}\sqrt{t} - \frac{d}{\lambda} q \tag{10}$$

4. Results and discussions

4.1. Optimum heating temperatures

In order to determine 'minimum-optimum' heating temperatures, the experimental plan involved heating bolts, by soaking them in water over a 48 h period at temperatures ranging from 20 to 80°C, then peeling and sampling them (Section 3.1). The soaking period was long enough to ensure that the temperature within the relatively small bolt (400 mm diameter, 600 mm length) was homogeneous, so as to avoid any temperature gradient within the bolt. The conclusions on the influence of heating temperature on veneer thickness variation, air leakage (measured with the fuitometer) and lathe checking (measured with the SMOF) are detailed in Paper I and are summarised below.

4.1.1. Effect of heating temperature on thickness variation

Although the effect of heating on thickness variation differs between softwoods and hardwoods, Fig. 13 shows reasonably small thickness variation (COV) commensurate with the relatively low pressure bar setting used during the experiments (Bp = 5 %, Section 3.1). For softwood species such as spruce, heating reduces variation in veneer thickness, making it more uniform, as can be seen from the decreased thickness variation as heating temperature rises (Fig. 13).

	20°C	**30°C**	**40°C**	**50°C**	**60°C**	**70°C**
Beech	83	83	83	85	83	83
Birch	84	84	84	84	84	84
Spruce	91	91	91	91	91	91

Table 3 Number of samples tested to measure thickness variation

For spruce, the inconsistency in the COV at 30 and 70°C might be explained by two factors: (1) experimental error (most probably the predominant factor at 30°C) and (2) the heterogeneous microscopic structure of spruce (likely to be the predominant factor at 70°C) (Navi and Heger 2005). At 70°C, the earlywood fibres of spruce weaken and tear under the cutting knife creating an uneven, 'woolly', surface which explains the increase in thickness variation. The heterogeneous (compared with the rather more homogeneous structures of beech and birch) structure of spruce probably explains why the phenomenon is so visible in this species. The results of CI obtained in spruce at 80°C (see next section) also support this assumption.

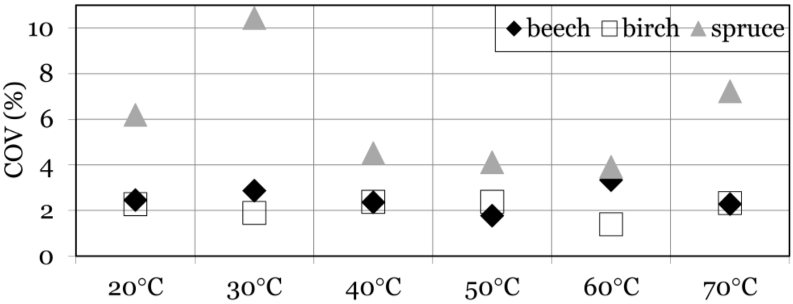

Figure 13 Influence of heating temperatures on thickness variation (COV) – results are not available at 80°C due to experimental error

4.1.2. Effect of heating temperature on veneer checking index

Apart from the inconsistent results for spruce at 80°C, which may be due to experimental error, the CI[4] is always found to be positive denoting that air leakage on the 'loose' side is higher than on tight side (Fig. 14). This observation confirms that the fuitometer may be used to qualitatively evaluate the amount of lathe checking that forms on the 'loose' side of the veneer (El Haouzali 2009). As may be seen from Fig. 14, up to a temperature of 70°C, there is a tendency for the CI to decrease with increasing heating temperature demonstrating the positive influence of heating on reducing veneer lathe checking. Fig. 15 confirms this positive influence by showing a reduction in lathe check depth at 70°C, which is more noticeable in beech and birch.

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[4] $\text{CI (in mm of water)} = \text{water level}_{\text{on tight side}} - \text{water level}_{\text{on loose side}}$ (4)

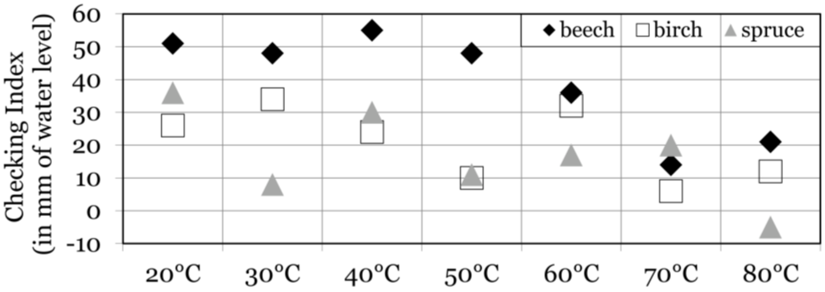

Figure 14 Influence of heating temperature on checking index (CI)

The slight increase in CI at 80°C (Fig. 14) observed in both beech and birch and the negative CI of spruce at the same temperature, may be due to the formation of 'woolly' surfaces and deeper checks. The results shown in Fig. 14 are mean values calculated on the number of specimens presented in Table 4.

	20°	**30°C**	**40°C**	**50°C**	**60°C**	**70°C**
Beech	83	83	83	85	83	83
Birch	84	84	84	84	84	84
Douglas-fir	68	73	80	107	82	78
Spruce	91	91	91	91	91	91

Table 4 Number of samples tested to measure CI

4.1.3. Effect of heating temperature on the distribution of checks

All three species exhibited the same behaviour with respect to check depth. As may be seen from Fig. 15, when the most frequent values are considered, check depths were roughly constant up to a temperature of 50°C, before decreasing at 60 and 70°C. This means that high heating temperatures produce veneers with shallower lathe checks. With respect to the interval between two adjacent checks, beech and birch behave alike and in the same manner as check depth, namely that high heating temperatures tend to produce veneers with a greater number of more closely spaced checks (Fig. 16). These results should, in theory, be verified by a constant Checking Ratio, CR (Eq. 2)[5], which is only confirmed in the case of beech (Fig. 17).

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[5] $$\mathrm{CR} = \frac{\mathrm{CIn}}{\mathrm{CD}} \qquad (2)$$

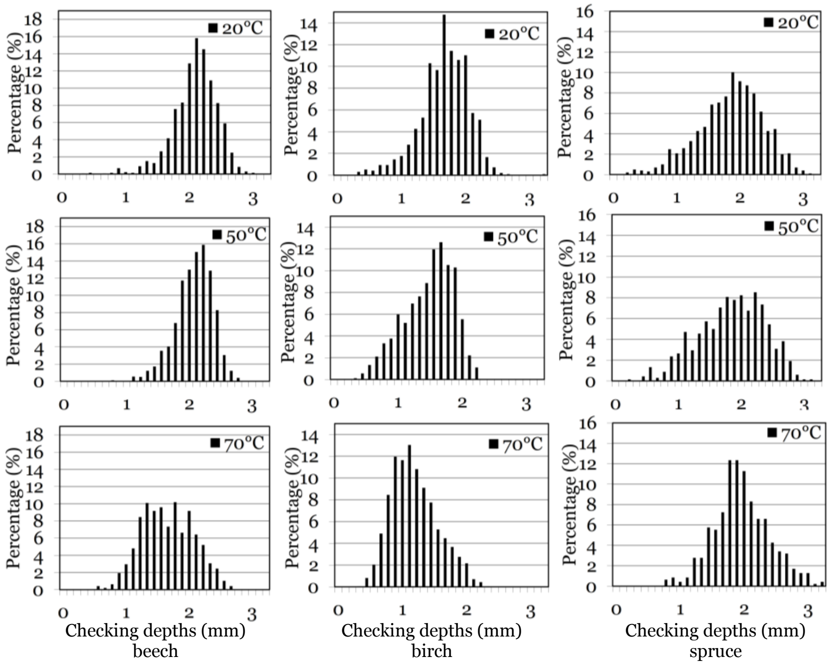

Figure 15 The distribution of check depth as a function of heating temperature[6]

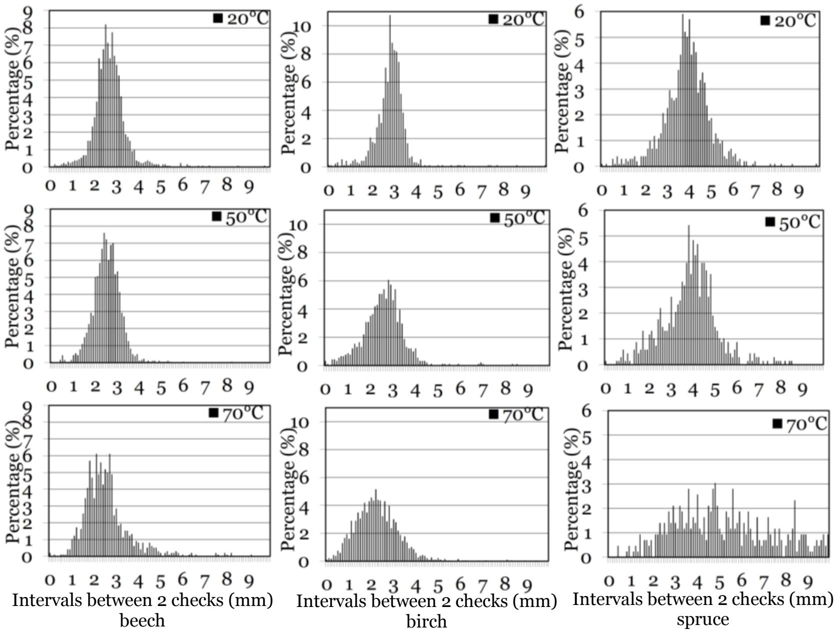

Figure 16 The distribution of the intervals between two checks as a function of heating temperature[6]

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[6] See Paper I for diagrams at all temperatures (20°C, 30°C, 40°C, 50°C, 60°C, 70°C) for beech, birch and spruce. Diagrams at 60°C and 70°C differ from diagrams from 20°C to 50°C that exhibit roughly the same characteristics

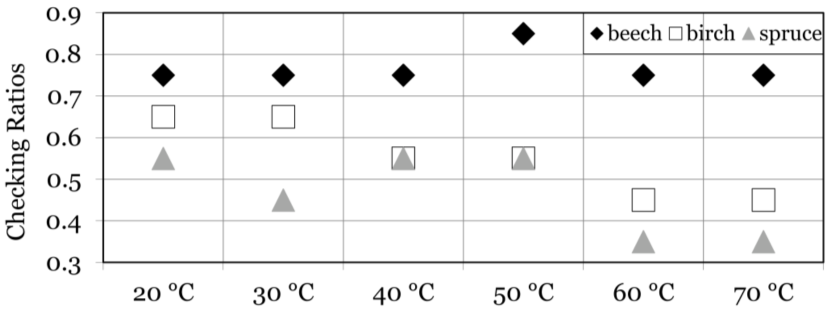

Figure 17 The influence of heating temperature on checking ratio (CR)

Another observation from Figs. 15 and 16 is that both distributions get gradually broader as temperature increases. Spruce, however, exhibits curious behaviour at 70°C: as may be seen from Fig. 16, the distribution of the intervals between two checks becomes so broad that there is no clear maximum frequency value. When the distributions are so broad, determining the most frequent values is not a statistically relevant way of characterising the checking distribution. For this reason a statistical analysis based on evaluating the coefficients of skewness[7] and kurtosis[8] of the distributions (Section 3.3.2) was chosen. For all species, the skewness and kurtosis of the intervals between two checks tends to decrease with increasing heating temperature (Fig. 18). The skewness and kurtosis of spruce are lower than that of beech and birch at all temperatures and skewness drops to 0 and kurtosis becomes negative at high temperatures. The conclusions that can be drawn from this confirm that the checks are deeper and more widely spaced at low temperatures than at high temperatures which produce smaller but more closely packed checks.

The mechanisms of lathe check formation therefore seem to become more unpredictable as the heating temperatures rise. One hypothesis is that this phenomenon is an indication of the growing impact of wood anatomy and the reduction in the stress field as a result of reaching the glass transition temperature, which occurs in the range of 50–100°C for green wood (Olsson and Salmén 1997). This hypothesis is supported in particular in the case of spruce, in which there is a big difference between earlywood and latewood (Raiskila et al. 2006) as well as higher lignin content (Fengel and Wegener 1984). This may explain why the impact of heating temperature is

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[7] Skewness is a measure of the asymmetry of the distribution

[8] Kurtosis is a measure of the peakedness of the distribution

more visible in spruce than in a more homogeneous species such as beech. Trying to establish a link between this phenomenon and wood anatomy remains awkward and would need further investigation.

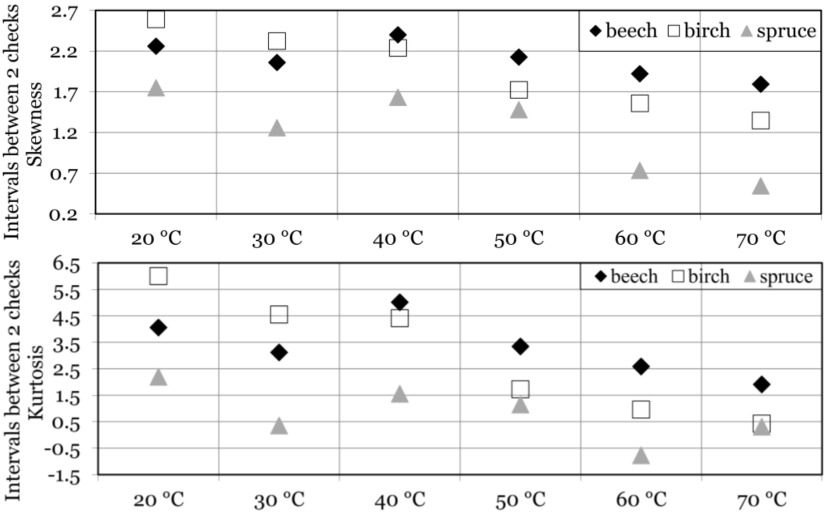

Figure 18 Influence of heating temperatures on skewness and kurtosis for intervals between two checks

4.1.4. Conclusions about optimum heating temperatures

For beech, birch and spruce, it is difficult to define 'minimum-optimum' heating temperatures based on the results that have been obtained. It appears that low temperatures produce veneers with deeper and more widely spaced checks than high temperatures where the checks are shallower and closer. At high temperatures, the check formation mechanism is less periodic and becomes governed by wood anatomy and is therefore less predictable - especially in the case of heterogeneous spruce. Even at 50°C, the positive effect of heating ensures efficient peeling. All the findings presented above indicate that there is no need to heat up the wood to higher temperatures (at least in terms of check formation). This criterion of 50°C increases the chances that an IR heating system embedded on a lathe would be able to heat wood quickly enough to ensure successful peeling. Overall, however, these results demonstrate the efficiency of the SMOF device in quantifying veneer lathe checking (by means of the intervals between two checks and check depths measured on the very long length of veneer ribbon tested) but that its use is restricted to the research scale given the difficulty in developing the SMOF device into on-line measurement system operating on the edge of the veneers.

4.1.5. Supplementary studies on cutting efforts

The precise measurement of cutting effort as a function of the soaking temperature of the bolts being peeled would be a useful tool that would bring additional data to determine more accurately 'minimum-optimum' heating temperatures. Supplementary tests were carried out using the industrial peeling lathe available at Arts et Metiers ParisTech, Cluny, France that was equipped with in-line Kistler piezo-electric sensors providing data about cutting efforts. The resulting data are the mean and standard deviation of cutting effort (in daN) applied on the cutting knife - Xk and Yk (Fig. 19).

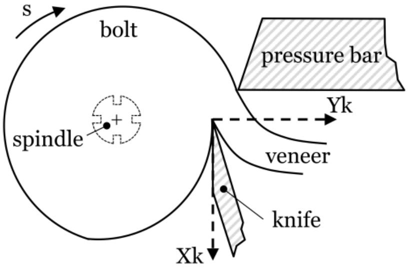

Figure 19 Efforts applied on the cutting knife (Xk is vertical and Yk horizontal)

Looking at the results with the pressure bar, bolts heated to either 30°C or 50°C result in roughly the same amount of efforts on the cutting tools as the unheated control bolt at 20°C (Fig. 20). Up to 50°C, heating temperature influences the cutting efforts in the case of Douglas-fir to a small extent (10% in Xk, 20% in Yk). This finding is at variance to observations in oak and chestnut (Marchal 1989). However, above 50°C, a decrease begins leading to a reduction of 31% in Xk and of 46% in Yk as the temperature rises from 50°C to 80°C (Fig. 20). The difference in cutting efforts measured with or without the pressure bar diminishes as the heating temperature increases, showing that the transfer of effort from the pressure bar to the cutting knife, present when the wood is unheated, disappear when the wood is heated. Nevertheless, coefficients of variation (COV) in cutting efforts (the error bars in Fig. 20) do not, as might be expected, exhibit any regular decrease as heating temperature increases. COV in cutting efforts measure noises due to vibrations caused by the cutting tools encountering knots. Consequently, the heating of bolts aimed at softening knots locally should reduce the impact of intra-ring heterogeneity and limit the efforts on the cutting tools (Marchal et al. 2004). However, at only 2%, the percentage of knots in the Douglas-fir veneers tested was small and might well account for the lack of reduction in coefficients of variation.

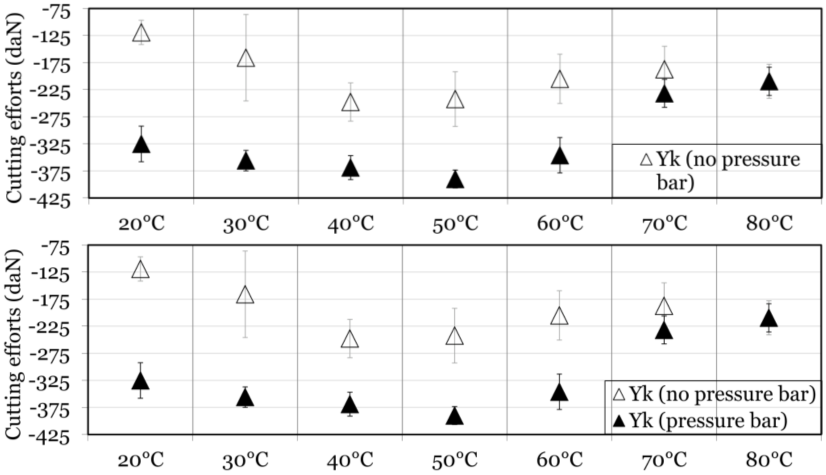

Figure 20 Influence of heating temperatures on cutting efforts of the cutting knife for Douglas-fir (standard deviations detailed) with pressure bar Bp at 5 % and without pressure bar

Unfortunately, due to measurement difficulties, the cutting efforts on the other wood species under investigation could not be studied. It would be of great interest to continue such a study on cutting efforts using the micro-lathe available at Arts et Metiers ParisTech, Cluny, France. This device can peel disks free from defects, providing more accurate results on the one hand but, due to the thickness of the disk, increasing the difficulty of controlling the heating temperature on the other.

4.2. Optical properties of wood

An integrating sphere enabled the experimental measurement of the spectra of normal hemispherical spectral reflectance and transmittance over the wavenumber σ range 550 to 5500 cm^{-1} (i.e. wavelengths L from 1.8 to 18 μm) in green wood samples to be made. From these results it was possible to estimate the amount of energy absorbed by the wood and the penetration depth of the IR radiation. Such data are necessary to develop accurate numerical models designed to simulate the thermal behaviour of wood being heated by an external IR source (Section 4.4), but which are lacking in the literature – especially in green wood where the MC distribution is complex. If it could be shown that wood can absorb IR energy to a certain depth, then equations predicting the heating of wood layers beneath the surface by an external IR source should take into account the volumetric absorption of IR energy within wood and not only the transfer of the heat absorbed by the surface layers through conduction to the inside layers. This study also investigated the influence of moisture and knots on the optical properties of green wood as well as the effect of remoistening wood which is not detailed here, but can be found in Paper II.

4.2.1. Amount of energy absorbed and penetration depth

Fig. 21 shows that both transmission and reflection increase with higher frequencies, i.e. at shorter wavelengths. The amount of energy effectively absorbed by the wood is more significant at longer wavelengths than in the near-IR range next to the visible range, below 2500 cm^{-1}. Up to 4000 cm^{-1}, the 0.5 mm sample absorbs nearly all incident energy (absorption is close to 0.95) and no energy is transmitted through the samples. In contrast, the 0.2 and 0.3 mm thickness samples were found to transmit energy. In the 1800-3000 cm^{-1} range, transmission was found to be around 0.3 for the 0.2 mm thick samples and around 0.1 for the 0.3 mm thick samples. This indicates that between 550 and 4000 cm^{-1} around 70% of the incident radiation is absorbed by the first 0.2 mm of wood and around 90% of the incident IR radiation in the first 0.3 mm of wood. The thinner the sample, the more radiation transmitted through it and the thicker the sample, the greater the amount of reflected and absorbed radiation. The relatively low penetration depth of 0.3 mm might be explained by the heterogeneous structure of wood which can be modelled as a network of cellulose microfibrils embedded in a matrix of hemicelluloses and lignin, interspersed with water and void spaces. In the case of homogeneous materials, radiation propagates linearly with progressive exponential absorption following Beer-Lambert’s law. However, the different refractive indices in heterogeneous materials backscatter the penetrating radiation preventing linear propagation, so that the strength of the radiation becomes smaller as it penetrates deeper.

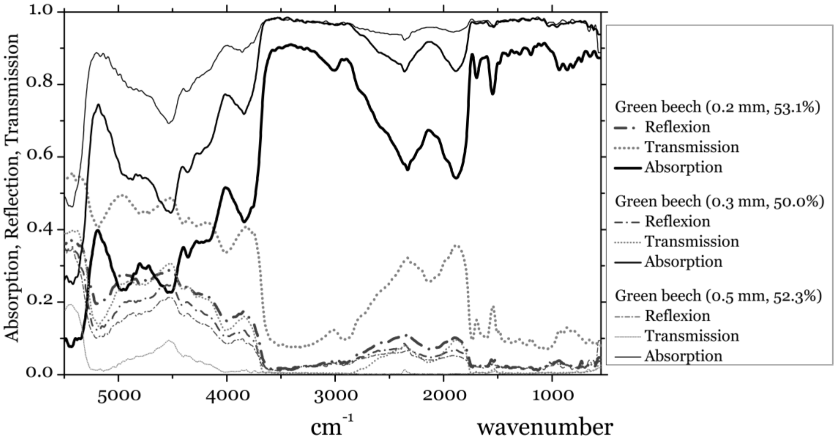

Figure 21 Reflection, transmission and absorption spectra for 0.2mm, 0.3mm and 0.5mm thick green beech samples (at 53.1%, 50.0% and 52.3% respective MC)

4.2.2. Effect of moisture on the optical properties of wood

Fig. 22 shows the reflection, transmission and absorption spectra at different MC for a 1.6 mm thick beech sample. All samples with thicknesses greater than 0.5 mm, and all species tested, exhibited similar behaviour. Reflection varied between 10 and 30% with the most significant amount of reflected radiation occurring on drier wood. Transmission could be neglected because it remains constantly weak (less than 5%) without being influenced by the amount of water in wood. Therefore, Tr is negligible and the complement to 1 of reflectivity gives absorptivity A[9] (Eq. 5). Absorption varied from 70 to 90% with the most significant amount of absorbed radiation occurring in wetter wood. The presence of water in wood is thus beneficial in terms of IR penetration because it increases the amount of absorbed energy. However, if this substantial increase serves to heat the water present in wood, it is of no interest for the purpose being investigated herein, namely to heat the wood cell walls with IR radiation.

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[9] $A = 1 - R - Tr$ (5)

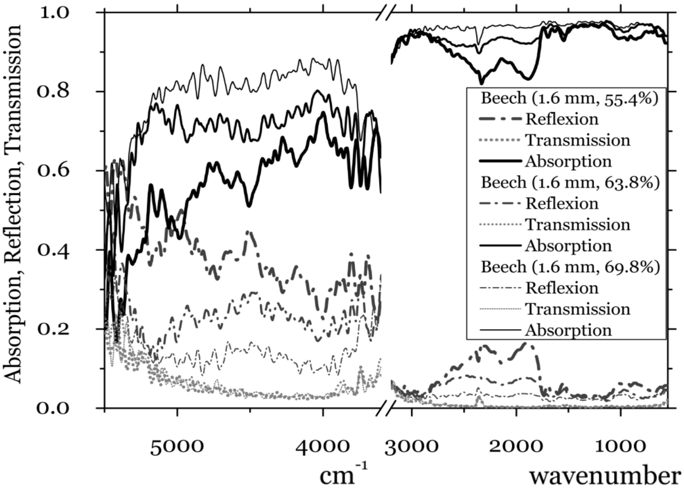
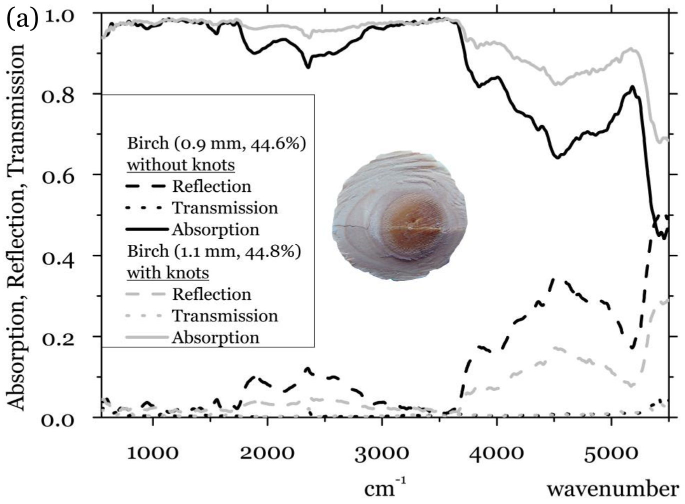


Figure 22 Reflection, transmission and absorption spectra for 1.6mm thick green beech sample at 55.4%, 63.8% and 69.38% MC

4.2.3. Effect of knots on the optical properties of wood

This investigation is of interest since the characteristics of knots – for instance high density and variable grain direction (Kollmann and Côté, 1968) are known to be detrimental to cutting tools. If knots were to absorb more energy than the surrounding wood, IR could be used, for example, to preferentially heat the knots thereby softening them and making them easier to be cut across the grain during veneer peeling. Experimental results have shown that the presence of knots may be seen to increase penetration depth by several tenths of millimeters (Fig. 23). Fig. 23a (resp. Fig. 23b) shows that samples of 0.9 mm (resp. 0.5 mm) of birch (resp. Douglas-fir) feature absorption curves that are less close to 1 than the ones at 1.1 and 0.7 mm respectively – which means that they enable some IR radiation to transmit. A possible explanation for this is that the denser wood in knots contains a relatively greater number of molecules able to absorb energy. Moreover, the different orientation of the fibres around the knots may also affect energy absorption. Both wood density and fibre orientation have been noted by Zavarin et al. (1990) to be factors influencing energy absorption in wood.



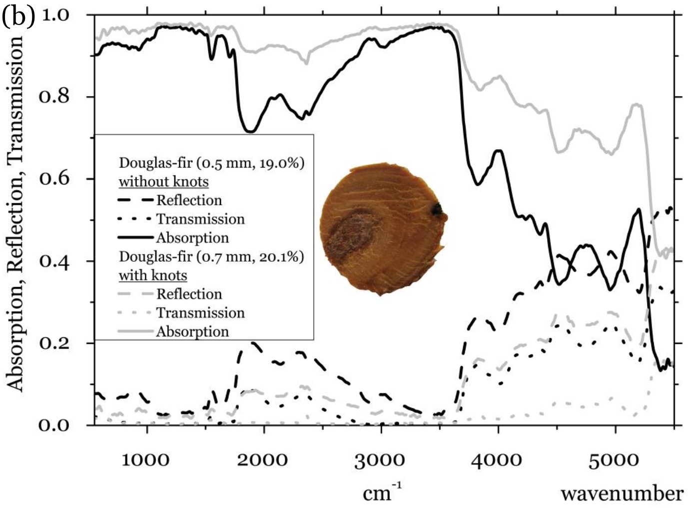


Figure 23 Reflection, transmission and absorption spectra of samples with and without knots for (a) birch and (b) Douglas-fir (thickness sample and sample MC in brackets)

4.2.4. General conclusions on optical properties of wood

For clear wood, it is not possible to deliver energy deeper than up to 0.3 mm below the wood surface because 70 to 90% of all incident IR radiation on the wood surface is absorbed in this layer. In the case of knots, however, it is possible to deliver the energy several tenths of millimeters deeper. These results illustrate that IR radiation can heat the surface layers, but then penetration deeper into the wood is by conduction. Some wood features, such as the presence of knots and of free water in wood (the latter two having a more significant effect), increase the amount of energy absorbed. These findings do not necessarily suggest that the IR heating of green wood is impracticable, but they highlight the fact that IR radiation is mainly absorbed near the surface without penetrating deeply into the wood. Equations predicting the heating of wood layers beneath the surface by an external IR source should only take into account the transfer of the heat absorbed by the surface layers by conduction to the inside layers. Consequently, the equations governing the numerical modelling should not integrate any volumetric absorption of IR into wood but are governed by Eq. 7[10] - the transient heat transfer equation for conduction derived from Fourier's law.

4.3. Thermal properties of green wood

The TPS technique was used to characterise the thermal behaviour of green wood, providing empirical equations to predict the values of thermal conductivity, λ, heat capacity, C, and thermal diffusivity, κ, at the macroscopic level on the one hand and wood MC on the other. The target of this work was to feed the numerical models with these inputs. For this purpose, the natural features of wood such as its anisotropy and knots were also studied because of the possible influence on the thermal behaviour of green wood.

With the TPS technique, the temperature measurement is localised at the heating element. As explained earlier (Section 3.5), the probe size is limited by the characteristic time and by the size of the sample to avoid edge effects: the probe cannot encompass the whole sample. The influence of heterogeneities cannot be completely eliminated if the probe location is changed: the pattern of annual rings varies and the heat flows through the different densities of earlywood and latewood at different rates. However, the repeatability of the experiments was demonstrated by moderate standard deviations. The coefficients of determination, R^2, relative to the equations presented in Figs. 24 , 25 and 26 and in Table 6 are based on calculations made on the number of tests presented in Table 5.

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[10] $$\rho c \frac{\partial T}{\partial t} = \nabla(\lambda \nabla T) \qquad (7)$$

	With knots	Without knots	
		radial	tangential
Beech	11	49	63
Birch	8	47	86
Douglas	8	64	82
Spruce	20	70	78

Table 5 Number of tests to measure the thermal properties

4.3.1. Relationship between thermal conductivity, λ, and MC

Fig. 24 compares the λ values obtained experimentally with the HotDisk® with those obtained by the steady-state guarded hot plate method (Sonderegger et al. 2011). Apart from beech, the experimental values for λ consistently match the results from the literature (Sonderegger et al. 2011).

The reason for this difference might arise from the different experimental methods used between the literature and the experiments performed here. There is no significant difference in λ between the radial and tangential directions for wood in the green state – apart from spruce. It seems that the presence of free water in the cell overrides any effects arising from the anisotropy of the wood. The exception in the case of spruce might be explained by the presence of ray cells that promote heat transfer in the radial direction ($\lambda R > \lambda T$).

4.3.2. Relationship between heat capacity, C, and MC

Fig. 25 compares the C values obtained in this work with those of Sonderegger et al. (2011) and oven-dry values at 20°C found in the literature (Jia et al. 2010, Kollmann and Côté 1968, Steinhagen 1977). The gradients of the linear relationships between C and MC above f.s.p are steeper than below the f.s.p (results from literature), most probably arising from the dominating effect of the free water. The scattered results for Douglas-fir and spruce can be interpreted to mean that C in the green state is not unique for all wood species. There are probably two different ranges of C values depending on whether the material is a hardwood or softwood: the former in the green state would need more energy for heating than softwoods. This behaviour is different from that described in the literature below the f.s.p. Fig. 25 also confirms the assumption made in Section 3.6 that the effect of MC on C is more significant than the effect of density because from 0 to 30% MC, at constant density, C retains the same value but increases highly with MC above f.s.p.

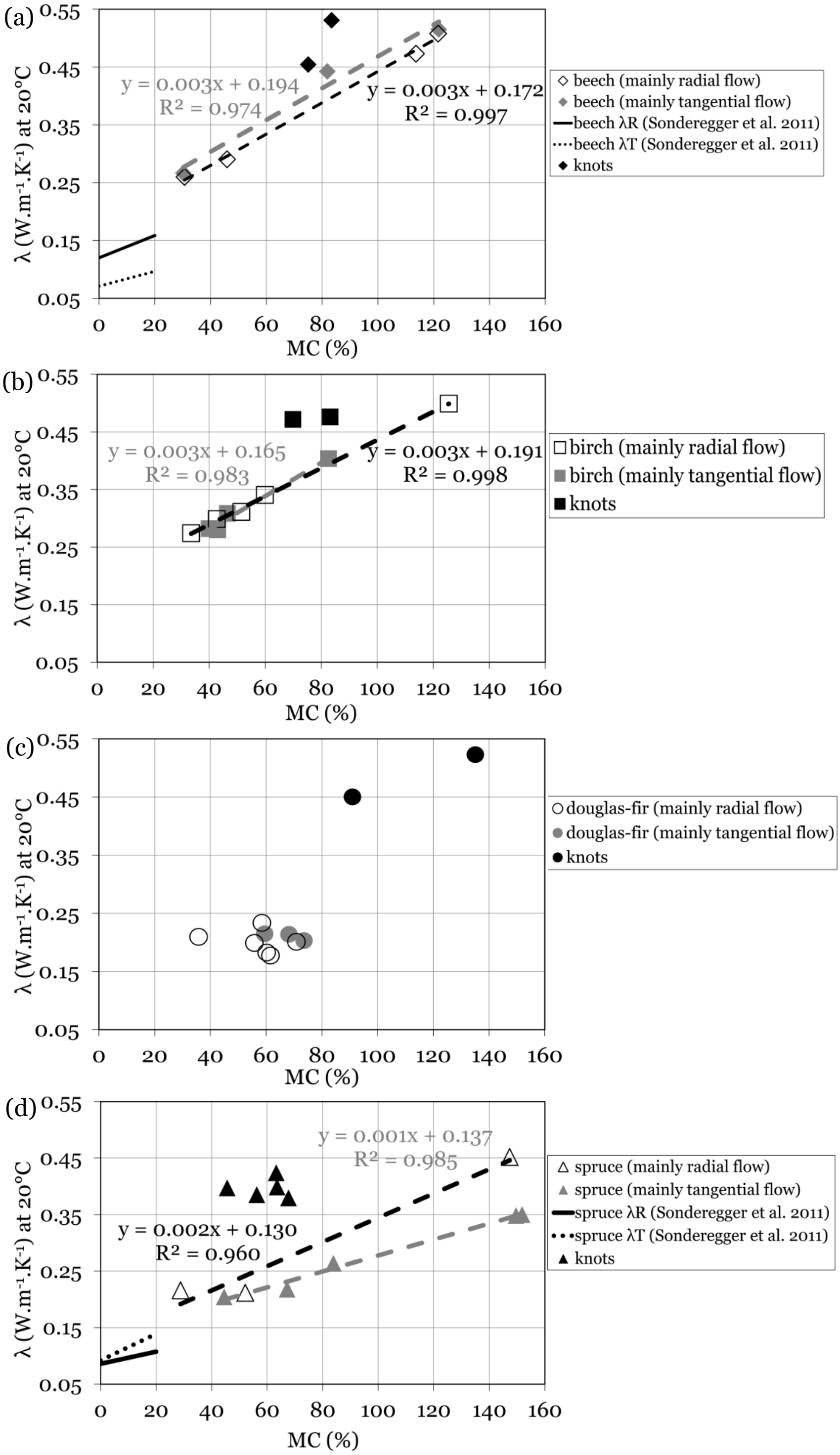

Figure 24 Thermal conductivity λ (in $W.m^{-1}.K^{-1}$) of (a) beech, (b) birch, (c) Douglas-fir and (d) spruce in the green state with and without knots obtained using the HotDisk® (dotted lines are linear regressions on experimental data)

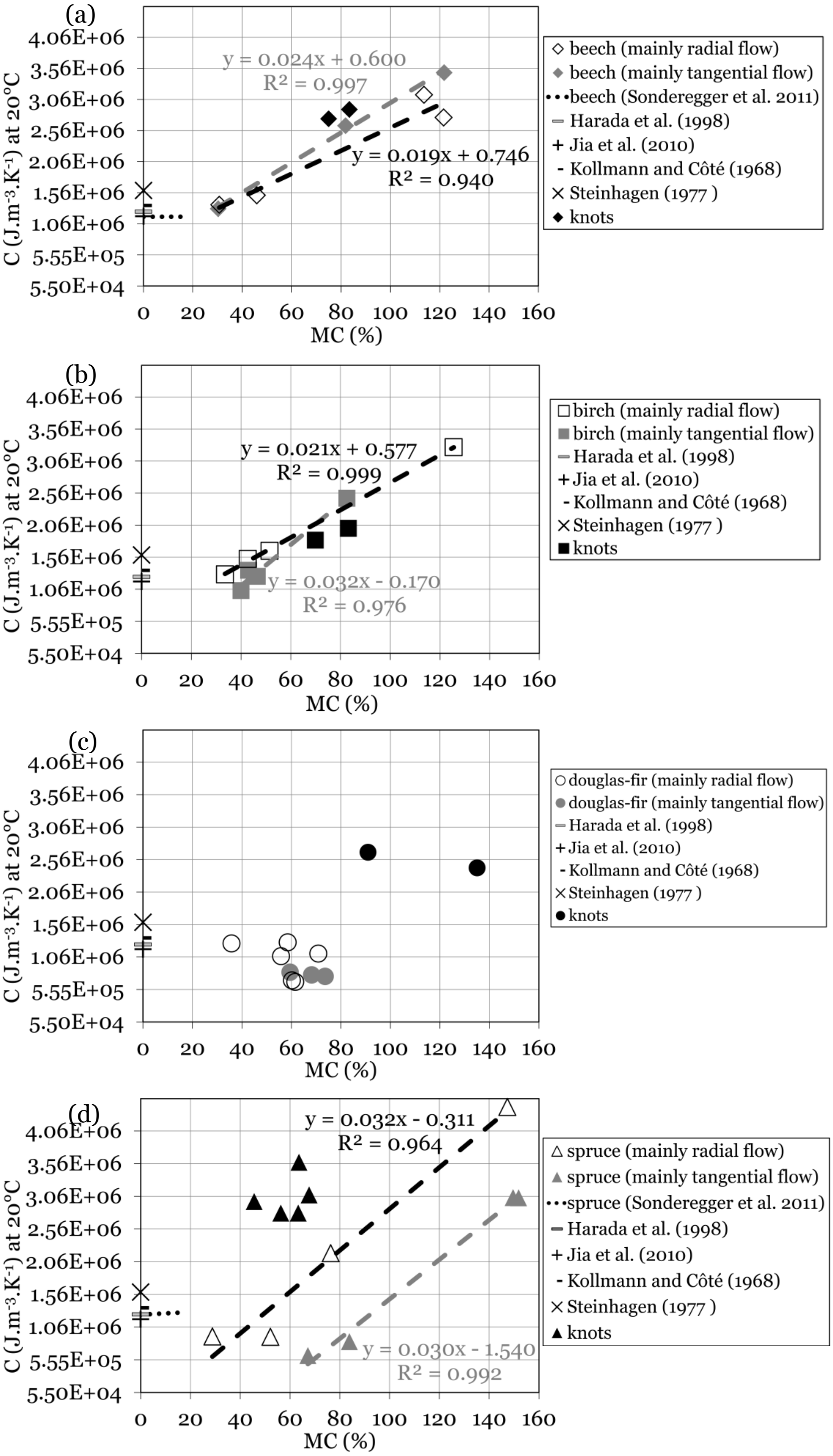

Figure 25 Heat capacity C (in J.m^{-3}.K^{-1}) of (a) beech, (b) birch, (c) Douglas-fir and (d) spruce, with and without knots, in the green state measured using the HotDisk® (dotted lines are linear regressions on experimental data)

4.3.3. The relationship between thermal diffusivity, κ, and MC

Fig. 26 shows κ values obtained experimentally. The comparison is available only in the radial direction because samples for the flash method were obtained from veneers peeled tangentially (Beluche 2011). The results obtained with both methods are close to each other while the flash method differs from the HotDisk®: the flash method consists of (nearly) instantaneously radiating a sample on its front face and then recording, as a function of time, the temperature increase on its rear face (Parker et al. 1961). The percentage differences between both methods are low (4% difference for Douglas-fir at 56% MC and 7% difference for beech at 46% MC). The similarity of the data in Fig. 26 is an indication of its reliability.

4.3.4. Thermal characteristics of knots

In Figs. 24, 25 and 26, the black points represent the thermal characteristics of knots measured with the HotDisk® method compared to the values of clear wood (mainly tangential flow in grey, mainly radial flow in white, Fig. 10). For all species, λ is higher for knots than for clear wood. Apart from spruce, C is also higher for knots than for clear wood. This is quite logical as the density of knots is higher, therefore representing more material to heat and requiring more energy. The different results for spruce might be explained by the resin content of the softwood or might be due to some experimental difficulty in covering the knots with a HotDisk® probe of correct radius (see the pictures of some tested knots in Fig. 23). In any case, such a study on knots would necessitate further experimental tests to confirm the results found here namely that knots require more energy to heat but diffuse heat more rapidly to the inside of the wood.

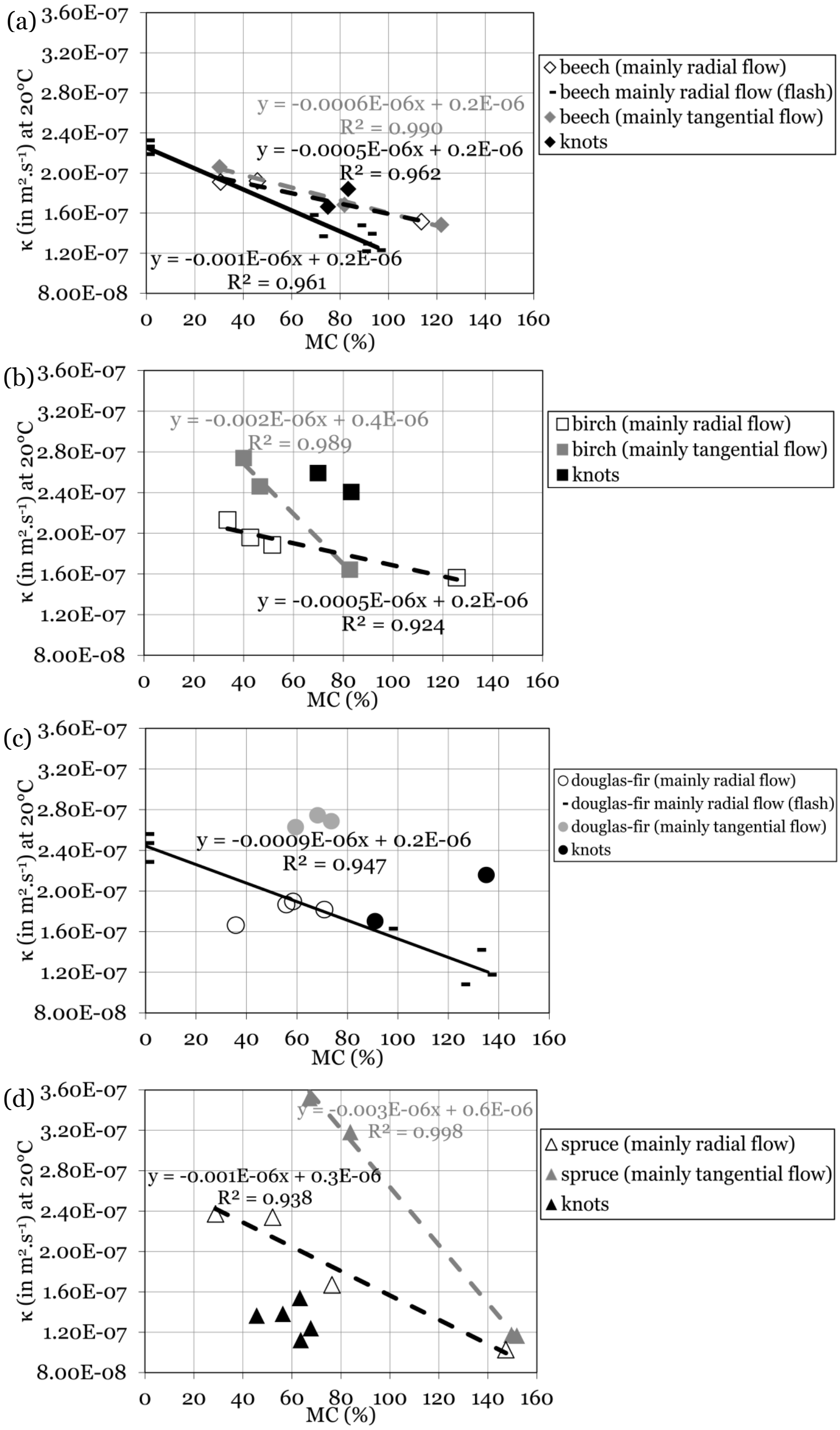

Figure 26 Thermal diffusivity κ (in m².s⁻¹), measured in the green state with the HotDisk® method, of (a) beech, (b) birch, (c) Douglas-fir and (d) spruce, with and without knots (dotted lines are linear regressions of experimental data with the HotDisk®, straight lines are linear regressions of experimental data with the flash method, Beluche 2011)

4.3.5. Conclusions on wood thermal properties

Table 6 presents the predictive equations for λ, C, and κ obtained by the HotDisk®. As is clearly visible, the relationship with MC above the f.s.p is good, as expressed by the high coefficients of determination, R^2. From these results, it can be concluded that:

(1) the thermal behaviour of water, which is more conductive and which has a higher heat capacity than wood, overrides that of wood, thus at higher MC the thermal behaviour of green wood tend towards that of water. However, the insulating properties of wood material limit the thermal behaviour of green wood which never reaches that of water at any MC, even above 100%.

(2) in clear wood above the f.s.p, there is still a linear relationship between the thermal properties λ, C and κ on the one hand, and MC on the other. Wood C and λ increase with MC but wood κ decreases with MC. Therefore wet wood requires more input energy in heating than dry wood but it takes more time for heat to transfer within wet wood and the temperature reached at a given depth in a given amount of time is higher in the case of wet wood.

(3) in the green state, the influence of anisotropy R-T is negligible in these species, with λ being the same in the radial and tangential directions, whilst C would differs between hardwoods and softwoods, being higher in hardwoods.

Table 6 and conclusions (1) and (2) are significant: by knowing the wood MC, it is now possible to deduce the thermal properties (λ, C) that would be necessary to calculate the heating rates (Section 4.4). Conclusion (3) strengthens the knowledge of the thermal behaviour of green wood but is of less interest for the purpose of the study.

	Predictive equations for thermal conductivity (λ), thermal diffusivity (κ), and heat capacity (C)	
	Equations in radial direction	**Equations in tangential direction**
HotDisk®		
Beech	λR = 0.003 MC + 0.172 (R^2 0.997)	λT = 0.003 MC + 0.194 (R^2 0.974)
Birch	λR = 0.003 MC + 0.191 (R^2 0.998)	λT = 0.003 MC + 0.165 (R^2 0.983)
Spruce	λR = 0.002 MC + 0.130 (R^2 0.960)	λT = 0.001 MC + 0.137 (R^2 0.985)
Beech	CR = 0.019 MC + 0.746 (R^2 0.940)	CT = 0.024 MC + 0.600 (R^2 0.997)
Birch	CR = 0.021 MC + 0.577 (R^2 0.999)	CT = 0.032 MC - 0.170 (R^2 0.976)
Spruce	CR = 0.032 MC - 0.311 (R^2 0.964)	CT = 0.030 MC – 1.540 (R^2 0.992)
Beech	κR = -0.0005 MC + 0.2 (R^2 0.962)	κT = -0.0006 MC + 0.2 (R^2 0.990)
Birch	κR = -0.0005 MC + 0.2 (R^2 0.924)	κT = -0.002 MC + 0.4 (R^2 0.989)
Spruce	κR = -0.001 MC + 0.3 (R^2 0.938)	κT = -0.003 MC + 0.6 (R^2 0.998)
Flash		
Beech	κR = -0.001 MC + 0.2 (R^2 0.961)	
Douglas-fir	κR = -0.0009 MC + 0.2 (R^2 0.947)	

Table 6 Equations and coefficients of determination of linear regressions plotted for λ, C and κ in the radial and tangential directions (adapted from Paper III)

4.4. Results and comparison of heating rates simulated numerically, calculated analytically and measured experimentally

With all the results obtained by this stage, it is possible to:

- simulate numerically the heating rates of a rotating green bolt by implementing in the model the equations which govern the heat transfer in the green bolt i.e. the equations of conduction with no volumetric absorption of IR radiation;

- check the reliability of this simulation by comparison with experimental results – using the MC of real case samples to characterise them thermally and simulate their behaviour under IR heating in the model;

- verify the feasibility of an IR heating system – by considering that achieving a temperature of 50°C in the time-frame allowed by the peeling process would be a criterion for success.

4.4.1. Validating the hypothesis of semi-infinite behavior in 1D Cartesian coordinates

In comparing experimental data to numerical results, the difficulty of assessing the effective real flux density received by the sample, which is necessary input data for the numerical simulation, was faced. Since it was not possible to reliably measure the absolute value of the flux density experimentally, the following alternative approach was adopted. If the experimental situation could be reduced to semi-infinite behaviour in 1D Cartesian coordinates described by simple analytical considerations, the surface temperatures could be used to derive the flux density received by the sample. This hypothesis would be validated if the surface temperatures plotted as a function of the square root of time $T_{surf} = f(\sqrt{t})$ showed the same linear behaviour as predicted by the simplified analytical equation, Eq. 8[11]. In view of the variability of the experimental measurements of $T_{surf} = f(t)$ on the different replicate samples (due to the natural heterogeneity of wood) it is more reliable to check this hypothesis on the results of $T_{surf} = f(\sqrt{t})$ obtained by numerical simulation. Fig. 27 shows the results for beech in the early stages of heating (up to 3√s). The table inserted in Fig. 27 summarises the corresponding results obtained in the cases of birch, Douglas-fir and spruce. From the results presented in Fig. 27, two conclusions can be drawn. Firstly, the linearity of the relationship $T_{surf} = f(\sqrt{t})$, confirmed by the high coefficients of determination R^2, validates the assumption that the log can be treated as a semi-infinite body with a step increase in surface temperature of a half-space. Secondly, for the four species, the near equivalence of α_{surf}^{simul} (calculated by linear regression analysis of numerical simulation curves) and $\alpha_{surf}^{anal} = \frac{2q}{\sqrt{\pi}\sqrt{\lambda\rho c}}$ (calculated with the simulation parameters) confirms the suitability of a 1D analytical equation in Cartesian coordinates (Eq. 8[11]) to be used to evaluate the surface temperature increase of a green log rotating under external IR heating. The slight difference between α_{surf}^{simul} and α_{surf}^{anal} in the case of spruce and Douglas-fir can be explained by the lack of linearity at the beginning of the curve (which is also visible in the other species) due to a perturbation at the early stages attributable to the numerical simulation.

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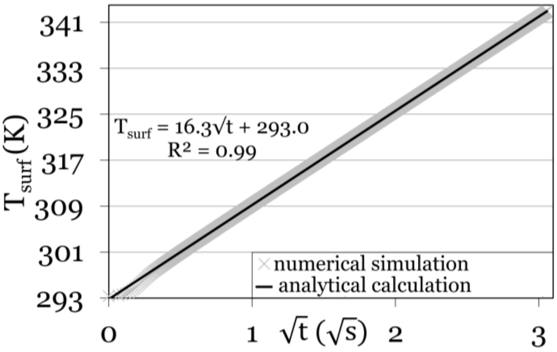
[11] $T_{surf} = \frac{2q}{\sqrt{\pi}\sqrt{\lambda\rho c}}\sqrt{t}$ (8)



	R²(*)	α_{surf}^{simul}	α_{surf}^{anal}
Beech	0.99	16.3	16.3
Birch	1	15.4	15.4
Douglas-fir	1	24.4	24.3
Spruce	0.99	19.6	19.5

(*) calculated on 80 values

Figure 27 Comparison of Finite Element simulated surface temperatures of rotating log and analytically calculated surface temperature response of half space. The temperatures are represented as a function of the square root of time for beech. Table: Comparison of numerical and analytical values of the slopes α_{surf}^{simul} and α_{surf}^{anal} of $T_{surf} = f(\sqrt{t})$ with their corresponding coefficients of determination, R^2, in the case of beech, birch, Douglas-fir and spruce

By deconvoluting the recorded surface temperature data, T_{surf}, using the inverse method proposed by Beck et al. (1985), it is possible to recover the signal q as it existed before becoming convoluted by the impulse response of the half-space. The result of this procedure gives the maximum value (found to be around 10 000 $W.m^{-2}$) of the estimated heat flux density, q_{est}, and the spatial profile of the effective real flux density received by the sample which is necessary data for input into the model in order to compare the simulation to the experimental results (Fig. 28). Fig. 28 compares for one sample the normalised values of the estimated heat flux density, q_{est}, with the measured IR sensor signal, q_{mes} - which corresponds directly to the electric signal produced by an IR sensitive sensor placed on the sample surface. The reliability of the deconvoluting procedure is assessed in Fig. 28 by the good fitting of the two curves. This provides further confirmation (with the results presented above) of the ability of analytical equations to describe the temperature increase in a rotating green log under external IR heating.

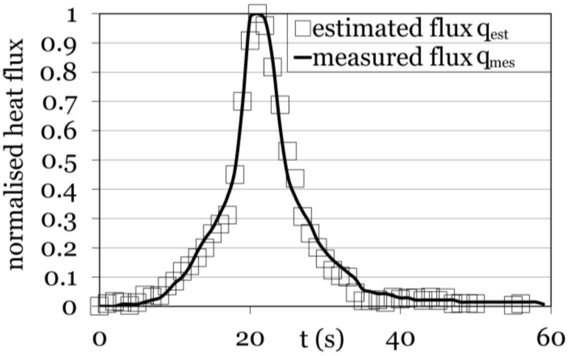


Figure 28 Comparison of estimated heat flux density and the measured IR sensor signal on the sample surface (normalised values are represented)

4.4.2. Heating rates of surface temperatures

In Figs.29, 30 and 31, the residuals are calculated with the difference between experimental and modelled results and are plotted below each graph. Fig. 29a compares the surface temperatures T_{surf} = f(t) of beech at 43% MC, obtained experimentally from surface thermocouples (Section 3.7) with the numerical simulation results modelled using similar parameters. Similar results were also obtained for birch at 85% MC (Fig. 29b), Douglas-fir at 115% MC (Fig. 29c) and spruce at 55% MC (Fig. 29d). In the 20 first seconds, the increasing slopes of the experimental curves are steeper than simulated (the residuals drop consequently below 0). This difference might be explained by some eventual moisture gradient within wood created when drying, being responsible for heterogeneity in the thermal properties of wood which are impossible to evaluate accurately and to implement in the model. Moreover variations in the surface emissivities of different wood samples can lead to some errors in the heat flux received by the samples. However, apart from this difference, these results show reliable agreement between the numerical estimation and measurement (as can be seen by residuals which balance around 0).

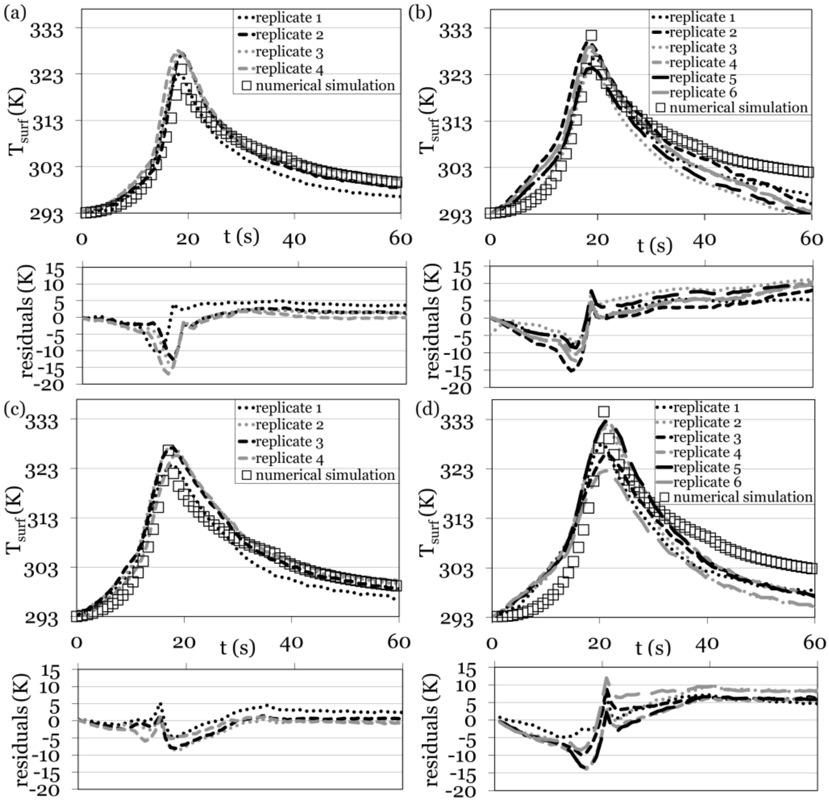


Figure 29 Comparison of numerical simulation curves of surface temperatures $T_{surf} = f(t)$ to experimental results obtained on different replicates of (a) beech at 43% MC, (b) birch at 85% MC, (c) Douglas-fir at 115% MC and (d) spruce at 55% MC (residuals are plotted below each graph)

4.4.3. Heating rates within wood

For several replicates of birch at 85% MC and Douglas-fir at 115% MC, Figs. 30a and 30b compare the temperatures $T_{3mm} = f(t)$ obtained experimentally from the thermocouples embedded 3 mm below the wood surface, with numerical simulation results modelled using similar parameters. These results show good agreement between numerical estimation and measurement with low residuals relatively close to 0.

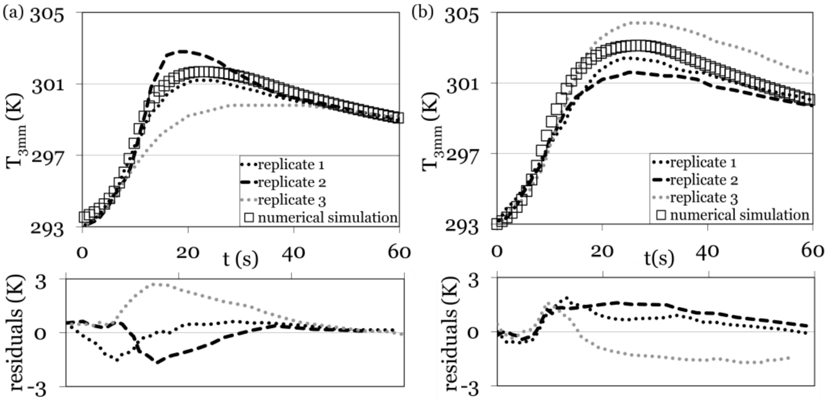


Figure 30 Comparison of numerical simulation curves of temperatures measured at 3 mm depth T_{3mm} = f(t) to experimental results obtained on different replicates of (a) birch at 85% MC, (b) Douglas-fir at 115% MC (residuals are plotted below each graph)

However, around the maximum temperature, the residuals increase. Difficulty in fitting the numerical simulation to the experimental data may arise from three factors: (1) the imprecise insertion depth of the thermocouples; the margin of error in the insertion depth of the thermocouples was estimated to be ±0.5 mm, which clearly might have had an effect, (2) the effect of drying during heating; the difference in the block MC before and after heating, ΔMC_S, remained low (never exceeding 5%), however, even though it could not be reliably measured, this change was attributed to water evaporating from the surface layers of the samples, (3) the influence of sawing; the differences in densities (and thus in thermal properties) between earlywood and latewood may have a greater influence in quarter sawn samples where annual rings are parallel to the IR flux (Fig. 6). In order to take the effect of drying on thermal properties of wood into account, it is possible to estimate to 50% the margin of error in the MC. Assuming both effects (1) and (2), Fig. 31 plots the envelope curves (in dotted lines) of temperatures below the wood surface, T_{3mm} = f(t), simulated numerically in the most favourable case, where both insertion depth and MC are underestimated (Fig. 31a plots $T_{2.5mm}$ = f(t) at 21% MC and $T_{3.5mm}$ = f(t) at 65% MC for birch) and in the least favourable case when insertion depth and MC are overestimated (Fig. 31b plots $T_{2.5mm}$ = f(t) at 27% MC and $T_{3.5mm}$ = f(t) at 83% MC for spruce). When plotting these envelope curves, the effect of drying (2) predominates over the effect of the imprecise insertion of the thermocouples (1). The envelope curves surround all the experimental curves, which demonstrate that taking into account these two effects is more representative of the reality of the experiments.

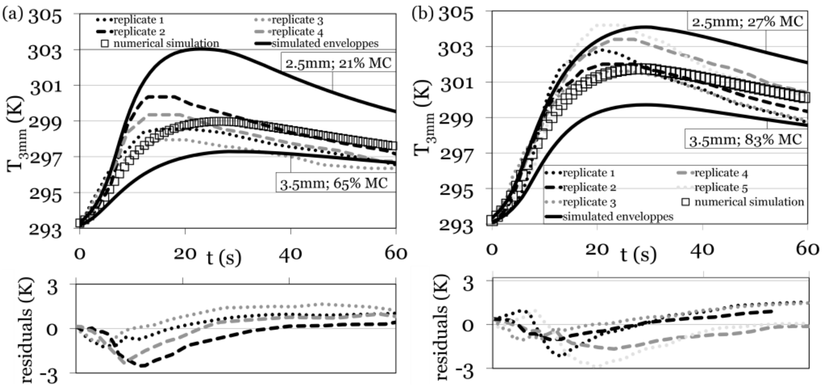


Figure 31 Comparison of experimental results measured at a depth of 3 mm with numerical simulation curves of temperatures T_{3mm} = f(t) and their envelopes $T_{3\pm0.5mm}$ = f(t) (dotted lines) obtained on different replicates of (a) beech at 43±22% MC, (b) spruce at 55±28% MC (residuals are plotted below each graph)

4.4.4. Conclusions on heating rates

By comparing experimental to numerical simulation results, the ability of the numerical model using finite elements to simulate, in 2D, heat transfer within a log and to output the temporal evolution of surface and below surface temperatures, has been validated. During this validation process, it has been demonstrated that simple analytical equations, that assume the behaviour to be that of a semi-infinite body in 1D Cartesian coordinates, can estimate the heating rates and the maximum temperatures achievable at the surface and below the surface (Eqs. 8 and 10). With both methods, the inputs are the thermal and physical properties of green wood and the heat flux density of the IR source. With these analytical equations (Eqs. 8 and 10), it is possible to rapidly calculate the temperature at a certain depth below the surface and the maximum surface temperature reached by a green log which is be particularly useful in setting up the parameters for an IR heating system. None of the simulation presented could achieve temperatures around the required temperature of 50°C established beforehand. Increasing the IR heat power enables the heating of the wood surface but the temperature at the cutting plane, located at several millimeters beneath the surface, remains low and the time needed for the heating of wood by conduction is too long compared to the time available at existing industrial peeling speeds.

5. Conclusions and perspectives

The results of this study demonstrate that, at peeling speeds currently used in the plywood and LVL industry, it is not possible to heat green wood with on-line IR radiation and achieve a temperature of 50-60°C at the cutting plane. With regard to this problem, however, an experimentally validated numerical mode has been developed, which can for a given peeling speed, s, determine the heating flux density, q, required to reach a given heating temperature several millimeters beneath the wood surface. Conversely, for a given heat flux density, q, the temperature at a given depth can be used to determine the appropriate peeling speed. Additionally, it has been demonstrated that the situation of a log rotating under external IR heating could be described by simplified 1D analytical equations of a half space, which would be useful for rapid calculations.

When talking about the future of IR as means of warming logs prior to peeling, one opportunity would be to use IR as additional heating on the lathe to maintain the hot log at the required temperature while turning on the lathe. The means of preheating could be microwave, given its efficiency at heating logs rapidly (Coste and De Bevy 2005). In this regard, the results of an going investigation (not reported herein) being carried out at Aalto University to assess the influence of the heating method (soaking or IR) on the surface properties (colour and wettability at 12% MC) of green wood would be particularly important in order to understand whether IR can degrade the surface of veneer.

However, in achieving the main targets of this study, deeper knowledge has been gathered about green wood and some significant new findings have been obtained especially concerning (1) green wood interaction with IR radiation and (2) green wood thermal characteristics.

(1) clear wood absorbs 70 to 90% of all incident IR radiation in the first 0.2 to 0.3 mm surface layers;

(2) above the f.s.p, clear wood requires more input energy in heating than dry wood (higher C for wet wood); it takes more time for heat to transfer within wet wood and the temperature reached at a given depth in a given amount of time is higher in the case of wet wood (lower κ for wet wood). Above the f.s.p, there is still a linear relationship between the thermal properties λ, C and κ on the one hand, and MC on the other but, in the species tested, the influence of anisotropy on thermal properties in the transverse directions is negligible.

Below are listed some conclusions that have arisen through using the different techniques applied to this research:

- Concerning the fuitometer

The fuitometer – whose primary aim is to measure surface quality – has proven his ability to be used as an indirect measure of lathe checks formed on veneer 'loose' side and degrading veneer surface quality. The results are less valuable and not as precise as the results from the SMOF in terms of different CD_i and CIn_i because it gives a mean value of the measured surface quality. However, the fuitometer is a reliable alternative to the SMOF for stiff veneers which cannot bend over the pulley.

- Concerning the SMOF

This study supports the view that the SMOF could form the basis of an important, non-destructive, testing method to monitor the quality of veneer produced at the research level. However, further studies should establish the link between lathe checking and gluing with respect to the mechanical properties of plywood since recent studies on the influence of check depth on bond quality in plywood have demonstrated that this has a significant impact (Rohumaa et al. 2013). Heating temperatures would then be determined according to the check distribution required as a function of the end-uses of the veneers. Future work could describe lathe checking with checking frequency CF by taking into account peeling speed, s (Eq. 11). The interest in using CF over checking intervals CIn_i would be to correlate with the frequencies of acoustic signals emitted by the cutting knife during peeling (Denaud et al. 2012). Using CF would also enable the development of an on-line monitoring system for lathe checking, which is not possible with the SMOF due to the long time required for screening the veneers compared to the industrial rate of peeling.

$$\text{CF (in Hz)}=\frac{1}{x_{i+1}-x_i}.s \qquad (11)$$

where x_i is the position of the lathe check along the veneer length

- Concerning the TPS

The comparisons with proven older techniques such as the steady-state and flash methods have demonstrated similar results, establishing that the TPS technique offers new opportunities for characterising the thermal properties of wood especially in the green state. The difficulty encountered in this work concerned water transport which could have affected the results because one part of the absorbed heat may have contributed to water transfer instead of an increase in temperature, thereby leading to erroneously higher measured λ values. However, the small input power of the HotDisk® leads to a maximum temperature increase of 1 to 2 K, which is insufficient to bring about water mass transfer by evaporation. Moreover, if during the present experiments, it was not possible to take into account eventual water transfer by capillarity within the sample, the MC was nearly constant with very limited changes during the short measurement time.

- Concerning the integrating sphere

Future work studying temperature rise within the absorption area would contribute to a deeper understanding of the interaction between IR radiation and wood. Precise characterisation of the values used for the emissivity of green wood would contribute to a more accurate model from the physical point of view, but would not significantly influence the resulting temperatures. When thinking about some of the limits encountered during this study, consideration should be given to the difficulty in maintaining the MC wood samples above f.s.p. In addition to which, the notion of there being an 'minimum-optimum' heating temperature at the cutting plane is open to conjecture in light of the knowledge already acquired by Marchal et al. (1993) concerning the exact microscopic scale location at which the maximum efforts occur. The idea is that if the maximum efforts would effectively occur slightly above the cutting plane, it would not be necessary to heat the wood so deeply. This would promote the idea of heating green wood by a radiant energy penetrating into the wood but not validate the feasibility of IR heating, the penetration of which into green wood remains limited.

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Errata

Aalto-DD 200/2013

This manuscript, which is a summary of research work carried out as a PhD under a co-tutelle agreement between Aalto University, School of Chemical Technology, Department of Forest Products Technology in Finland and Ecole Nationale Supérieure des Arts et Métiers in Cluny, France, concerns a study of the infrared heating of green wood whilst peeling as an alternative to the soaking traditionally used in industry but which has many economic and environmental disadvantages.

Ce manuscrit de thèse, résumé d'un travail de recherche réalisé dans le cadre d'une cotutelle entre l'Université d'Aalto, School of Chemical Technology, Department of Forest Products Technology en Finlande et l'Ecole Nationale Supérieure des Arts et Metiers de Cluny en France, porte sur l'étude de la chauffe infrarouge du bois vert au cours du déroulage comme altermative au procédé d'étuvage, utilisé dans l'industrie pour préparer le bois à la coupe mais dont les inconvénients industriels et

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9 789526 054643

ISBN 978-952-60-5464-3
ISBN 978-952-60-5465-0 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934
ISSN 1799-4942 (pdf)

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