Applied Mathematics and Computation 267 (2015) 465–475

Contents lists available at ScienceDirect

Applied Mathematics and Computation

journal homepage: www.elsevier.com/locate/amc

Application of multiphysics and multiscale simulations to optimize industrial wood drying kilns

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ARTICLE INFO

Keywords:
Finite element simulations
Coupled moisture and heat transport
Wood drying simulations
Convective drying simulations

ABSTRACT

Timber industry and export are an important part of Estonian economy, making affordable industrial scale equipment an important investment for small or starting companies. These companies often develop on-site equipment for wood processing and drying, utilizing pre-existing infrastructure to minimize cost and risk. However, under these conditions custom design of the wood drying kilns is often required.

In the present study, a finite element simulation based approach is used to simulate and optimize the industrial wood drying process and the design of the custom-made kilns in a multiscale–multiphysics modeling framework. Air flow is calculated by the Navier–Stokes equations or κ–ε turbulence model followed by heat transport in the solid and gas phase and moisture dynamics in wood and air. The dense packing of the processed materials is handled by utilizing a porous media approach and homogenization procedure, leading to effective simulations of the moisture and heat balance.

Multiphysics–multiscale simulations are successfully adapted to optimize the industrial design of wood drying kilns. The optimization of the kiln design is achieved by estimating the necessary ventilating power and ensuring homogeneous drying of the processed material.

1. Introduction

A significant portion of Estonian territory is covered with forests, making timber industry an important part of the Estonian economy. To increase the value of the production and minimize risks, small or starting companies require cheap equipment, capable of industrial scale processing and drying of wood. They often start by utilizing and rebuilding pre-existing infrastructure by fitting it with custom-made equipment. To make effective wood drying possible under these conditions, custom-made kilns are usually required. One of the simplest systems is low speed convective drying, where air circulation is used for heat and air moisture transport [1].

However, the drying process of wood is a complex nonlinear phenomenon that depends on a number of factors like air velocity, temperature and moisture. Therefore, computer simulations are often required to obtain a successful design of the custom equipment. Air movement can be solved by either Navier–Stokes equations or suitable turbulent flow models, like κ–ε, κ–ω, low Reynolds number κ–ε, etc. Many of these models are readily available in several commercial (Comsol Multiphysics, Ansys Fluid Dynamics) or open source software packages (OpenFOAM). While uniform air movement is one

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http://dx.doi.org/10.1016/j.amc.2015.01.104
0096-3003/

of the pre-request of successful drying, the air flow must be coupled to heat and moisture mass transport and the drying kinetics to obtain the final description of the process. The moisture transport in air is strongly influenced by heat transport. For example, a coupled heat, air and moisture transport model (HAM model) was used by Steeman et al. in [2–4] to study heat and moisture transport in air and porous media. The proposed model was further validated in a benchmarking study involving experiments in a well-controlled climate chamber showing good agreement between the experiment and the model [5].

For the effective simulation of the drying process, heat and moisture transport in air must be coupled to those in wood. The drying process of wood, however, is a complex process due to the microstructural properties of the material. Wood can be an extremely heterogeneous material as its properties can depend significantly on factors like moisture content, growing conditions, cutting conditions, previous storage conditions etc. Wood can contain the moisture as free liquid water or water vapor in cavities and cell lumens or chemically fixed water in the cell walls. To simulate the drying process in the microstructure of wood, several possible models can be used. The diffusion model [6,7] assumes that the mass transfer in wood is controlled only by diffusion. The multiphase model [8–10] assumes the presence of all possible phases – free water, bound water, water vapor and wood. In Luikov's approach [11,12], wood is modeled as a capillary porous medium and is assumed to be isotropic and homogeneous. The comparison of these three approaches [13] shows quite a similar performance, providing detailed spatial description of moisture balance during the drying process. However, while these approaches provide detailed information about the process, they are restricted to small scale systems. If drying in the whole kiln is considered, such models can be computationally too demanding, requiring accurate geometrical representation of the material and leading to unreasonably complex meshes.

The other extreme involves only the global description of the drying process in the kiln, assuming uniform temperature and air flow, leading to the ordinary differential equation based approach [14,15]. In this approach, air and wood temperature dynamics, together with air and wood moisture balance are obtained, but spatial information about the local material behavior is lost. However, if the condition of uniform air flow is fulfilled, accurate, experimentally validated description of drying is obtained.

To overcome the problem of high computational costs of detailed models and the lack of spatial information of global system level modeling, the multi-scaling is used. The multi-scaling is resolved by introducing homogenization from system level modeling into the detailed models - the drying of the wood leads to very complex geometry due to the material storage. Accurate simulations of the phenomena need detailed mesh for conducting successful calculations. However, by utilizing the homogenization procedures, the actual material is replaced with effective media to solve the problem. The obtained effective media combines properties of both materials while losing the geometrical description of inner structure of drying wood stack, thus utilizing several length scales in describing the problem. This approach makes it possible to obtain spatial description of the processes taking place in the kiln while removing detailed geometrical description of the drying material. Thus, compromise between the methods is obtained – computational costs are significantly reduced while sufficiently detailed description of the system remains. This opens opportunities for relatively fast simulations of complex phenomena and allows using already existing optimization algorithms for tasks like geometry optimization and drying cycle design.

The aim of the present study is to obtain a multi-physics, multi-scale model of the drying process in the kiln. The model involves a homogenization procedure leading to the effective simulation of moisture and heat balance and the application of porous media flow of the dried air in the processed material. A framework for simulating the drying process in the wood drying kiln is presented, opening opportunities for the design and cost optimization of these devices.

2. Materials and methods

2.1. The simulated geometry

Two geometries of the convective wood drying kiln are presented in Fig. 1. Geometry 1 (Fig. 1(a)) requires a full 3D model for successful simulations. Geometry 2 (Fig. 1(b)) can be simulated using a 2D approximation due to the symmetry in the z-direction. Both geometries consist of the wood drying chamber, inlet and outlet. In geometry 2, ventilation channels are added to remove the moist air from the system. The geometries are divided into two main regions – the porous region and free air region. The *porous region* contains both air and the drying wood while the *free air region* consists of only the air in the rest of the system. The main intention of the 3D calculations is to provide demonstration of methodology in symmetry independent case, therefore, the moist air is removed through the ventilation outlet. This approach simplifies both, the geometry and interpretation of air flow field, while retains all the important factors responsible for the drying process of the material.

These geometries are motivated by the physical limitations of specific, already existing buildings reconstructed as the kilns, available infrastructure for the heating of the kiln, and the total cost of the design and construction of the final solution.

The walls of the kiln are represented by the boundary conditions of the heat equation since the temperature distribution in the walls is not needed as an output of these simulations, thus reducing the computational costs. The drying chamber is divided into two regions – the free air region and the porous region, containing the dried material. Since the drying material can exhibit a very complex geometrical structure (Fig. 1(c)), it is not reasonable to model it directly by an accurate geometrical representation. It would lead to a complex geometry, needing a very fine mesh and thus, increasing the computational