Jerzy WERES[1], Wiesław OLEK[2], Sebastian KUJAWA[1], Michał SIATKOWSKI[1]
Poznan University of Life Sciences
[1] Institute of Biosystems Engineering, Department of Applied Informatics
[2] Department of Mechanical Engineering and Thermal Techniques
ul. Wojska Polskiego 28, 60-637 Poznan, Poland
e-mail: weres@up.poznan.pl

INTEGRATION OF SOFTWARE COMPONENTS FOR DETERMINATION AND ANALYSIS OF PROPERTIES OF AGRI-FOOD AND FOREST PRODUCTS

Summary

Knowledge of properties of agri-food and forest products is necessary to understand and predict their behavior in many processing operations like heating, cooling and drying in which heat and water transport affect the final product quality. It is difficult to represent properties of biomaterials in mathematical models to simulate the heat and water transport processes - shape of biomaterials is complex, material structure is non-homogeneous and anisotropic, and properties are functions of temperature and moisture content. Original algorithms and software components developed in earlier papers were modified and integrated to improve accuracy and efficiency of identifying, predicting and analyzing properties of agri-food and forest products. The integrated computer-aided approach was based on image analysis, geometry modeling and finite element analysis for solving coefficient inverse problems of heat and water transport. The approach resulted in more accurate predictions of investigated transport processes in biomaterials, and was more effective.
Key words: *software development and integration, heat and water transport, geometry modeling, inverse finite element analysis*

INTEGRACJA KOMPONENTÓW OPROGRAMOWANIA DO OKREŚLANIA I ANALIZY WŁAŚCIWOŚCI PRODUKTÓW ROLNO-SPOŻYWCZYCH I DRZEWNYCH

Streszczenie

Znajomość właściwości produktów rolno-żywnościowych i drzewnych jest niezbędna, aby zrozumieć i prognozować ich zachowanie w wielu procesach przetwórczych, takich jak ogrzewanie, chłodzenia czy suszenie, w których transport ciepła i wody kształtuje końcową jakość produktów. Odwzorowywanie właściwości biomateriałów w matematycznych modelach, aby symulować procesy transportu ciepła i wody jest trudne – kształt tych materiałów jest skomplikowany, ich materialna struktura jest niejednorodna i anizotropowa, a ich właściwości są funkcjami temperatury i zawartości wody. W niniejszej pracy zmodyfikowano i zintegrowano oryginalne algorytmy i komponenty oprogramowania zbudowane w ramach wcześniejszych prac, aby poprawić dokładność i efektywność identyfikowania, prognozowania i analizowania właściwości produktów rolno-żywnościowych i drzewnych. Zintegrowane, wspomagane komputerowo podejście zostało oparte na analizie obrazu, modelowaniu geometrii oraz analizie metodą elementów skończonych, zaadaptowanej do rozwiązywania współczynnikowych zagadnień odwrotnych transportu ciepła i wody. Podejście to przyczyniło się do zwiększenia dokładności prognozowania badanych procesów transportowych w biomateriałach i przy tym do podniesienia efektywności analiz.
Słowa kluczowe: *wytwarzanie i integrowanie oprogramowania, transport ciepła i wody, modelowanie geometrii, analiza odwrotna metodą elementów skończonych*

1. Introduction

Knowledge of material properties is necessary to understand, predict and control behavior of materials subjected to such operations as heating, cooling and drying. Heat and water transport processes, involved in these operations, decisively affect the final product quality. Unfortunately, it is difficult to represent properties of agri-food and forest products and use their appropriate values in mathematical models of heat and water transport. Shape of such products is complex, material structure is non-homogeneous and anisotropic, and the properties are functions of temperature and moisture content.

In designing and controlling processes comprising heating, drying, cooling and storing of agri-food and forest products it is reasonable to support scientists and engineers with software appropriate for predicting behavior of investigated products, based on heat and water transport models in which material properties are adequately represented.

Attempts to determine and analyze material properties of agri-food and forest products in relation to improving mathematical modeling of the heat and water transport are well described in the literature [1, 7, 8, 9, 12, 13, 14, 15, 19, 20, 21]. However, there is a little information about the role of inaccurate modeling of the product geometry, about possibilities of coefficient identification by the inverse problem analysis, and about developing software dedicated to solving such problems.

Recent developments in image analysis and geometry modeling [2, 3, 6, 17, 21, 22], in numerical approaches to representing geometry within finite element (FE) models [4, 21, 22, 23], in optimization algorithms [11, 16], in FE analysis for solving coefficient inverse problems of heat and water transport [13, 20], and in software development [5, 10, 18] are a basis upon which the software for analyzing agri-food and forest product properties could be integrated and improved.

The objective was to enhance algorithms and to integrate software components described in earlier papers [12, 13, 20, 21] to improve accuracy, efficiency, and consistency of identifying, predicting and analyzing properties of agri-food and forest products in heat and water transport processes.

2. Material and methods

Behavior of the following materials subjected to the heat and water transport processes was investigated: corn kernel hybrid variety Pioneer (FAO 280), pine and beech wood, and wood-based panels. The materials examined were non-homogeneous, anisotropic and irregularly-shaped bodies, and the following properties were estimated and analyzed to improve predictions: 3D coordinates of the FE mesh nodes, thermal conductivity, moisture transport coefficient and convective moisture transfer coefficient.

The geometry representation was based on image analysis, FE mesh generation and visualization methods [3, 4, 6, 17, 21, 22, 23]. The developed procedures comprised: microtome cutting of samples embedded in synthetic resin, acquisition of digital photographs, image processing and analysis for consecutive sample layers – edge detection by Canny algorithm for external and internal boundaries, and construction of a FE mesh of 3D isoparametric elements. Visualization was based on the 3D nodal coordinates of the FE mesh. It was enhanced with NURBS, textures and illumination, and the following operations: moving, rotating, scaling, plane-cutting and time-stepping were implemented to illustrate property changes.

A procedure was developed to collect experimental data and to identify properties of unknown values which were necessary for mathematical modeling of heat and water transport. It was based on an original inverse FE approach composed of direct FE algorithms for solving heat and water transport problems in biomaterials, local and global constrained optimization algorithms and an algorithm for operational control and quality assessment [11, 12, 13, 16, 20]. The quality assessment enabled selection of an appropriate algorithm ensuring low prediction inaccuracy and satisfactory performance.

Software components were modified according to proposed improvements in algorithms. Integration of the components was achieved by developing a common user interface and a common database system. Software development methods corresponded to software engineering standards [5, 18] accompanied by the UML 2.4.1 notation. The Visual Studio 2013 programming environment was used to implement software in C# v. 5.0 [10], and the Intel Visual Fortran Composer XE for Windows with IMSL was used to code FE algorithms.

3. Results and discussion

The software was enhanced and integrated to increase accuracy and efficiency of estimating and analyzing properties of agri-food and forest products subjected to heat and water transport processes. The resulting software was used to analyze behavior of corn kernels of the hybrid Pioneer, FAO 280, pine and beech wood, and wood-based panels. Algorithms were optimized to deal with non-homogeneity, anisotropy and shape-irregularity of examined products, and to deal with strong dependencies: the property dependence on temperature and moisture content and the process dependence on variations in boundary conditions of the third kind. The following properties were estimated to improve predictions: FE nodal coordinates, thermal conductivity, moisture transport coefficient and convective moisture transfer coefficient.

The approach was based on image processing and analysis, 3D geometry measurement from imaging data, and FE meshing and visualization (Fig. 1). The designed procedures were implemented to analyze behavior of dried corn kernels.

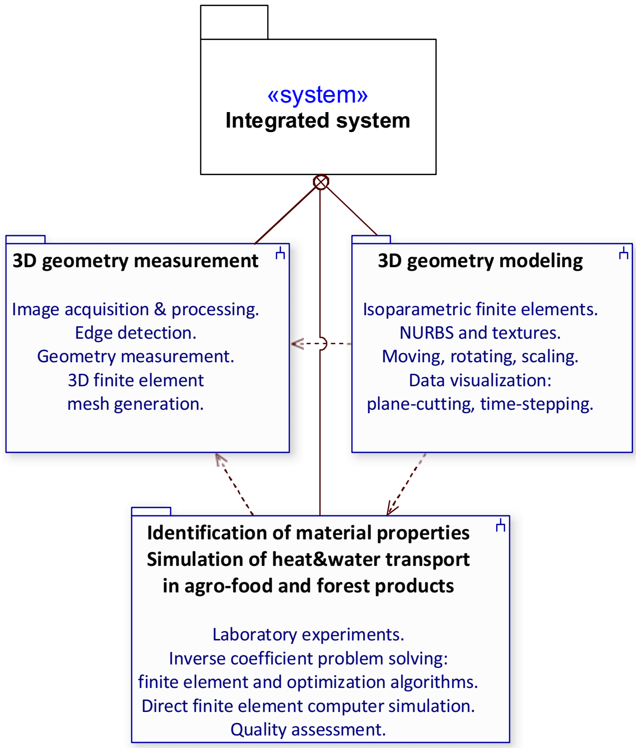

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Fig. 1. System of integrated subsystems for determination and analysis of properties of agri-food and forest products in a form of the UML diagram of nested packages

Rys. 1. System zintegrowanych podsystemów do określania i analizy właściwości produktów rolno-spożywczych i drzewnych w postaci diagramu zagnieżdżonych pakietów w notacji UML

A sample kernel was cut into layers with a microtome, and digital photographs of the consecutive layers were acquired. Next, the images were processed and analyzed - external edges and internal boundaries between the product components were detected. According to the FE mesh parameters the primary mesh was automatically generated in 3D. Location of nodes was manually refined, and finally all the nodal coordinates were written to an output table. The kernel geometry model was constructed using 3D isoparametric finite elements. Structure parameters of the 3D FE mesh were the input data, and the global array of 3D nodal coordinates was the output (Fig. 2).

For visualization reasons the model was smoothed by NURBS and enhanced with a texture and illumination (Fig. 3).

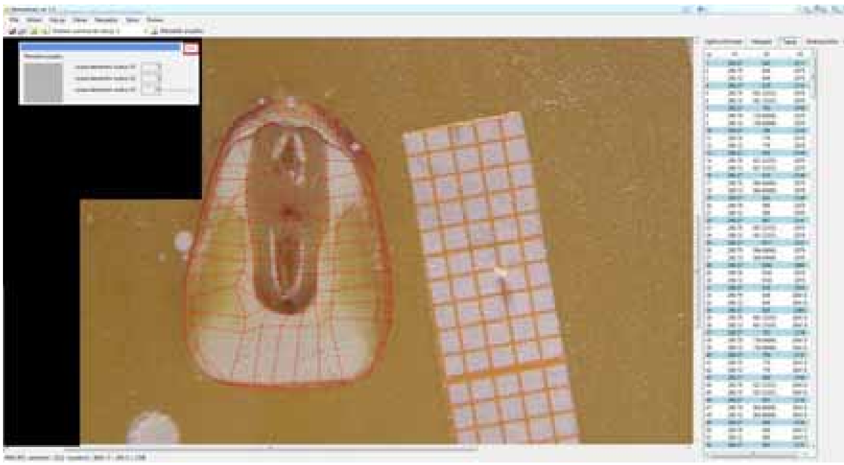

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Fig. 2. Integrated component for edge detection for consecutive layers, geometry measurement and FE mesh generation. Input: parameters of the 3D FE mesh. Output: array of the 3D FE mesh nodal coordinates

Rys. 2. Zintegrowany component do wykrywania krawędzi kolejnych warstw, pomiaru geometrii i tworzenia siatki MES. Wejście: parametry trójwymiarowej siatki MES. Wyjście: tablica współrzędnych węzłów siatki MES w przestrzeni 3D

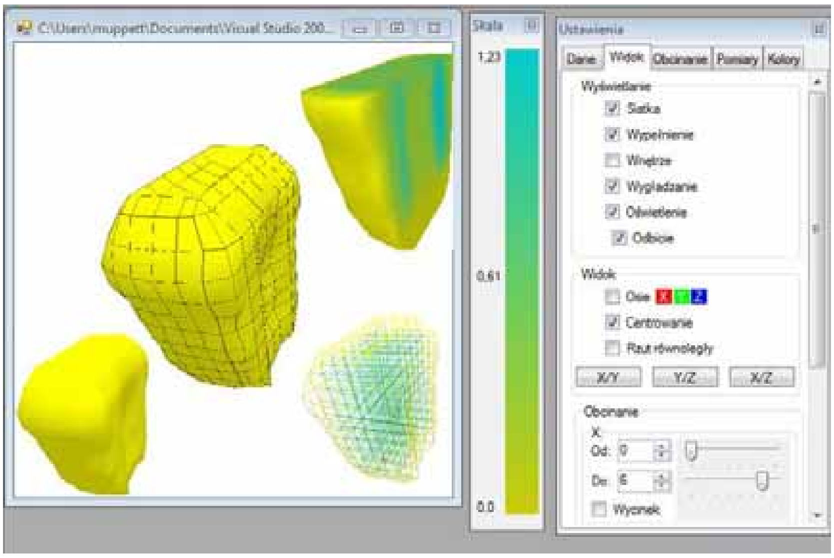

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Fig. 3. Integrated component for visualization of the geometry model. Available functions: NURBS smoothing, texture and illumination enhancement, moving, rotating, scaling and plane-cutting

Rys. 3. Zintegrowany komponent do wizualizacji modelu geometrii. Dostępne funkcje: wygładzanie NURBS, nakładanie tekstury i oświetlenia, przesuwanie, obracanie, skalowanie i odcinanie płaszczyzn

Identification of unknown values of properties necessary as the input to the heat and water transport model was performed by the inverse FE analysis (Fig. 4). Results of physical experiments (temperature and/or moisture content values) and values predicted by the FE model were used to compute the objective function, the minimum of which was computed by the most accurate and effective optimization algorithm for a given case (the algorithms examined – local approach: trust regions and variable metric; global meta-heuristic approach: simulated annealing, tabu search and genetic algorithm). Thus, the optimal property values were estimated. Next, they were used to predict temperature and/or moisture content in investigated products by the direct FE analysis. The FE model was developed as an approximation of the partial differential equations of heat conduction and water diffusion with appropriate initial and third kind boundary conditions. The model was supplied with identified values of properties investigated. The quality of procedures was measured by the global and local relative errors – the predicted results (temperature and/or moisture content values) were related to the experimental results. It allowed for selection of most accurate and efficient procedures to estimate property values, and next – to provide satisfactory simulation results.

As an exemplification of obtained results a prediction of bound water content *M* supplemented with local relative error e_1 versus square root of time $\sqrt{t}$ for adsorption in the radial direction of modified beech was given in Fig. 5. The analysis was enhanced by adding a relaxation term $M_\infty = c + d \cdot [1 - exp(- t / \tau)]$ to the convective boundary condition, according to reasoning presented in [13], and c, d and τ are parameters to be identified (τ – relaxation time). The global relative error e_2, reduced to a level of 1.18% due to the inverse FE analysis (3PAR model, dashed line), was even lowered to 0.09% due to insertion of the relaxation term and identification of additional parameters (5PAR model, solid line).

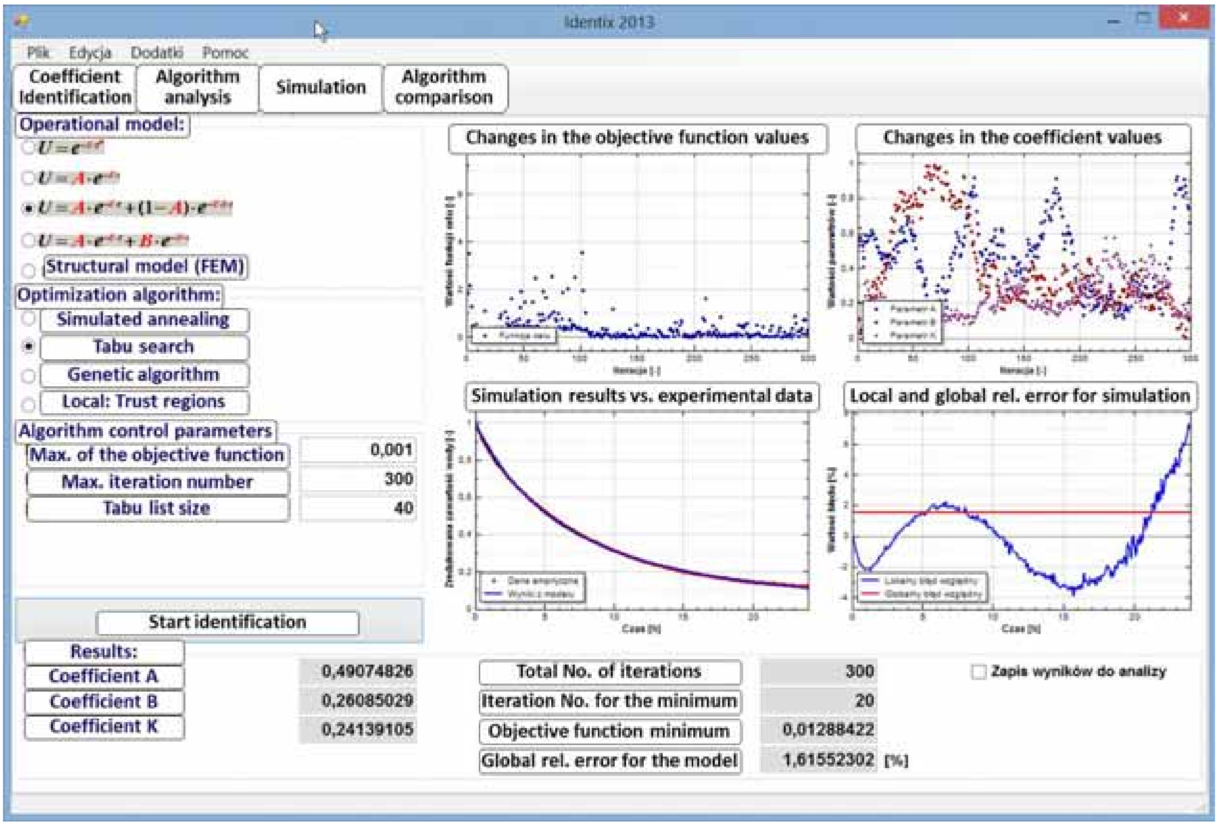

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Fig. 4. Integrated component for inverse and direct FE analysis – estimation and analysis of properties of agri-food and forest products subjected to heat and water transport, and for assessing quality of algorithms

Rys. 4. Zintegrowany komponent do odwrotnej i bezpośredniej analizy MES – oszacowanie i analiza właściwości produktów rolno-spożywczych i drzewnych poddanych procesom transportu ciepła i wody oraz do oceny jakości algorytmów

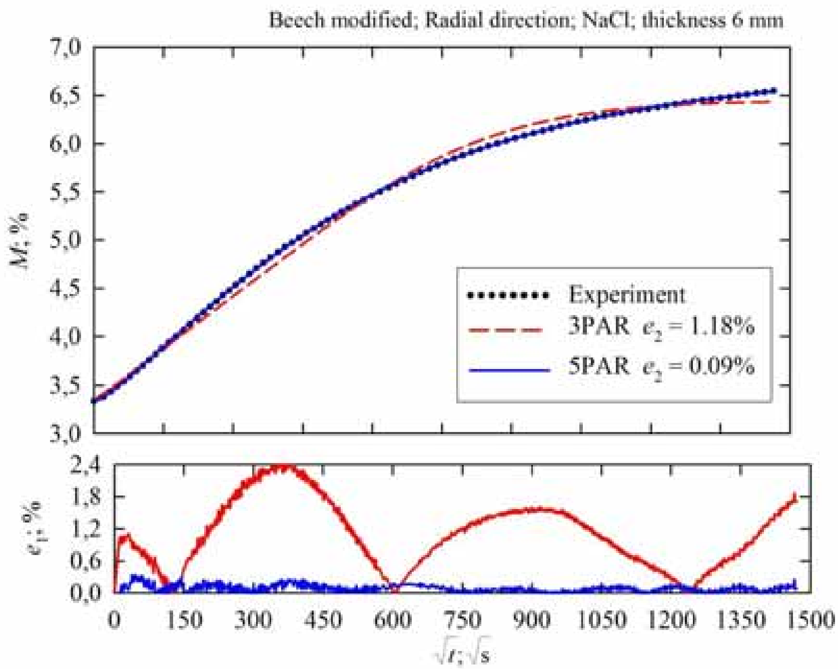

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Fig. 5. Prediction of bound water content M versus square root of time √t for adsorption in the radial direction of modified beech, and changes in the local relative error e_1. Introduction of the relaxation term M_∞ to the convective boundary condition [13] reduced the global relative error e_2 to 0.09%

Rys. 5. Prognozowanie zawartości wody związanej M jako funkcji pierwiastka kwadratowego czasu √t dla adsorpcji w kierunku promieniowym modyfikowanego drewna buku oraz zmiany lokalnego błędu względnego e_1. Wprowadzenie członu relaksacyjnego M_∞ do warunku brzegowego [13] zmniejszyło globalny błąd względny e_2 do 0,09%

4. Conclusions

The algorithms were enhanced and the software components were integrated to support identification and analysis of properties of agri-food and forest products subjected to heat and water transport. The algorithms were based on edge detection, geometry modeling, objective function minimization and inverse/direct finite element analysis. User interfaces, databases and software performance control were integrated. The approach was more effective and accurate compared to previous attempts, measured by relative errors of predicted temperature and/or moisture content values versus results obtained in physical experiments. The developed software satisfied both the requirements and the metrics: functionality, usability, effectiveness and efficiency.

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