Modeling and Simulation of Biomass Drying Using Artificial Neural Networks

Sławomir Francik, Bogusława Łapczyńska-Kordon, Renata Francik and Artur Wójcik

Abstract Willow (*Salix viminalis*) is a moist material after the crops. Therefore, the content of water in this type of material has to be lowered by drying before any further mechanical or thermal processing, in order to increase its calorific value. The process of drying is energy-intensive. Thus it is advisable to search for optimal methods and parameters of drying. The optimisation requires evolving a model that is based on the crucial parameters of the process. One of the possible solutions is to apply models of Artificial Neural Networks. Artificial Neural Networks belong to the group of methods of artificial computational intelligence and are often used in modelling various phenomena and processes. The aim of this work was to develop models using Artificial Neural Networks to describe the process of convective drying of the willow woodchips. As a result of presented work we obtained neural models describing alterations of water content, changes of the temperature and the mass of the chips. The presented models are highly accurate. We used experimentally obtained data in order to validate the models. It is important to underline that the data were not applied while the artificial neural networks were being developed. Subsequently, the models were used to simulate the process of drying what allowed us to define the optimal parameters of drying willow woodchips characterised by different moisture content.

Keywords Biomass · Willow (*Salix viminalis*) chips · Drying
Model · Artificial neural networks

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1 Introduction

Recently, the Renewable Energy Sources have become one of the major objects of interest. That results from continuously increasing need for energy all over the world. The exhaustion of conventional sources of energy, such as oil, coal, and natural gas, and the pollution of environment triggered off dynamic development of research aimed at identifying pure sources of energy that could be more effective and more efficient—Renewable Energy Sources (RES). Renewable energies are energy sources that are continuously replenished by nature. They can be derived either directly (for example thermal, photo-chemical, and photo-electric), or indirectly (such as wind, hydropower, and photosynthetic energy stored in biomass) from the Sun. They can also be obtained from other natural movements and mechanisms of the environment (such as geothermal and tidal energy). It is estimated that RES could potentially deliver the amount of energy that would comprise the amount 3000 times larger than the current world-wide need for energy. According to the reports we will observe 2.7-fold increase of the global RES-based production of electrical energy from 2010 till 2035 [1].

Biomass is one of the commonly used sources of renewable energy [2]. This term is used for all organic material originating from plants, trees and crops, and is essentially the collection of the Sun energy that is processed, converted and stored in the form of the products of photosynthesis. Biomass energy is renewable and sustainable. Its characteristics are comparable to the characteristics of fossil fuels. Biomass can be directly burned to obtain energy, it can also be converted to various liquid or gas fuels (biofuels) [1].

Solid biofuels are another type of biomass that is frequently exploited. One of the examples is wood obtained from plantations maintained for energetic purposes (for example Short Rotation Woody Crops). Wood biomass and the one derived from energy-related plants is often converted into briquettes or pellets and constitutes their primary ingredient [3–6].

The entire process of production of briquettes and pellets requires a few steps employing several technological processes that eventually lead to obtaining a high quality product [3, 7].

The biomass used in the production is initially broken into pieces. Unfortunately, the obtained chips are often characterised by high moisture content. Therefore, in order to proceed with the following technological procedures, it is prerequisite to make the chips undergo thorough drying processes [8–10].

2 Modelling the Drying of Woodchips

Development of various models is the object of numerous research projects. A vast number of scientists, who focus their work on Renewable Energy Sources, predicate their research on creating suitable models. The issues concerning modelling that is related to RES were profoundly reviewed in [11].

Drying is an energy-intensive process what results in high costs. Therefore, the optimisation of the process of drying is pivotal in the aspect of cost minimisation. In such a case applying a model describing the process of drying is inevitable. Moreover, due to the complexity of the process it is necessary to create many different models of drying of biomass that are adjusted to various conditions. Hence a lot of effort is put in research aimed at elucidating the biomass drying process (including drying of woodchips), creation of the most accurate models and their optimisation [10, 12–17].

One of the types of willow—*Salix viminalis* is one of the most commonly used types of trees in the biomass production. First its sprouts are broken into pieces in the process of chipping. Subsequently, they are dried. The models of drying of willow woodchips were proposed and described in many scientific articles and reports [8, 9, 18–20].

According to the information available in the literature Artificial Neural Networks (ANN) are one of the newest modelling tools. They belong to the group of methods known as Computational Intelligence which, in turn, constitutes a subtype of Artificial Intelligence. The beginning of ANN development is assumed to fall on development of a mathematical model of neurone by McCulloch and Pitt in 1943 and introduction of the concept of adaptation of connections between network nodes in the process of learning neural networks by Hebb. The first simulation program of the ANN was made by Rochester in 1956 year. In the 1958 was created the first neurocomputer (Perceptron) by Rosenblatt and Wightman. Presently, there is no scientific field where the ANN was not used [21].

So far ANN were used in the models of many processes, including the processes of drying of food products, such as grains [22, 23], barberry (Berberis) fruits [24], apples [25] or onion [26]. Moreover, ANN were also used in modelling the drying of wood [27–30].

One of the criteria taken into account during the validation of mathematical models is accuracy. According to the literature, the models based on ANN are significantly more accurate than any other types of existing mathematical models [22, 23, 25, 26, 28, 30]. The results presented in our previous papers also provided some further proofs for this notion [31–38].

3 The Aim and the Scope

The work presented in the manuscript was aimed at formulating a comprehensive tool useful in simulation and optimisation of the processes of convective drying of the willow (*Salix viminalis*) woodchips that applies Artificial Neural Networks.

In order to achieve the main goal of our work we independently formulated three neural models representing the overall process of convective drying of the willow woodchips:

– neural model of the changes observed in the content of water in the chips,
– neural model of the changes of temperature of the chips,
– neural model of the changes of the mass of the chips.

The previously described model of the changes observed in the water content in the chips [34] and the model of the changes of temperature of the chips [33] were modified and updated for the purposes of this work.

4 Materials and Methods

All the three above-mentioned neural models were based on the experimentally obtained data measured and recorded during the process of convective drying. The analyses were performed using the biological material extracted from the willow *Salix viminalis*. The material was dried in a form of chips that were approximately 2 cm long. The samples were extracted directly before the beginning of the drying in order to avoid any additional effects of unintended, uncontrolled, spontaneous drying of the samples. The values of their mass differed among all samples and were dependent on the differences in the length of their diameter.

Prior to the drying process the examined material was weighted using an electronic scale WPE 300 (accuracy 0.01 g). The woodchips were dried using a convective dryer (ELKON KC 100 N) with the drying agent flow, in the temperature 40, 50, 60 and 70 °C. The drying process was ended when the equilibrium moisture content was established. The measurements of the mass, temperature or the moisture content in the samples were carried out every 5 min. The temperature was measured using a thermocouple NiCr-NiAl that was located inside a woodchip and its accuracy was up to 0.01 °C.

20 samples were dried in each individual case of given conditions (temperature values: 40, 50, 60 and 70 °C). The obtained data were sufficient to go to the next step, namely the process of ANN learning based on 6060 patterns.

The major goal was to create neural models quantitatively describing the process of convective drying of willow woodchips. Prior to the design of the neural models three semantic models were developed:

– the model of the changes of water content in the woodchips

$$Y_1 = f(X_1, X_2, X_3, X_4, X_5, X_6)$$

– the model of the changes of the temperature of the woodchips

$$Y_2 = f(X_1, X_2, X_5)$$

– the model of changes of the mass of the woodchips

$$Y_3 = f(X_1, X_2, X_3, X_4, X_5, X_6, Y_2)$$

where:

X_1 time of drying [min.]
X_2 temperature of the air [°C]
X_3 length of the sample (initial) [mm]
X_4 diameter of the sample (initial) [mm]
X_5 average content of water (initial) [kgH_2O/kg d.m.]
X_6 initial mass of the sample [g]
Y_1 content of water [kgH_2O/kg d.m.]
Y_2 temperature of the sample [°C]
Y_3 mass of the sample [g].

The development of the models was performed using a specialised software Statistica Neural Networks. The entire collection of 6060 patterns obtained as a result of the measurements was randomly divided into three categories: 3636 learning patterns, 1212 validation patterns and 1212 test patterns. In order to develop as accurate models as possible we applied the procedure of multiple repeats since the process of ANN learning proceeds stochastically. 100 ANNs were designed for each of the three, above-mentioned models. The architectural characteristics of the designed ANNs differed between each other (different number of layers in the network, different number of neurons in each layer, different activation functions). We kept only 10 most accurate models using the software Statistica Neural Networks. Subsequently, we chose the networks that were characterised by the lowest value of root mean square error (RMS), calculated for the validation data (patterns):

$$RMS = \sqrt{\frac{\sum \left(Y_{i,ANN} - Y_{i,OBS}\right)^2}{n}}$$

where:

$Y_{i,ANN}$ the initial value of a variable obtained as a result of neural modelling,
$Y_{i,OBS}$ the initial value of a variable obtained as a result of measurements,
n the number of patterns (reflecting the amount of input data).

5 Results and Discussion

As a result of the research three neural models were obtained. All of the models belonged to a class of feedforward artificial neural networks being multilayer perceptron (MLP). We distinguished the following most accurate models:

– the model of changes of the content of water in the woodchips: a four-layer neural network consisting of 6 neurons in the input layer, 15 neurons in the first hidden layer, 14 neurons in the second hidden layer and 1 output neuron (MLP 6:6-15-14_1:1),
– the model of changes of the temperature of the woodchips: a four-layer neural network consisting of 3 neurons in the input layer, 9 neurons in the first hidden layer, 5 neurons in the second hidden layer and 1 output neuron (MLP 3:3-9-5-1:1),
– the model of changes of the mass of the woodchips: three-layer neural network consisting of 7 neurons in the input layer, 9 neurons in the hidden layer and 1 output neuron.

The obtained neural models are highly accurate. The RMS calculated for the ANN describing changes of the content of water in the woodchips was 0.0179 [kgH_2O/kg d.m.]. In the case of the ANN describing changes of temperature RMS equalled 2.65 [°C] and in the case of the ANN describing changes of the mass RMS was 0.0634 [g]. In each case the RMS was calculated for the collection of validation data that had been separated before the beginning of the development of the main model. The validation patterns were not included in the data used in the learning process.

Figures 1, 2 and 3 present examples of the trends in changes of the content of water, temperature and the mass of the woodchips obtained for the validation data.

The analyses of changes of the content of water, the temperature and the mass of the woodchips as a function of the time of drying also prove high accuracy of the obtained models. The comparison of the values calculated in each neural model with the values measured during the experiments (collection of validation data) shows that they are consistent. Thus not only do we infer about the high quality and the accuracy of the proposed models but we also interpret that the models can be generalised.

Figure 4 is showing a scheme representing the functional links in the developed neural models. Entering the values of the input variables results in generating the values of the output variables as a response of the ANN what, in consequence, allows simulation of the process of drying of the willow woodchips and its further optimisation.

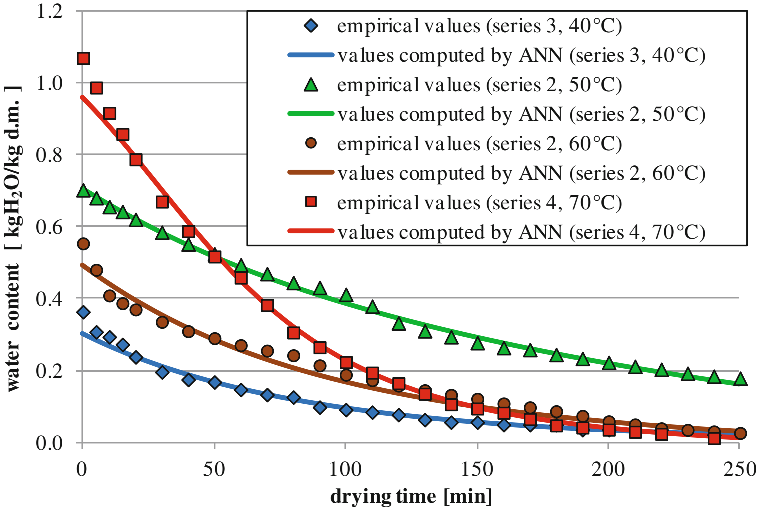


Fig. 1 Example trajectories of water content changes depending on time for empirical values and values computed using the model ANN (validation data set)

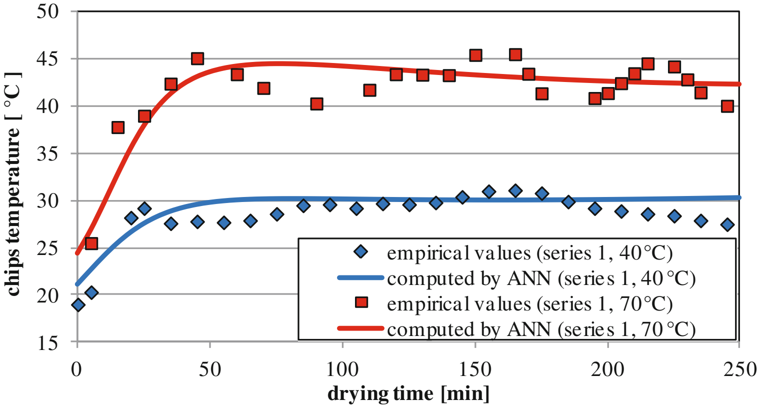


Fig. 2 Example trajectories of chips temperature changes depending on time for empirical values and values computed using the model ANN (validation data set)

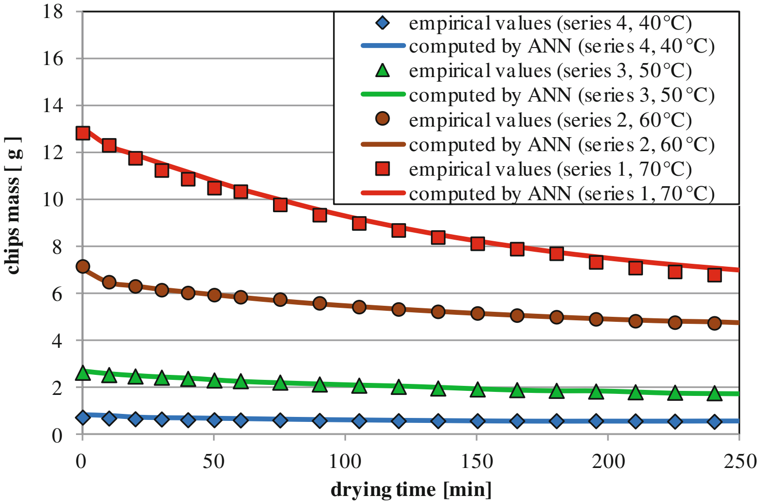
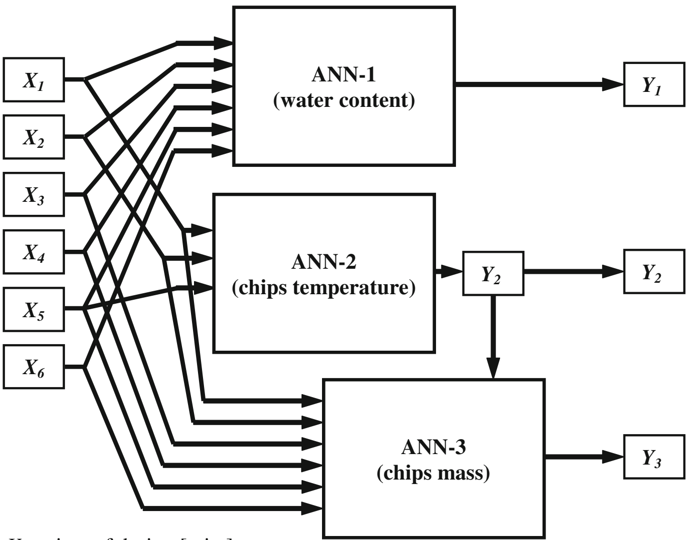


Fig. 3 Example trajectories of chips mass changes depending on time for empirical values and values computed using the model ANN (validation data set)



X_1 – time of drying [min.]
X_2 – temperature of the air [°C]
X_3 – length of the sample (initial) [mm]
X_4 – diameter of the sample (initial) [mm]
X_5 – average content of water (initial [kgH_2O/kg d.m.]
X_6 – initial mass of the sample [g]
Y_1 – content of water [kgH_2O/kg d.m.]
Y_2 – temperature of the sample [°C]
Y_3 – mass of the sample [g]

Fig. 4 A scheme of functional links in the three proposed neural models

6 Conclusions

First of all, the analysis of the results, which encompass the changes of the water content in the willow woodchips in time and the changes of the temperature and the mass of the samples as a function of time, proves that proposed neural models are correct in the aspect of logic. It is manifested by the fact that the recorded changes of the listed values are consistent with the theoretically predicted changes of the values representing the content of water, the temperature and the mass in time in the case of the solid samples during the process of their heating. The models were also empirically verified as correct. The estimated root mean square error values are very low. These values were obtained by comparing the experimentally measured values with the values generated in the model based on the Artificial Neural Networks.

The obtained models are a subclass of feedforward artificial neural networks known as multilayer perceptron. We distinguished four-layer models with 2 hidden layers and three-layer models with 1 hidden layer. Combining the three described models together is essential for delivering a complete description of the process of drying of the willow woodchips, simulating the process, which in turn is critical for the proper optimisation.

Further research is going to be aimed at developing and engineering a software or a computer application that will use the obtained models in order to automatically simulate the process of drying of the willow woodchips what would be used in the optimisation of the process.

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