WOOD RESEARCH
64 (1): 2019
127-136

NUMERICAL INVESTIGATION OF WOOD DRYING

Burak Turkan, Akin Burak Etemoglu
Bursa Uludag University, Faculty o Engineering, Mechanical Engineering Department
Bursa, Turkey

(Received August 2018)

ABSTRACT

In this study, forced convective drying process of wood material with rectangular shape was investigated. Firstly, governing equations for the flow field were solved by using ANSYS Fluent. Then average heat transfer coefficient on the surface was calculated by using Standard k-ε Turbulence Model. It was found that mass transfer coefficient making use of the relationship between heat and mass transfer. Simultaneous heat and mass transfer equations were solved transiently with Comsol Multiphysics using surface boundary conditions for selected air velocity, air temperature and material thickness. In drying process the moisture and temperature distributions inside the solid were obtained transiently. The mathematical model for equations was formed using Fourier heat and Fick diffusion models. Results acquired from the present model were compared with a study results which are available in literature and it was shown a very good agreement.

KEYWORDS: Fluent, Comsol, drying, numerical study.

INTRODUCTION

Despite the availability of many raw materials along with the developing technology, wood material has not lost its daily popularity due to its superior features and appearance, and its use of industry has continued to increase. The wood should be kept healthy for a long time because of its wide use in daily life. For this reason, the drying of the medium to be used when the wood is in the form of lumber is important in terms of energy wastage, economic reasons, product quality and environmental protection. If the material is not dried up to the moisture content of the environment to be used, moisture exchange will continue between the material and the environment, so the shape change will occur (Senel 1993).

Oumarou et al. (2015) have studied the thermal behavior of wood drying at high temperature in three dimensions. They have done some parametric studies to optimize the system. As a result of the studies made, it has been seen that the parameters affecting product quality are the thermal conductivity and moisture diffusivity. Kumar et al. (2012) have developed a mathematical model of simultaneous heat and mass transfer during forced convection and drying in their work. Using this model, the moisture and temperature distribution in the fruit during drying was estimated. Conti et al. (2012) compared the results of the mathematical model representing the drying of the wood material they used in their work with the results of the experiment. Colakoglu (2009) calculated the moisture distribution in the wood by analysis of the end elements. The Fourier's law and the Fick's law define moisture diffusion and heat conduction during drying. Younsi et al. (2008) investigated the three-dimensional wood drying process at high temperature both by CFD analysis and experimentally. In doing so, they considered the flow field to be turbulent. Hussain and Dincer (2003) quantitative model heat and moisture transfer simultaneously during forced convection drying of a moist two-dimensional rectangular cross-section product in their work was examined. Ratanawilai et al. (2015) investigated the drying characteristics of rubberwood with hot air heating (in range of air temperature from 60°C to 80°C) and microwave heating (power input of 200 W) experimentally. He et al. (2016) presented a study on the moisture content distribution and water diffusion coefficient during ultrasound assisted vacuum drying of wood.

Understanding the mechanisms during the drying process of solid objects is essential for dryer design, quality control and energy savings. Thus, in literature, numerical investigations are presented for simulating heat and moisture transfer. Vega et al. (2016) investigated the maximum temperature value on the product surface when drying fruits and vegetables. They have dried the apple slices experimentally in the automatic control unit. Defraeye et al. (2016) used a neutron X-ray film to visualize the distribution of moisture in the product when the fruit slices were dried with forced convection. Ruhanian and Movagharnejad (2016) have experimentally examined the drying of the thin potato layer in the infrared convective dryer.

Udayraj et al. (2014) developed a numerical model for estimating the moisture content of a food product. Lemus-Mondaca et al. (2013) have examined both the numerical and the experimental drying of a solid food product using different drying air temperatures from 40°C to 80°C. Karim and Hawlader (2005) developed a mathematical model that solves the heat and mass transfer equations during forced convection drying of tropical fruits.

In this work, we first calculated the heat and mass transfer coefficients in ANSYS Fluent. Later, simultaneous heat and mass transfer equations were solved with the help of Comsol Multiphysics for wood drying. Wood thickness (3-5-7 cm), drying air velocity (1-2-4 $m\cdot s^{-1}$) and drying air temperature (40-60-80°C) changes were examined. In addition, validation studies were conducted with experimental and numerical results in the literature.

MATERIAL AND METHODS

In the study, moisture and temperature distribution in the material were investigated according to time in two dimensions depending on the product thickness. Conservation equations are solved using Ansys Fluent package program which uses Finite Volume Method (FVM) for a two dimensional rectangular patterned model for drying process. In the quarter of the model, the average convection coefficients of the surfaces with air-contact heat and mass transfer were calculated. In the forced convection drying analysis, the Reynolds number was modeled as turbulent in-channel flow turbulence as the air velocity exceeded 10000 for 1-2 and 4 $m\cdot s^{-1}$ (Curcio et al. 2008). The average heat transfer coefficients in the surface are calculated from the turbulence models by using the Standard k-ε Model, which is the most used in the literature for the turbulent flow drying problems in the channel. The mass transfer coefficient is calculated by using the Lewis relation between heat and mass transfer. Heat and mass transfer coefficients are given in Tab. 1. Then the partial differential equations of the mesh structure shown in Fig. 1 are solved using Comsol Multiphysics finite element analysis.

Tab. 1: Average heat transfer coefficients calculated for different variables (temperature, velocity and thickness).

Parameter name	Value		
Variable thickness (cm)	3	5	7
(Constant 40°C, 2 $m \cdot s^{-1}$, 40%)			
Heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)	9.13	9.10	9.06
Mass transfer coefficient ($m \cdot s^{-1}$)	0.00811	0.00808	0.00805
Variable velocity ($m \cdot s^{-1}$)	1	2	4
(Constant 40°C, 3 cm, 40%)			
Heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)	7.74	9.13	10.2
Mass transfer coefficient ($m \cdot s^{-1}$)	0.00681	0.00811	0.01020
Variable temperature (°C)	40	60	80
(Constant 2 $m \cdot s^{-1}$, 3 cm, 40%)			
Heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)	9.13	9.14	9.16
Mass transfer coefficient ($m \cdot s^{-1}$)	0.00811	0.00862	0.00912

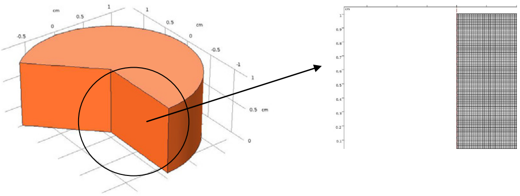


Fig. 1: The model used in analyses and mesh structure.

Simultaneous heat and mass transfer equations with respect to variables such as air velocity, temperature and product thickness are solved using time dependent boundary conditions.

Mathematical modelling for the numerical analysis

The energy conservation equation in solids based on Fourier's law can be given as follows:

$$\rho c_p \left(\frac{\partial T}{\partial t}\right) + \nabla = 0 \tag{1}$$

where:
c_p - specific heat capacity of wood ($J \cdot kg^{-1} \cdot K^{-1}$);
k - thermal conductivity of wood ($W \cdot m^{-1} \cdot K^{-1}$);
ρ - density of wood ($kg \cdot m^{-3}$).

And the mass conservation equation in solids based on Fick's law can be given as follows:

$$\frac{\partial M}{\partial t} + \nabla\left(-D_{eff} \nabla M\right) = 0 \tag{2}$$

where:
Deff - effective diffusion coefficient ($m^2 \cdot s^{-1}$);
M - moisture content (g water /g material).

Initial and boundary conditions

The initial moisture content (on wet basis) of the wood was obtained to be 40% and initial temperature of wood is 25°C.

Heat transfer boundary conditions

The surface boundary condition for heat transfer is given by:

$$-n(-k\nabla T) = h_t (T - T_s) \tag{3}$$

where: h_t - heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$);
T_s - drying air temperature (°C).

Symmetry boundary condition for heat transfer is given by:

$$n(k\nabla T) = 0 \tag{4}$$

Mass transfer boundary conditions

The surface boundary condition for mass transfer is given by:

$$-n(D\nabla M) = h_m (M - M_s) \tag{5}$$

where: h_m - mass transfer coefficient ($m \cdot s^{-1}$),
M_s - equilibrium moisture content (g water/g material).

Symmetry boundary condition for mass transfer is given by:

$$n(D\nabla M) = 0 \tag{6}$$

Numerical study

A two-dimensional axisymmetric model was used to describe the simultaneous heat and mass transfer equations in the hot air convection drying process. Due to the axisymmetry of the wood slabs, only one-quarter of the planer intersection was taken into consideration in the numerical method. It is observed in the literature that this model approach has been used in some numerical drying studies (Sabarez 2012, Kumar et al. 2015).

To simplify the model, the following assumptions were made:

- There is no heat production inside the wood;
- The heat transfer in the wood was considered by conduction (Fourier's Law) and mass transfer occured with diffusion (Fick's Law);
- The shrinkage effect was neglected during the drying period;
- The thermophysical properties of the air and wood were constant during the drying process;
- The temperature and velocity of drying air are constant.

Parameters and thermophysical properties used in the analyses are presented in Tab. 2.

Tab. 2: Thermophysical properties and initial conditions of the wood

Parameter (Unit)	**Value**	**References**
Density (kg·m^{-3})	500	Lamnatou et al. (2009)
Air temperature (°C)	40-60-80	
Moisture content of wood (%)	40	Colakoglu (2009)
Air (m·s^{-1})	1-2-4	Fessel (1965)
Wood thickness (cm)	3-5-7	
Wood temperature (°C)	25	
Moisture content of air (%)	10	Colakoglu (2009)
Thermal conductivity (W·m^{-1}·K^{-1})	0.35	Lamnatou et al. (2009)
Heat of molar evaporation (J·kg^{-1})	0.24×107	Kocaefe et al. (2007)
Specific heat capacity (J·kg^{-1}·K^{-1})	1284	Lamnatou et al. (2009)
Moisture capacity (kg/kg)	0.01	Kocaefe et al. (2007)
Moisture conductivity (kg·m^{-1}·s^{-1})	1.8×10-8	Kocaefe et al. (2007)
Water molecular weight (g·mol^{-1})	18	Kreith (1986)

Wood materials were modelled for numerical simulation. Mesh independence study of moisture content was investigated and the maximum difference was found at 1%. Different mesh structures were applied to wood (Fig. 1). Finally, for the accurate solution, grid structure which consists of 4000 elements was selected. The time-dependent problem was solved by using implicit time stepping method. The nonlinear PDE (partial differential equations) were solved using Newton's method with relative tolerance 0.001 and absolute tolerance 0.0001 using the commercial Comsol Multiphysics 5.3. (2017). Non-linear partial differential transport equations were solved by the numerical method in order to determine the temperature and moisture content values of the air and wood material.

RESULTS AND DISCUSSION

Verification study

The results of two different methods in the literature were verified with the program used in this study. It has been found that the results obtained are in compatible with each other (Fig. 2).

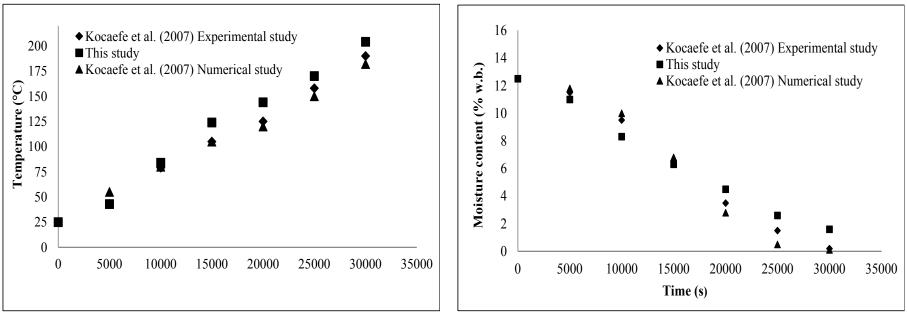


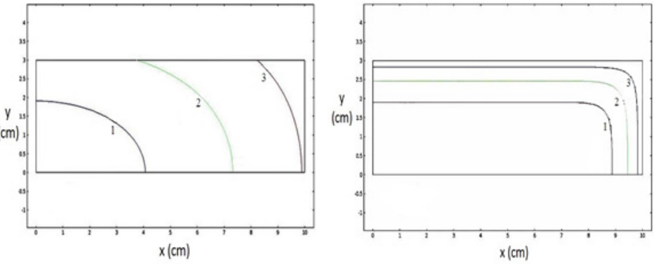
Fig. 2: Comparison of the model prediction with the given results in literature.

Heat and mass transfer analysis results

In this study, the thickness (3, 5 and 7 cm), air temperature (40°C, 60°C and 80°C) and air velocity (1, 2 and 4 m·s^{-1}) of the wood were analysed. Temperature and moisture content distributions were obtained after 2 hours of drying.

Model and measurement points used in analysis

Here, temperature and moisture measurements were made by reading the values on the curves numbered 1-2-3 in Fig. 3 (a) and (b) for each parameter (thickness, air temperature and air velocity).



(a) (b)

Fig. 3: Curves reading temperature (a) and moisture content (b) values.

In Fig. 4 (a), the temperatures of the first curve is for 3, 5 and 7 cm thick are 39.61°C, 38.38°C and 37.20°C after two hours, respectively. According to these results, the temperature in the inner regions was lower than the nearest portions due to the increase of the slice thickness. When the effect of the increase in thickness on the drying time of the material is examined, it is seen that the slowing of the diffusion in the material affects the drying time.

In Fig. 4 (b), the moisture content of the first curve was 35% for 3 cm thick material, 35% for 5 cm thick material and 35% for 7 cm thick material after two hours.

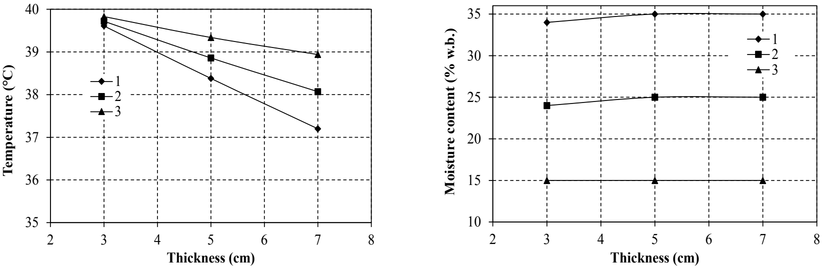


Fig. 4: The variation of temperature (°C) and moisture content (% w.b.) with different thickness (3, 5 and 7 cm) after 2 hours (air temperature = 40 °C, air velocity 2 m·s^{-1}).

According to these results, as the thickness increased, the moisture content increased slightly in the last drying zone. The increase in slice thickness of the product can be explained by the fact that the moisture value in the inner regions is higher than near the outer parts as a result of the reduced drying rate.

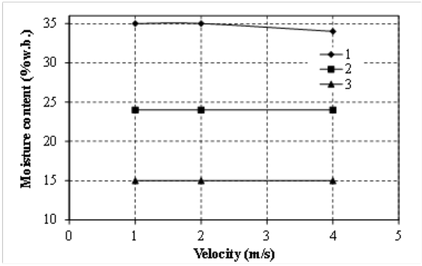


Fig. 5: The variation of temperature (°C) and moisture content (% w.b.) with different air velocity (1, 2 and 4 m·s^{-1}) after 2 hours (air temperature = 40 °C, thickness = 3 cm).

In Fig. 5 (a), the temperature of the first curve is 39.40°C for drying air velocity of 1 m·s^{-1}, 39.61°C for 2 m·s^{-1} drying air and 39.96 °C for 4 m·s^{-1} drying air after two hours of drying. Fig. 5 (b) shows that as the drying air velocity increases, the moisture content decreases at the last drying zone but does not change much. Fig. 6 shows that the temperature of wood is 39.61°C for 40°C, 59°C for 60°C and 78.70°C for 80°C drying air temperature two hours after drying, respectively.

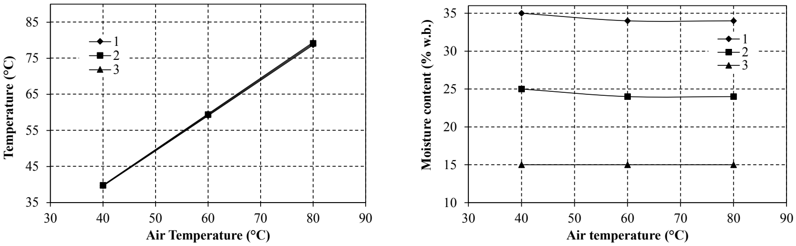


Fig. 6: The variation of temperature (°C) and moisture content (% w.b.) with different air temperature (40°C, 60°C and 80°C) after 2 hours (air velocity = 2 m·s^{-1}, thickness=3 cm).

According to these results, as the drying air temperature increased the temperature inside the product increased by 50%. Fig. 6 (b) shows that as the drying air temperature increases, the moisture content decreases very close to each other on first curve.

According to the parameters such as temperature, velocity and thickness obtained above, analyses were made for the wood material and the drying results after two hours were examined. As a result of the analyses made, it was seen that the effect of velocity and temperature parameters on early drying was not found much in long-term drying. Therefore, it is considered sufficient to take the drying time as two hours as the effect of the high velocity and the heat is not significant in the drying of the modeled wood as in this study. Also, as seen in the literature, the values of the variables such as velocity, temperature and thickness are close to each other and they are found to be compatible with the drying behavior of different parameters in the literature for the same time period (Hussain and Dincer 2003, Chen et al. 1999, Karim and Hawlader 2005, Curcio et al. 2008). It can be seen that the velocity and temperature parameters of the drying process do not affect the drying rate very much after two hours. The reason why the change is close to each other is that the material in the material evaporates and water remains in a small amount, which makes diffusion difficult. Although the air velocity was constant at 2 m·s^{-1} and analysed with different temperature values, the moisture contents of the samples changed closely. Therefore, it is important to determine the ideal drying conditions in order not to waste energy.

CONCLUSIONS

In this study, the conservation equations were solved first with the Fluent program and the average heat and mass transfer coefficient of the surface were found. Then, it was solved the heat and mass transfer equations depending on the time using Comsol Multiphysics. Numerical model can be used for modeling, optimization, estimation, monitoring and control of drying processes. For this purpose, different parameters, which affect the drying process such as air temperature, air velocity, dimension, depth and time, were investigated.

First, moisture content and temperature distributions were found at after two drying hours for three different thicknesses (3, 5 and 7 cm). According to these results, as the thickness increased, the drying time increased and drying was slowing down.

For three different drying air velocities (1 $m \cdot s^{-1}$, 2 $m \cdot s^{-1}$ and 4 $m \cdot s^{-1}$), the moisture content and temperature distributions were found at after two drying hours. According to these results, as the air velocity increases, the drying time tends to decrease but it does not change much.

Moisture content and temperature distributions were found at after two drying hours for three different drying air temperatures (40°C, 60°C and 80°C). These results show that the drying time did not change much for two hours as the drying air temperature increased.

At the same time, it was observed that increasing the velocity value above 1 $m \cdot s^{-1}$ did not affect the drying time in two hours. In case of drying at different temperatures, if the velocity value is taken as 2 $m \cdot s^{-1}$, it does not affect the drying period too much in the two hour period.

According to the results obtained, the effect of parameters affecting to dry in a short time, the drying times and the information about drying can be presented to the industrial users in a short time. Experimental and theoretical results have been verified and they are important for future studies.

As a result, it can be concluded that low velocity (1 $m \cdot s^{-1}$), high temperature (80°C) and low thickness (3 cm) material should be selected for faster drying. The data obtained were compared with the experimental and numerical solutions, and the results were found to be compatible with each other. According to this result, the mathematical model expressing simultaneous heat and mass transfers can be used to estimate the moisture and temperature distribution in the product during drying.

REFERENCES

1. Chen, H., Marks, B.P., Murphy, R.Y., 1999: Modeling coupled heat and mass transfer for convection cooking of chicken patties. Journal of Food Engineering 42(3): 139-146.
2. Comsol Multiphysics 5.3, 2017: Heat transfer model library, Heat transfer module user's guide. Chemical Reaction Engineering Module User's Guide. Comsol, Inc, USA.
3. Conti, C., Conti, A.C., Gava, M., Filho, H.J.S., 2012: Mathematical model of drying *Hevea Brasiliensis* wood. IUFRO Wood Drying Conference. Para, Brazil.
4. Curcio, S., Aversa, M., Calabro, V., Lorio, G., 2008: Simulation of food drying: FEM analysis and experimental validation. Journal of Food Engineering 87(4): 541-553.
5. Colakoglu, M.H., 2009: Determination of change in moisture ratios of some woods during air-drying by Finite Element Analsysis. Journal of Applied Sciences 9(22): 4091-4094.
6. Defraeye, T., Nicolaï, B., Mannes, D., Aregawi, W., Verboven, P., Derome, D., 2016: Probing inside fruit slices during convective drying by quantitative neutron imaging. Journal of Food Engineering 178: 198-202.

7. Fessel, F., 1965: Trocknung in Dampf-Luft Gemischen, Holztrocknung. Holzwirtschafliches Jahrbuch Nr. 15, Pp 69-100.
8. He, Z., Zhang, Y., Qiu, S., Zhao, Z., Yi, S., 2016: Water distribution during ultrasound assisted vacuum drying of wood. Wood Research 61(3): 341-350.
9. Hussain, M.M., Dıncer, I., 2003: Numerical simulation of two-dimensional heat and moisture transfer during drying of a rectangular object. Numerical heat transfer. Part A: Application: An International Journal of Computation and Methodology 43(8): 867-878.
10. Karim, M.A., Hawlader, M.N.A., 2005: Mathematical modelling and experimental investigation of tropical fruits drying. International Journal of Heat and Mass Transfer 48(23-24): 4914-4925.
11. Kocaefe, D., Younsi, R., Poncsak, S., Kocaefe, Y., 2007: Comparison of different models for the high temperature heat treatment of wood. International Journal of Thermal Sciences 46(7): 707-716.
12. Kreith, F., Bohn, M. S., 1986: Principles of heat transfer. 4th edition. N. York, 328 pp.
13. Kumar, C., Karim, A., Joardder, M.U.H., Miller, G.J., 2012: Modeling heat and mass transfer process during convection drying of fruit. 4th International Conference on Computational Methods (ICCM 2012). Australia.
14. Kumar, C., Millar, G.J., Karim, A., 2015: Effective diffusivity and evaporative cooling in convective drying of food material. Drying Technology 33(2): 227-237.
15. Lamnatou, C., Papqanicolaou, E., Belessiotis, V., Kyriakis, N., 2009: Conjugate heat and mass transfer from a drying rectangular cylinder in confined air flow. Numerical Heat Transfer, Part A: Applications 56(5): 379-405.
16. Lemus-Mondaca, R. A., Zambra, C.E., Vega-Gálvez, A., Moraga, N.O., 2013: Coupled 3D heat and mass transfer model for numerical analysis of drying process in papaya slices. Journal of Food Engineering 116(1): 109–117.
17. Oumarou, N., Kocaefe, D., Kocaefe, Y., 2015: Some investigations on moisture injection, moisture diffusivity and thermal conductivity using a three-dimensional computation heat treatment of wood at high temperature. International Communications in Heat and Mass Transfer 61: 153–161.
18. Ratanawilai, T., Nuntadusit, C., Promtong, N., 2015: Drying characteristics of rubberwood by impinging hot air and microwave heating. Wood Research 60(1): 59-70.
19. Ruhanian, S., Movagharnejad, K., 2016: Mathematical modeling and experimental analysis of potato thin-layer drying in an infrared-convective dryer. Engineering in Agriculture, Environment and Food 9(1): 84-91.
20. Sabarez, H.T., 2012: Computational modelling of the transport phenomena occurring during convective drying of prunes. Journal of Food Engineering 111(2): 279–288.
21. Senel, A., 1993: Parametres affecting drying of wood products. Gazi University Industrial Education Faculty Journal 1(1): 59-66 (in Turkish).
22. Udayraj, Md. A., Mishra, R. K., Chandramohan, V.P., Talukdar, P., 2014: Numerical modeling of convective drying of food with spatially dependent transfer coefficient in a turbulent flow field. International Journal of Thermal Sciences 78: 145-157.
23. Vega, A. M. N., Sturm, B., Hofacker, W., 2016: Simulation of the convective drying process with automatic control of surface temperature. Journal of Food Engineering 170: 16-23.
24. Younsi, R., Kocaefe, D., Poncsak, S., Kocaefe, Y., Gastonguay, L., 2008: CFD modeling and experimental validation of heat and mass transfer in wood poles subjected to high temperatures: a conjugate approach. Heat and Mass Transfer 44(12): 1497-1509.

*BURAK TURKAN, AKIN BURAK ETEMOGLU
BURSA ULUDAG UNIVERSITY
FACULTY OF ENGINEERING
MECHANICAL ENGINEERING DEPARTMENT
TR-16059 BURSA
TURKEY
*Corresponding author: burakt@uludag.edu.tr