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DRYING KINETICS OF CARROT BY FIXED BED DRYER

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Abstract. *The carrot (Daucus carota) is a vegetable rich in beta-carotene, soluble fibers, vitamin A and important minerals. Besides having low levels of fats, preventing the bad cholesterol. The carrot drying is important since it is accomplished a better using and obtaining of a product with greater added value, as the flour. Drying is a unitary operation that aims at the conservation of food, as it is the process of reducing the water activity in the substance. In this context, the present paper aimed to adjust the liquid diffusion model to the experimental data for the determination of the effective diffusion coefficient of water in carrot slices. To carry out the process, the carrot was dried in a fixed bed dryer by varying the operating temperatures. It was observed that the numerical solution of the liquid diffusion equation led to results with great fit with the experimental data, enabling the determination of the effective diffusion coefficients at the temperatures studied.*

Keywords: *Drying, Carrot, Liquid diffusion coefficient.*

1 INTRODUCTION

In recent years, there has been an upward trend in the consumption of dehydrated food such as fruits and vegetables, especially as a result of a greater market demand for these products. In this context, the food industry has been investing in the improvement of drying processes (Andreola et al., 2012). The carrot (*Daucus carota*) is a biennial plant of the Umbelliferae family, which is rich in carotene, a substance that in the body turns into vitamin A, of fundamental importance for the ocular system. It consists of 86.7% water, 10.7% carbohydrates, 1.2% protein and the rest of salts and fat (Jerônimo, 2013). In Brazil, 780.6 thousand tons of carrots were produced in 2014, concentrating mainly in the states of Minas Gerais, Bahia, São Paulo and Paraná. In this way, the carrot drying process has been targeted by food industries in the formulation of instant soups, baby food, purees, pastas, snacks and food supplements (Andreola et al., 2012).

Drying is one of the oldest forms of food preservation and basically consists of supplying a certain quantity of heat to a material that contains water, aiming at the partial or total vaporization of this water, having as final product a dry solid material (Carvalho et al., 2016). The moisture is transferred from the interior of matter to its surface, where evaporates to the environment (Wankenne, 2013).

Several empirical theories and formulations were developed to describe the phenomena of drying processes, among which we can mention: the capillary, liquid diffusion, condensation-evaporation, Luikov's and Fortes and Oko's theories. From these theories, the one of liquid diffusion has been used to relate the diffusion of water in the solid with the concentration or moisture in its interior. This theory can be used from adjustments of theoretical and experimental curves, to estimate the value of the effective diffusion coefficient of water (Brooker et al., 1992; Martinazzo et al., 2007; Costa et al. 2011).

Therefore, the present work aims to adjust the liquid diffusion model to experimental data for the determination of the effective diffusion coefficient of water in carrot slices. For this purpose, it was considered the one-dimensional model of liquid diffusion, which was solved numerically using the finite difference method in the discretization of the differential equation of the proposed model.

2 MATERIALS AND METHODS

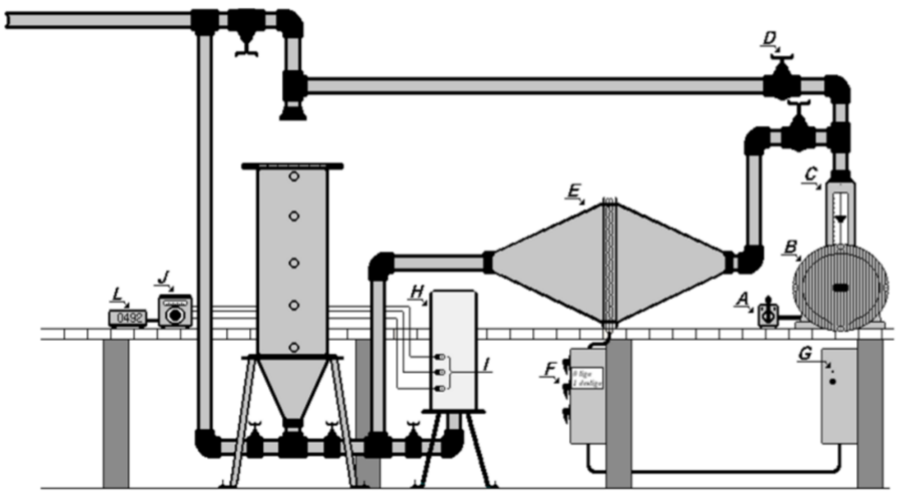
This work was carried out in the Laboratory of Biochemical Engineering of the Academic Unit of Chemical Engineering of the Federal University of Campina Grande – PB – Brazil. The raw material used was the carrot (Daucus carota), which was acquired in the local commerce of Campina Grande with initial water content of 88.06% in wet basis.

The peel of the carrot was initially removed and, in order to obtain homogeneous samples, it was sliced with an average thickness of 2 mm, with a cylindrical geometric shape and an average diameter of 28.4 mm. The conditions of the drying environment, such as the wet bulb and dry bulb temperatures were 22 and 25 °C, respectively.

The carrot samples were placed on a metallic basket, with a thin stainless steel screen, measuring the weight of the set through an analytical balance. The same was taken to the convective dryer, where two temperatures were adopted for comparison purposes, 40 and 60 °C.

The drying of the carrot slices was performed in a cylindrical convective dryer (Fig. 1) with a diameter of 180 mm. Atmospheric air was pumped through an electric heater which, with the aid of thermocouples and a temperature controller, ensuring a constant drying air temperature over time.

Figure 1. Representation of the equipment used to perform the convective drying



Legend: A. Compressor switch; B. Radial fan; C. Flowmeter; D. Regulating valve; E. Electric heater; F. Resistance switch; G. Control system key; H. Drying chamber; I. Thermocouples; J. Temperature controller; K. Digital millivoltmeter.

The reduction of the water content of the samples was monitored by gravimetric analysis, where during the first 60 minutes, the tray was weighed in 1-minute intervals, then at 2-minute intervals, and after 80 minutes at 5-minute intervals. The weighing was performed until the weight variations of the samples were insignificant.

To determine the dry matter, the drying of carrot slices samples was performed in an oven at 105 ºC, for 24 h, to find the initial moisture content of the carrot.

From the experimental data, the drying kinetics curves were made (graphics of the wet basis moisture (M_{bu}) as a function of time) and the drying rate curves (derivative of the drying curves with respect to time as a function of the drying time).

The moisture ratio was determined using Eq. (1), where M_0 is the initial moisture, M is the moisture at a respective time t and M_E is the moisture at the equilibrium condition.

$$MR = \frac{M - M_E}{M_0 - M_E} \tag{1}$$

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2.1 Mathematical Modeling

For the theoretical calculation of the effective diffusion coefficient of the carrot, it was employed the theory of liquid diffusion, known as the second law of Fick, which establishes a relation of the diffusion coefficient with the concentration gradient of a medium. Some considerations were made to obtain the theoretical model:

a) The carrot slices have homogeneously distributed properties;

b) The drying process is performed in a one-dimensional domain in the radial direction, in other words, it was considered angular and radial symmetry;

c) The thickness of the carrot slices was disregarded;

d) The volumetric deformation of the carrot slices was not considered.

Based on these considerations, the liquid diffusion model is reduced to:

$$\frac{\partial M}{\partial \tau} = \frac{\partial^2 M}{\partial r^2} \tag{2}$$

With the dimensionless terms defined by:

$$\tau = \frac{t \times D_{ef}}{R^2}$$

$$r = \frac{r'}{R^2} \tag{4}$$

Where M corresponds to the water content, t is the time, R the radius of the carrot slice, r' the radial position and D_{ef} is the effective diffusion coefficient of water.

The following initial and boundary conditions were adopted:

When τ = 0, ∀ r we have $M = M_o$; (5)

When r = 0, τ > 0 it was defined $\frac{\partial M}{\partial r} = 0$; (6)

When r = R, τ > 0 it was considered $M = M_e$. (7)

Where M_o is the initial water content and M_e is the equilibrium water content.

For the resolution of Eq. (2), (5), (6) and (7), the finite difference method was used to obtain the system of linear equations that was solved with the aid of the Jacobi method. The results of the simulations of the studied cases were obtained by a computational program coded in VBA-Excel.

2.3 Determination of Effective Diffusion Coefficient

The effective diffusion coefficient was obtained by the adjustment of the results of the numerical solution of the liquid diffusion model, defined by Eq. (2), to the experimental data of the drying of the carrot slices.

The analytical solution of Eq. (2) is presented as an infinite series which, when truncated in the first term (Eq. 8), provided an initial estimate of the effective diffusion coefficient for the fitting of the numerical solution with the experimental data.

$$\bar{M} = \frac{4}{\mu^2} exp\left(-\frac{\mu^2 D_{ef}}{R^2} t\right) \tag{8}$$

3 RESULTS AND DISCUSSION

In Fig. 2, the curves of the drying kinetics of carrot slices as a function of time are shown for two drying air temperatures. It is observed a reduction of the moisture ratio in the first hours of the drying process, and after that, it remains constant when the equilibrium moisture is reached. It is also observed in this figure that the temperature of the drying air has a significant influence, since increasing the temperature of the drying air favors a faster evaporation of the water on the surface of the carrot slice and, therefore, the migration by diffusion of internal moisture to the surface of the carrot and the cycle is repeated until the equilibrium moisture is reached.

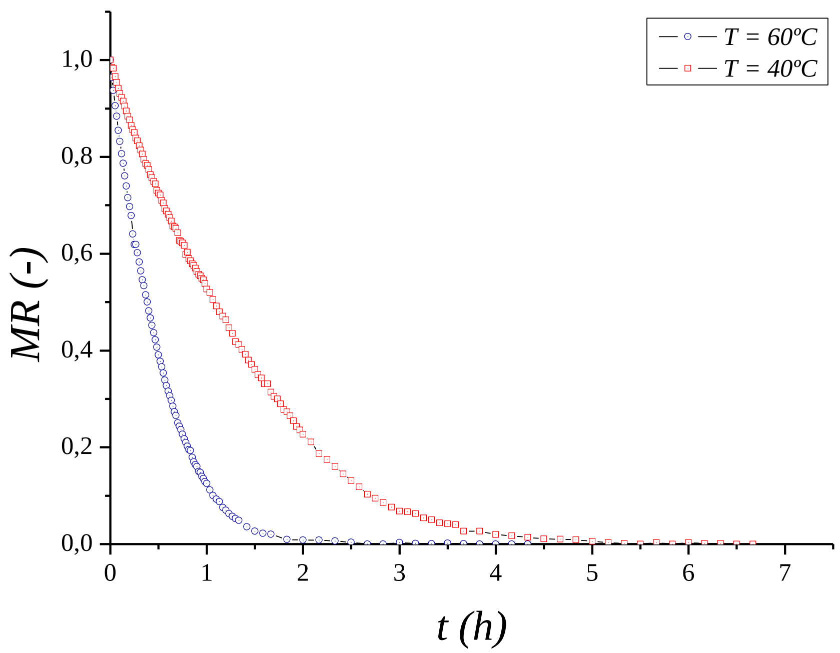

Figure 2. Drying kinetics of carrot for the studied temperatures

The results confirm the behavior observed by several studies reported in the literature, such as (Hofsky et al., 2009; Machado, et al., 2012), in which it was studied the pineapple drying and it was stated that the drying air temperature is one of the parameters that exerts the greatest influence on drying kinetics; Gouveia et al. (2002), Menezes et al. (2013) and Delmiro (2016) observed similar behavior in the drying of cashew, yellow passion fruit bagasse and carrot, respectively.

In order to determine the effective diffusion coefficient (D_{ef}), it was employed the solution of the liquid diffusion equation from the computational program developed in VBA-Excel, adopting the discretization method of finite differences. The value of D_{ef} was initially estimated from the linearization of Eq. (8) and these results are shown in Fig. 3 and 4. Therefore, the estimated values for 40 °C and 60 °C are, respectively, 7.73 x 10^{-5} and 4.71 x 10^{-4} $m^2.h^{-1}$.

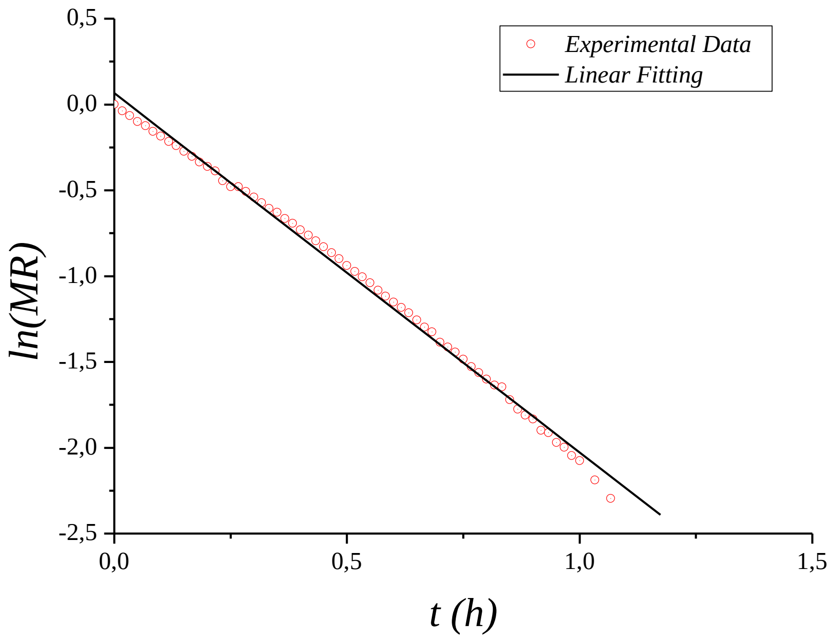

Figure 3. Analytical estimation of the effective diffusion coefficient at 60 °C

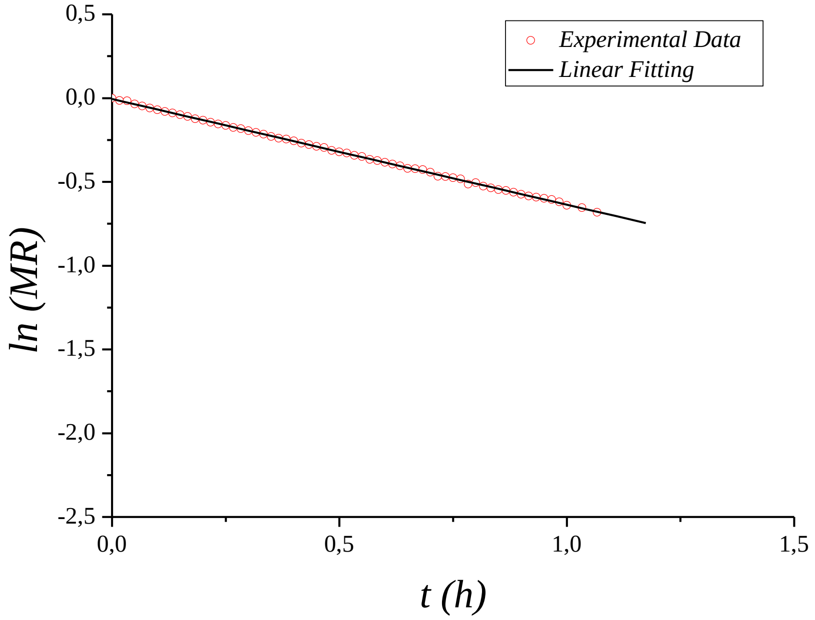

Figure 4. Analytical estimation of the effective diffusion coefficient at 40 °C

The estimated values for the effective diffusion coefficients (D_{ef}) were used in the determination of the D_{ef} value, which was determined numerically, so that it would fit in the best way with the experimental data. These adjustments are shown in Fig. 5 and 6, for the temperatures of 40 °C and 60 °C, respectively.

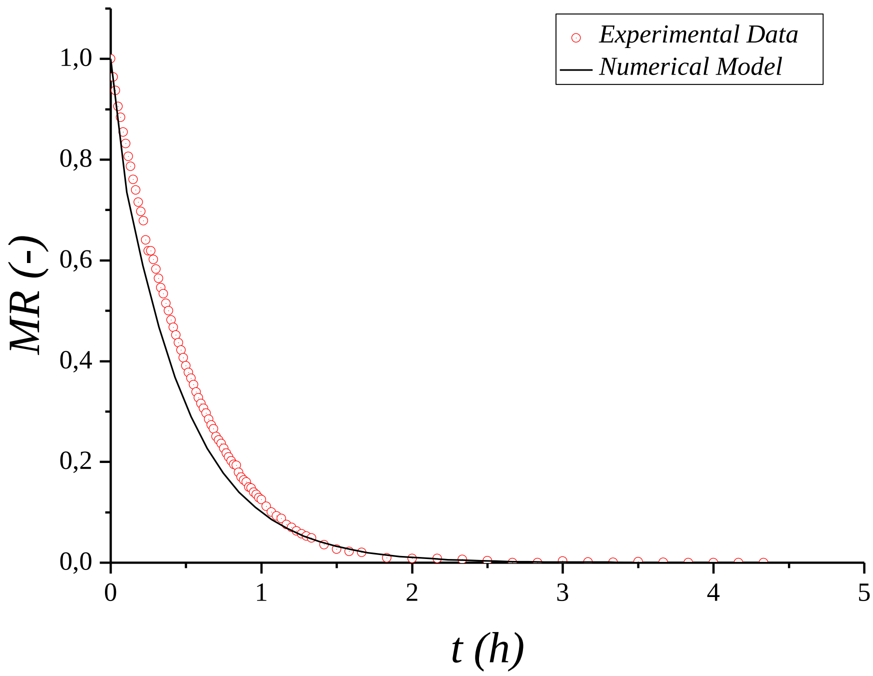

Figure 5. Drying kinetics of carrot at 60 °C with adjustment by the numerical model

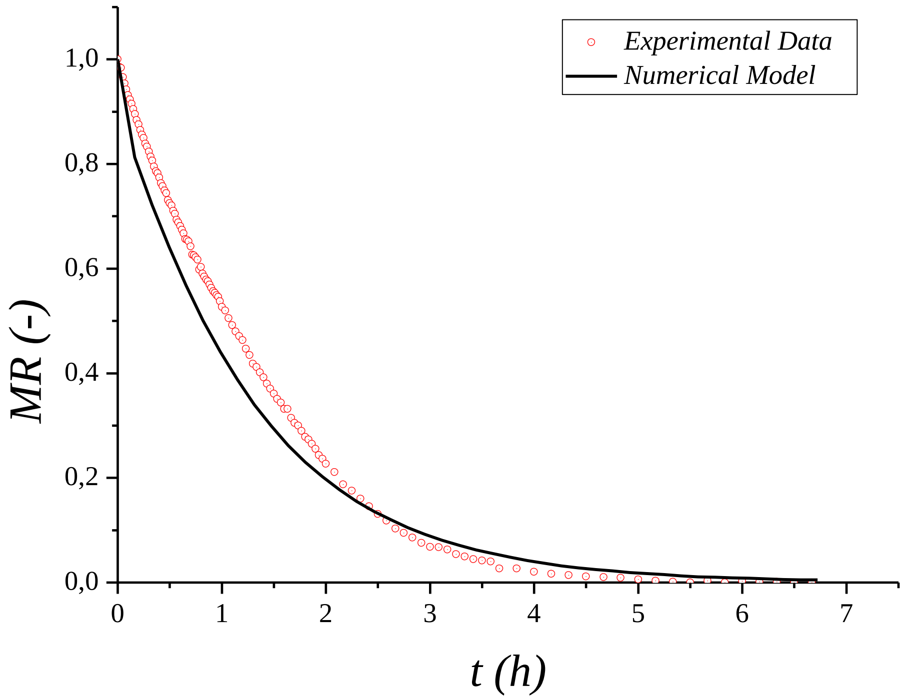

Figure 6. Drying kinetics of carrot at 40 °C with adjustment by the numerical model

Table 1 presents the values of the effective diffusion coefficients D_{ef} determined numerically and analytically. The results indicate a significant discrepancy, which can be explained by the consideration made when the series was truncated in the first term, which leads to significant estimation errors.

Table 1. Effective diffusion coefficients

Temperature (°C)	**Numerical** D_{ef} ($m^2 . h^{-1}$)	**Analytical** D_{ef} ($m^2 . h^{-1}$)	**Relative Error (%)**
40	3.45×10^{-5}	7.73×10^{-5}	55.37%
60	1.05×10^{-4}	4.71×10^{-4}	77.70%

Figures 7 and 8 show the moisture or water content profiles as a function of the radial position in the carrot slice for different drying times. The curves clearly illustrate the water content inside the carrot, from the center to the surface (that is, at r equal to the radius, R, of the carrot slice).

The results of Fig. 7 and 8 indicate that with the passage of drying time, a reduction in the water content inside the carrot slice is observed, as a result of the evaporation of surface water and the migration of the water from the center to the surface. After about 1.5 h, the layer closest to the center of the carrot approaches the equilibrium moisture content for both 60 °C and 40 °C temperatures. The drying process is increasingly governed by internal resistances (Nunez et al., 2012).

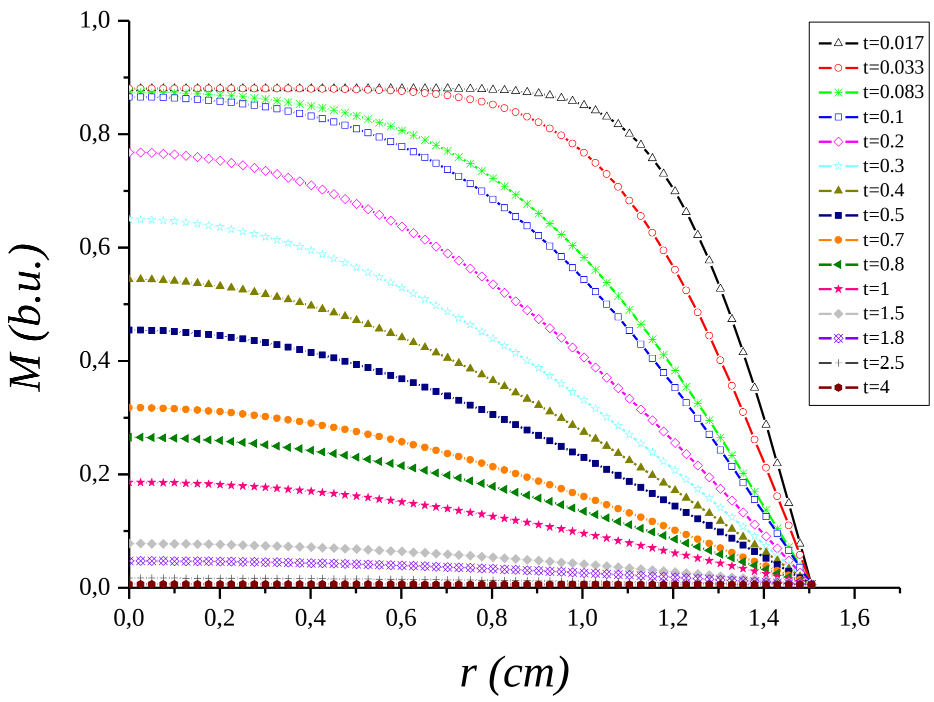

Figure 7. Predicted moisture distribution for different drying times at 60 °C

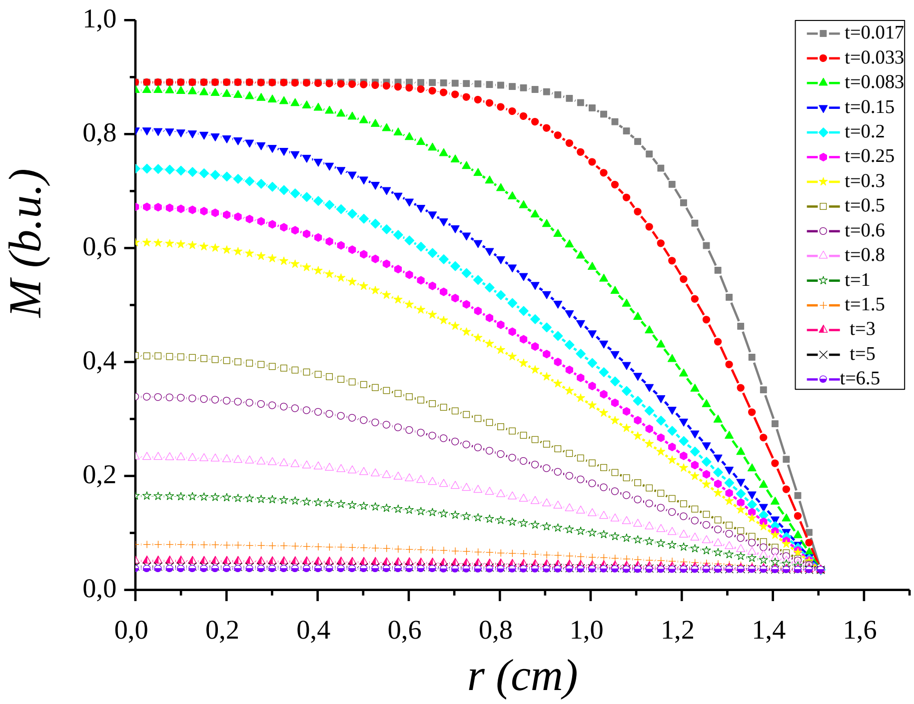

Figure 8. Predicted moisture distribution for different drying times at 40 °C

4 CONCLUSIONS

From the experimental data and the numerical results obtained, it is possible to conclude that:

- The temperature of the drying air has a preponderant role in the drying process of the carrot slices;
- The numerical solution of the liquid diffusion equation using the finite difference method led to results with great fit with the experimental data;
- From the numerical solution, it was possible to determine the effective diffusion coefficients of the carrot slices at the temperatures studied;
- The numerical solution enabled to evaluate the evolution regarding to the time of the profiles of water content inside the carrot slices where the reduction of water was observed;
- The analytical solution of the liquid diffusion equation in the form of an infinite series truncated in the first term leads to results with significant relative errors compared to the numerical solution.

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