OBSERVATION OF THE DRYING PROCESS IN SECONDARY SCHOOL

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ABSTRACT

Some years ago we built a solar dryer during an extracurricular class. Although we had no opportunity to analyse the drying procedure itself, with the help of students we did some experiments and measurements associated with the device. In latter works we used an electric dryer to physically capture the drying by eliminating the environmental effects. We made a series of experiments that are comprehensible in high school. We measured mass reduction of different fruits due to the loss of water over time and compared our results – which resembled the evaporation of a fluid consisting of two constituents – with the literature. A statistical model has been derived to demonstrate the drying.

INTRODUCTION

Some few years back in our school [Eötvös József Secondary School] extracurricular lectures ran on environmental physics, especially focused on environmental flows and solar energy. Related to the latter topic, former students built a solar dryer. They also monitored how it is functioning and made measurements with it. This work – besides raising the motivation of students – has succeeded in an educational point of view by showing it is capable of synthesising the notion of energy and it made possible for students to put abstract conceptions and quantities into use (e.g.: power, efficiency, luminosity).

In the last two years a new research subject adaptable in secondary schools has come into sight connected to the solar dryer. It is plausible to study the process of drying itself instead of the characteristics of a drying machine. The subject has an extended technical literature, but this ought to be made comprehensible for students. In the present article we are to show a train of thought on how the description and measurements are made comprehensible to students. We also show the resemblance of fruit drying and the evaporation of two-constituent compounds and introduce a toy model using dices to demonstrate evaporation.

INSTRUMENTS AND MEASUREMENTS

To describe drying quantitatively we had to work out a measurement procedure which is reproducible. A solar dryer is not suitable for this as it does not fulfil the criteria that the power density required for the loss of water should be constant in time. To exclude this and other environmental effects we obtained an electric dryer.

As a subtask we can compare the two devices by their evaporating efficiency. This quantity is defined arbitrarily and could be calculated from measurement data. A possible definition to this efficiency could be the following:

the ratio of the energy needed for a certain amount of water to evaporate from a standardized pot in an hour and the energy used during the process.

In our case, we used a Petri dish (9.5 cm diameter) as the pot and we filled it with 50 g of water. The energy used by the electric dryer could be calculated from its power, while in the case of the solar dryer it is to be calculated from solar radiation and the effective size of the solar panel. Our measurements showed that the evaporating efficiency of the electric dryer is $\eta_{electric}$ = 2.5% and the same for the solar one is η_{solar} = 0.3%.

During our measurements with the electric dryer we registered the mass of the fruits (apple and banana slices) in the dryer over time. For this, we used a kitchen scale due to the dimensions of the dryer.

Measurements were also made on evaporation. In these cases - again - the mass of a compound of two constituents was registered over time. With a sugar-water compound being the subject of such experiment we used the above set-up due to time it requires to evaporate (we had to speed up the process to fit a double-length class), but when we investigated the evaporation of a paraffin-oil and pentane as a compound we used an analytic balance instead, because the time required was much shorter than in the case of sugar-water.

ANALYSIS OF DATA

There are several mathematical models that describe the drying of sliced vegetables and fruits. It is usual in food engineering articles covering the subject to compare these models to their measurements and use the model that fits the data better. For an example Akpinar et al., 2006 in [1], Akpinar, 2006 in [2] or Diamante and Munro, 1993 in [3] have gathered some of the models to choose the best one describing their measurement data. Table 1 shows the collection of models that are widely used.

Table 1. Mathematical models used to describe drying. This table is an excerpt from [1]

Mathematical models widely used to describe the drying kinetics (Akpinar, Bicer, & Midilli, 2003; Akpinar, Bicer, & Yildiz, 2003; Akpinar et al., 2003a; Ertekin and Yaldiz, 2004; Günhan et al., 2005; Togrul and Pehlivan, 2003; Yaldiz and Ertekin, 2001)

Model no	Model name	Model
1	Newton	$MR = \exp(-kt)$
2	Page	$MR = \exp(-kt^n)$
3	Modified Page (I)	$MR = \exp[-(kt)^n]$
4	Modified Page (II)	$MR = \exp[(-kt)^n]$
5	Henderson and Pabis	$MR = a \cdot \exp(-kt)$
6	Logarithmic	$MR = a \cdot \exp(-kt) + c$
7	Two-term exponential	$MR = a \cdot \exp(-kt) + (1-a)\exp(-kat)$
8	Wang and Singh	$MR = 1 + at + bt^2$
9	Verma et al.	$MR = a \cdot \exp(-kt) + (1-a)\exp(-gt)$

From this we will use the Modified Page (I) model because it gave the best fits – among the models mathematically comprehensible for an average high school student – with our experiments. For the description we will use quantities generally used in food engineering. These are: moisture content (on wet basis) and moisture ratio. M is used to denote the former one, while MR the latter. These quantities depend on time and are defined as:

$$M(t) = \frac{m_w(t)}{m(t)}, \quad (1)$$

$$MR(t) = \frac{M(t) - M_e}{M_i - M_e}. \quad (2)$$

In the formulas above m(t) denotes the mass of the sample, $m_w(t)$ the mass of water contained in the sample while M_i stands for the initial moisture content and M_e for the one in equilibrium, given the conditions (temperature and relative humidity in the dryer).

One could see that to determine the moisture ratio additional information is needed besides the moisture content, and this is the weight of dry matter in the sample. This will be marked with m_d. Equivalent to this is either the initial or the equilibrium moisture content. Unfortunately, neither of these could be measured with standard high school equipment, so a good guess on either of them is needed. In our case the guess is the data available in [4] to determine M_i for banana and apple – the fruits measured. Under the condition that m_d is constant, we see that $m_w(t)=m(t)-m_d$. Also, we can write the constants M_e and M_i with the masses:

$$M_e = \frac{m_w(\infty)}{m(\infty)} = \frac{m(\infty) - m_d}{m(\infty)}, \tag{3}$$

$$M_i = \frac{m_w(0)}{m(0)} = \frac{m(0) - m_d}{m(0)}. \tag{4}$$

The equation we will use (Modified Page model) to fit our data is the following:

$$MR(t) = \exp[-(kt)^n]. \tag{5}$$

This could be linearized easily in the following way:

$$\log(-\log(MR(t))) = n\log(k) + n\log(t). \tag{6}$$

This equation easily fits our data from experiments for given time intervals. We will discuss the results for both drying and evaporation in the upcoming sections.

DRYING PROCESS

The data from measurements with apple and banana and the result of the analysis described above are shown on Figs.1 to 3.

In Fig.3. deviations from linear could be seen at the high time values for both fruits. We suppose that the model we used lacks the correct description near the equilibrium. The fact that the concrete amount of dry matter is unknown also matters, especially at the equilibrium. Other than this, the linear fitting seems to be correct for most of the time with $R^2 = 0.997$ and the parameters are close to each other, n ~ 1.45 and k ~ 0.01.

Up to this point experiments and mathematical models were discussed, but as seen, we left out the actual physics of drying. This is because it is usually described by diffusion and other transport-equations. The different boundary and other conditions lead to the different mathematical constructions. This is a rather complex and difficult topic to discuss, even on extracurricular class, so we made a physical approximation and claimed that evaporation could be seen as a similar physical process to drying.

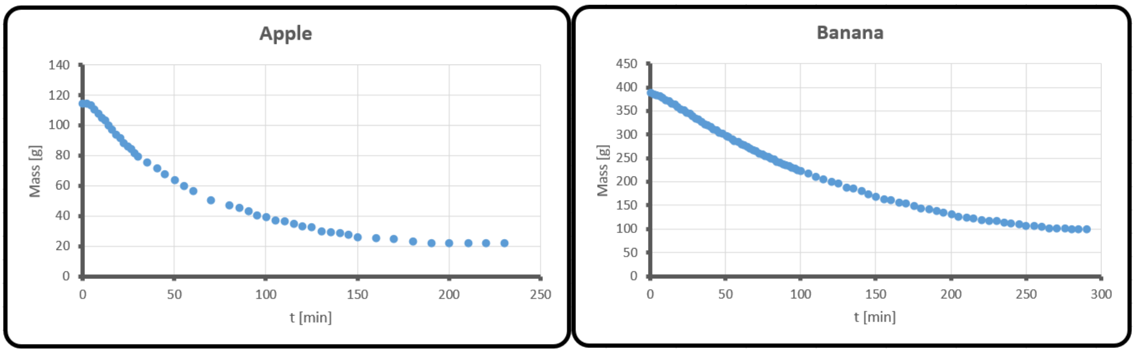

Fig.1. Mass of fruits over time: Left panel: apple. Right panel: banana

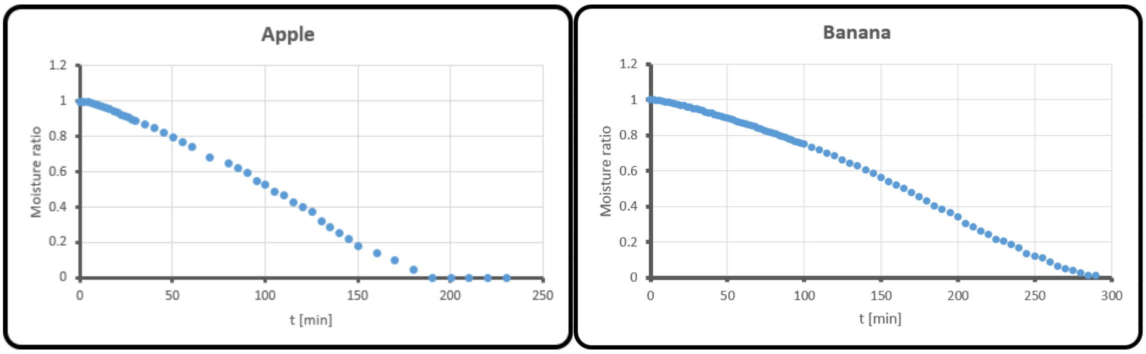

Fig.2. Moisture ratio of the fruits over time: Left panel: apple. Right panel: banana

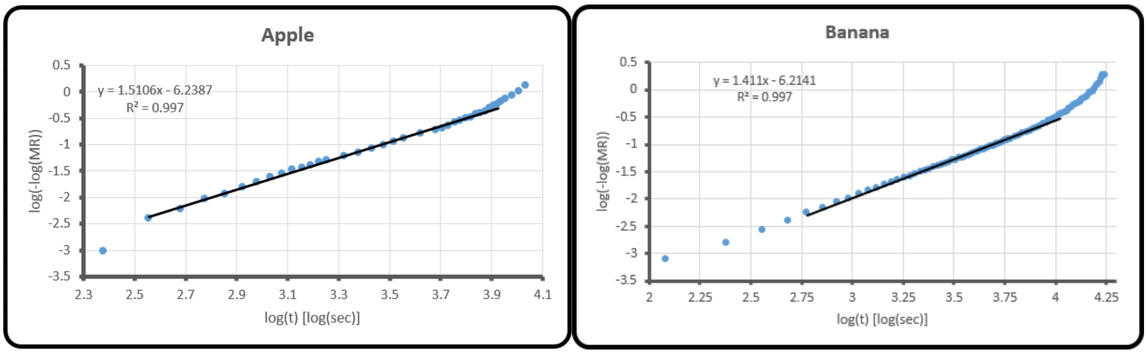

Fig.3. Values calculated using eq. (6), the line fitted with its parameters:
Left panel: apple, n = 1.5106, k = 0.0160. Right panel: banana, n = 1.4110, k = 0.0122

EVAPORATION

Experiments were made on the evaporation of two-constituent compounds – one of which is volatile (e.g. water) and the other is non-volatile – to physically model the drying process. The reason for this is that evaporation is a less complex phenomena taught on regular physics classes. The closest estimation of fruits (e.g. banana and apple) with two components is a sugar-water compound. In this physical model sugar represents the dry matter in fruits. The moisture content and moisture ratio was calculated for this compound from mass measured over time during the evaporation. The initial moisture content was 80%, which is a good generalisation for the fruits used previously. It is to be mentioned that the experiments with this compound were carried out with the same set-up as the one used in the case of fruit drying (an electric dryer on top of a kitchen scale), because the evaporation in open air took much more time than available for a double class (which is 120 minutes).

We investigated another compound, consisting of organic materials, paraffin-oil and pentane. Here, pentane was the non-volatile compound. This experiment is useful because in general, organic materials evaporate much faster, so in this case the set-up with the dryer was not needed to fit into the time of a class. An analytic balance and a petri dish was used instead to proceed with the measurements. The results, - extracted by the same analysis as in the case of drying before - can be seen in Fig.4.

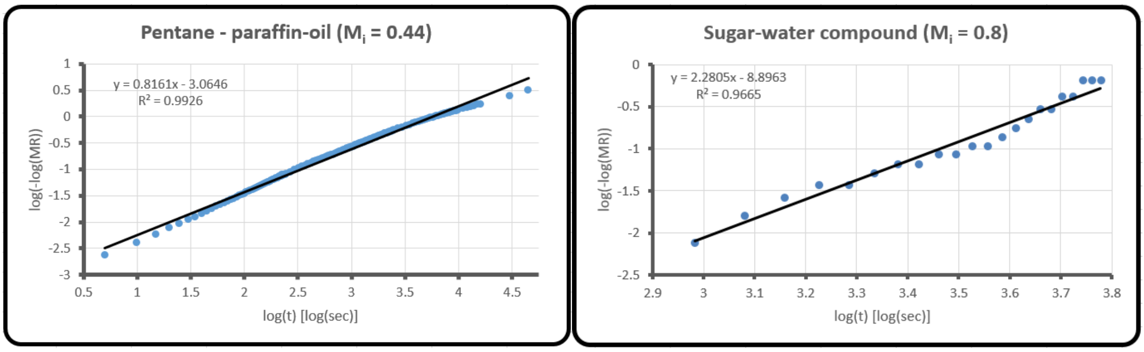

Fig.4. Values calculated using Eq. (6) for the description of evaporation, and the line fitted with its parameters: Left panel: pentane – paraffin-oil, n = 0.8161, k = 0.0233. Right panel: sugar-water, n = 2.2805, k = 0.0202

As seen in the figure, the mathematical model fits our data on evaporation well, in the case of the pentane – paraffin-oil even better than in the case of fruits. We think it is important that the dry matter content of the samples is known exactly this time, so this does not bring another uncertainty in the data.

To sum up: an approximation – a physical approximation – was made that the evaporation is similar to drying, and we described this with the same mathematical model successfully.

A TOY MODEL OF EVAPORATION WITH DICES

Investigating evaporation further, a toy model (or dice model, as it requires the use of dices) had been derived and was used successfully as a demonstration for this phenomena. To introduce this, we will need dices of two colours. Let us say that dices of one colour (these will be referred to as white dices from now on) represent the volatile component of a two-constituent compound (e.g. water), while the dices of the other (these will be referred as the red ones) represent a non-volatile component, or going further we could say that these stand for the dry matter in a given fruit. The ratio of the white dices to all of the dices represents a given initial moisture content, M_i. After this some dices are to be put on a table, which represents the surface of the compound or the fruit. After this initialisation we roll the white dices on the “surface” and if one of them is a six, we take that one out of the game – this is to be concerned as the loss of weight over time. This game or toy model supposes a constant surface area, so after taking dices out of the game one has to “refill” the table. This could happen in different ways, representing different physical conditions. Examples: one could refill from under the table with white and red dices in a way the ratio of whites and reds (taking into account both the dices on and under the table) remains constant, or this could be done with only white dices (see Fig.5.), this way the ratio will depend on time. After enough turns in the game, there will be no white dices left on the surface, so it ends.

This game could be introduced in high schools very easily as it demonstrates evaporation in a more engaging way than most books do. Also it is possible to analyse a game with the same method as used above for drying and evaporation. To exemplify this, Fig.6. shows data from a class where this model was introduced and tried with students.

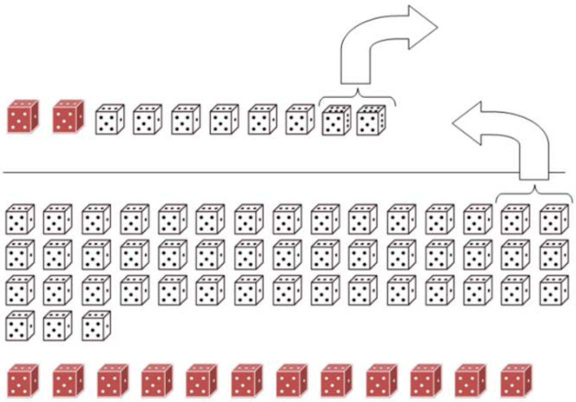

Fig.5. Example for the toy model introduced. It shows a possible pattern for replacing white dices on the surfaces.

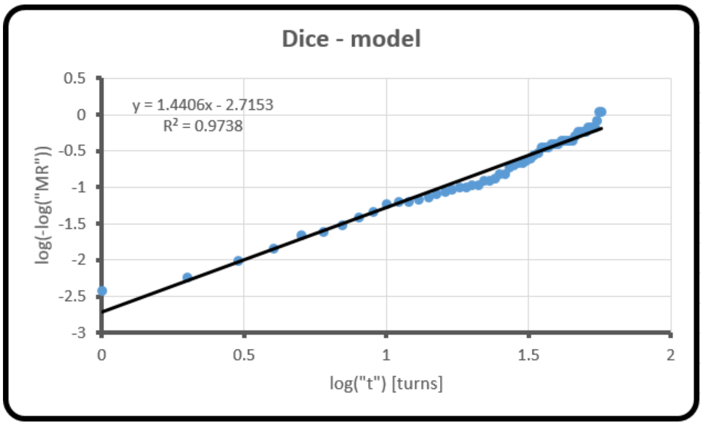

Fig.6. An example to show that the same data analysis could be done in the toy model.

CONCLUSIONS

We have shown a possible way of introducing supplementary material on fruit drying in high school physics (or other science) classes. This could prove a very rewarding area as it is possible to include device development (building a solar dryer), experiments and measurements (to explore the characteristics of a given device, or to investigate a physical process), data analysis with given mathematical models, linearization of equations, analogous thinking. It could also serve as an entry point for more advanced students into the topic of diffusion, or even model building with differential equations. We have also derived a new toy model of evaporation with dices. This proved to be a powerful demonstrational tool as it caught the attention of students besides those who were already interested.

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