

## VORTEX DEHYDRATOR FOR APPLE SNACKS

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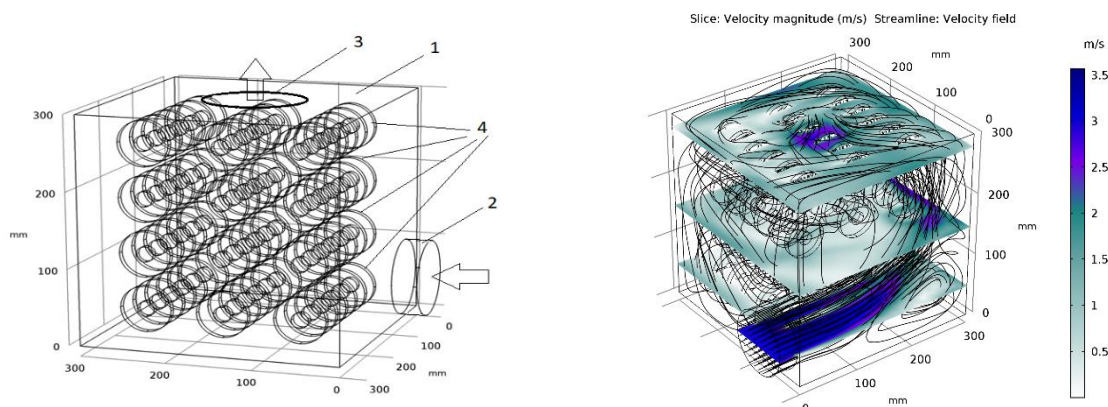
### Abstract

*The study aims at finding the rate of drying and other particulars of the convective dehydration process of apple rings in the domestic type apparatus. The rationale behind the design and key parameters of the vortex dehydrator are presented. Modelling of the drying process in the vortex dehydrator that provides a nearly uniform rate of convective drying of apple rings using airflow of ambient temperature and low humidity has been carried out and tested. The process also implies the convective drying of apple rings by air at the ambient temperature may be diversified by including a weak heating from the below at the final period of drying. The key modeling input parameters, such as the activation energy and mass transfer coefficients have been determined in customized experiments. Activation energy has been estimated for the single ring under natural convection condition; in the following this function has been used for calculation of drying rate of apple rings in the vortex unit under forced convection. The COMSOL Multiphysics 5.5 software package has been used for simulation of the drying curve, the temperature and water vapour concentration inside the apparatus during the dehydration process.*

**Keywords:** vortex dehydrator, apple rings, drying at ambient temperature, REA-approach

### INTRODUCTION

The commercial domestic dehydrator is commonly designed as a tray type dryer which is characterized with substantial non-uniform rate of drying from the bottom to the top (Sokhansanj & Jayas, 2015), causing inconvenience as necessity to trays swapping, hence generally the appliance cannot be operating without required from time to time actions. To resolve the problem, as the alternative design, the vortex dryer (Spotar, 2019) has been suggested by Spotar (2019) and studied by Spotar, Kopbayev, & Saliyeva 2019. The vortex flow in the mentioned dryer is organized by input of an operating air stream along the interior of the side wall, the blowing fan being positioned at the bottom, whereas the used wet air is removed through the round opening at the top cover (Fig.1). In particular, the apparatus does not possess the heater, nevertheless it has been shown that this vortex dryer ensures quite efficient dehydration of apple rings by ambient air of low or moderate humidity. This vortex dryer proved to be a simple robust apparatus suitable for application under condition of availability of low or moderate humidity air.



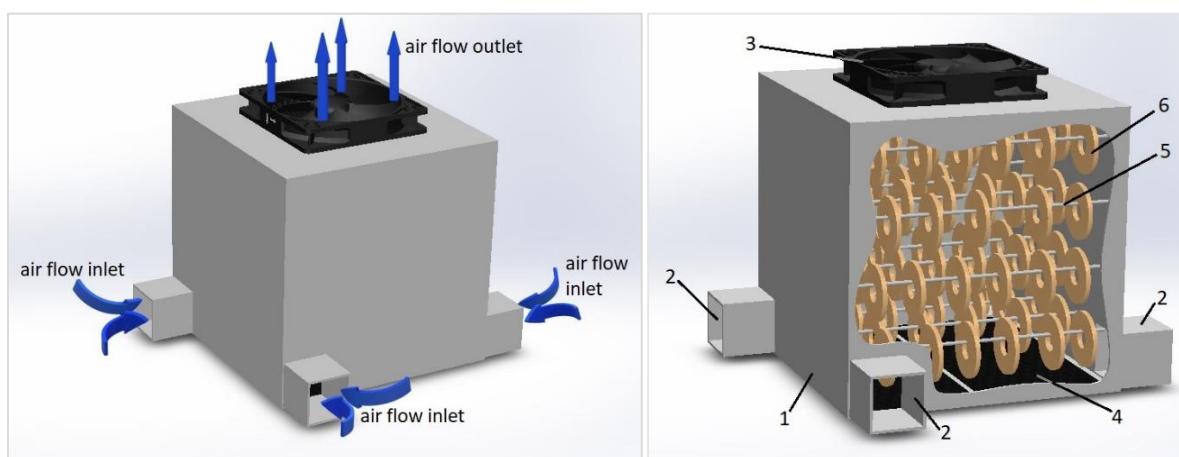
**Fig. 1.** Vortex dryer design and CFD flow streamline in the vortex dryer,  
Spotar, Kopbayev, & Saliyeva, (2019).

Nevertheless, along with observed overall uniformity of the drying process of the uploaded apple rings, due to asymmetric input of the air, the inlet region is under impact of a higher velocity magnitude (Fig.1) comparing with the bulk of the apparatus, causing a faster rate of drying of apple rings at the inlet. This drawback (although rather minor) has motivated towards development of the follow-up version of vortex dehydrator which operates under negative gage pressure. In the given paper the design, drying process modelling, and operation of this developed dehydrator are presented and discussed.

## 1. APPARATUS, MATERIALS AND METHODS

### 1.1. Apparatus

The vortex dehydrator in question is essentially a 280mm×280mm×280mm cubical case comprising 4 inlet ducts positioned at the sides bottom corners thus providing the angular momentum to generate the vortex flow inside the apparatus. The design concept of modified vortex dehydrator that has been employed in this study is presented in Fig. 2. The suction operating 18W axial fan mounted on the top wall serves for air propulsion through the unit and consequently for removal of spent wet air from the dehydrator. The creation of a 3-D vortex inside the apparatus aims employing the innate high mixing ability of the vortex flows (Gupta, Lilley & Syred 1984). As supplementary, the dehydrator is complemented with a film 14W heater which can be used to drive air at the end of the process. The local temperature of the bottom heated surface doesn't exceed  $\approx 40^{\circ}\text{C}$  under natural convection conditions (when the fan is off).



**Fig. 2.** A conceptual view of the vortex dehydrator. 1 - case, 2 – inlet stream conditioner (shaper), 3 – fan, 4 – film heater, 5 – support bar, 6 – apple ring



(a)



(b)

**Fig. 3.** The product loading configurations: (a) top view on the horizontal positioning of apple rings; (b) the vertical hanger with apple rings

While designing in mind, it was also counted that the dehydration time of apple slices substantially depends upon the characteristic thickness of the sample and openness of its surface to the operating convective air flow. To address the above factors, when uploaded, apple rings either were assembled on the parallel horizontal bars, Fig. 3(a), or were placed onto the vertical hangers, Fig. 3(b).

On the top of the above, in line with the described in above design concept, the 500mm size pilot dehydrator has been fabricated, but at the time of the paper writing, the testing program for this prototype has not been completed, although the preliminary tests yielded the fruitful outcomes (Fig. 4).



**Fig. 4.** The apple rings dried in the 500mm size dehydrator; herewith the rings were allocated on the greatly perforated trays

### 1.2. Materials

Apples of Golden Delicious variety has been used in the dehydration experiments. The average moisture content of the Golden Delicious apple rings samples was determined as  $\approx 87.5\%$  of the total mass, which corresponds to data of other researchers, for example as  $\approx 86\%$  (Cuccurullo *et al.* 2018). The fruits were washed with tap water, wiped to dry and then peeled and cut spirally using the apple peeler & corer

appliance. Then these apples were cut from one side to obtain  $\approx 6$  mm in thickness rings (hence, these apple pieces were not the solid rings but having one radial incision).

### 1.3. Methods

#### 1.3.1. Experiments

The dehydration experiments consisted in carrying out the drying of 1.5 - 2 kg of the fresh apple rings placed into the dehydrator shown in Fig. 2. The determination of drying rate of apple rings loaded into the shown above vortex dryer have been carried out using the digital balances *KERN EW 4200-2NM* by measuring the mass of the whole unit in 0.5 - 1 h intervals. All procedures were carried out in the laboratory under room temperature (25°C - 27°C) and humidity (18% - 22%); during each experiment temperature and relative humidity data were measured using the *Testo 610* metering system the and recorded accordingly. Since no air conditioning equipment has been employed to regulate the lab space temperature and humidity, the observed slight variations of the ambient temperature and humidity in the laboratory room were averaged to be used in the post-processing calculations.

#### 1.3.2. Modeling

The estimation of the drying rate of the apple rings in the vortex type of dehydrator presented in Fig. 2, has been carried out using a slightly modified balance model Spotar, Kopbayev, & Saliyeva, 2019). The key inputs employed by this model are the activation energy function under REA-approach (Chen & Putranto 2013) and the values of the mass transfer coefficients in water vapour convective diffusion from the ring samples. The model implies an idealized completeness of mixing process under action of the vortex flow configuration; the model results in a set of differential and algebraic equations for prediction the moisture content and temperature during the drying process. On the same ground of perfect mixing, we assume the mentioned model with a minor correction is applicable for the present vortex dehydrator operating under negative gage pressure.

The overall balance model for the drying process in the vortex dehydrator is specified by the following set of differential and algebraic equations, starting with the equation for the drying rate of a single apple ring as

$$m_s \frac{dX}{dt} = -h_m A (\rho_{v,s} - \rho_{v,b}) \quad (1)$$

where  $m_s$  is the mass of the dried apple ring (kg), i.e. ‘dried solid’;  $X = X(t)$  is the average water content on a dry basis ( $\text{kg} \cdot \text{kg}^{-1}$ ),  $t$  is time (s),  $\rho_{v,s}$  is the water vapour concentration at the apple ring surface ( $\text{kg} \cdot \text{m}^{-3}$ ),  $\rho_{v,b}$  is the water vapour concentration in the bulk interior of the dehydrator ( $\text{kg} \cdot \text{m}^{-3}$ ),  $h_m$  is the mass transfer coefficient ( $\text{m} \cdot \text{s}^{-1}$ ), and  $A$  is surface area of a single apple ring ( $\text{m}^2$ ).

Following the REA-method (Chen & Putranto 2013), the water vapour concentration at the product wet surface  $\rho_{v,s}$  is determined with application of the activation energy,  $\Delta E_v$  as

$$\rho_{v,s} = \rho_{v,sat} \cdot \exp \left[ -\frac{\Delta E_v}{R \cdot T(t)} \right] \quad (2)$$

where  $\rho_{v,sat}$  is the saturated concentration of the water vapour ( $\text{kg} \cdot \text{m}^{-3}$ ), approximated by

$$\rho_{v,sat} = K_v \cdot \exp \left[ -\frac{E_v}{R \cdot T(t)} \right], \quad K_v = 1.61943 \times 10^5 \text{ kg} \cdot \text{s}^{-1} \text{ and } E_v = 38.99 \text{ kJ} \cdot \text{mol}^{-1} \quad (3)$$

The activation energy  $\Delta E_v$  in Eqn. (2) is estimated experimentally from a customized monitoring of drying rate,  $dX/dt$ , as

$$\Delta E_v = -RT \left[ \frac{-m_s \frac{dX}{dt} \frac{1}{h_m A} + \rho_{v,b}}{\rho_{v,sat}} \right] \quad (4)$$

Under the REA-approach the dependence of activation energy of the product moisture content is provided as normalized relationship

$$\frac{\Delta E_v}{\Delta E_{v,b}} = f(X - X_b) \quad (5)$$

where  $f$  is a function of the water content difference, and  $\Delta E_{v,b}$  is the ‘equilibrium’ activation energy representing the maximum value of  $\Delta E_v$  under the specified humidity  $RH_b$  and temperature  $T_b$  of the operating ambient air

$$\Delta E_{v,b} = -RT_b \ln(RH_b) \quad (6)$$

A perfect mixing assumption implies that rate of dehydration is equally assigned for all  $N$  uploaded apple rings. A shrinkage effect due to reduction of the apple rings surface area during the drying process was accounted for by the following correlation (Putranto, A, Chen, XD, & Webley PA 2011)

$$A = A_0 \left[ \frac{\rho_w + \rho_s X}{\rho_w + \rho_s X_0} \right]^{\frac{2}{3}} \quad (7)$$

where  $A_0$  is the value of the initial surface area of the single fresh cut apple ring ( $\text{m}^2$ ),  $X_0$  is initial water content on dry basis,  $\rho_w$  is density of water ( $\text{kg}\cdot\text{m}^{-3}$ ), and  $\rho_s$  is the density of the dried apple solids ( $\text{kg}\cdot\text{m}^{-3}$ ).

The averaged bulk water vapour concentration in the dehydrator,  $\rho_{v,b}$  is obtained as a result of a completed mixing of the water vapour of concentration  $\rho_{v,in}$  carrying into the apparatus by the operating airstream  $Q$ , and water evaporating from  $N$  apple rings

$$\rho_{v,b} = \frac{\rho_{v,in} \cdot Q + N \cdot A \cdot h_m \cdot \rho_{v,s}}{N \cdot A \cdot h_m + Q} \quad (8)$$

When the convective drying process is carried out by running of the ambient air through the dehydrator, the average temperature of the gaseous medium inside the apparatus,  $T(t)$  (K), is lowered in relation with the inflowing air temperature,  $T_{amb}$  (K), due to heat consumption for evaporation of water from  $N$  apple rings:

$$T(t) = T_{amb} + \frac{dX}{dt} \cdot \frac{m_s \cdot \lambda \cdot N}{c_p \cdot \rho_{amb} \cdot Q} \quad (9)$$

where  $\lambda$  is the latent heat of water vaporization ( $\text{J}\cdot\text{kg}^{-1}$ ),  $c_p$  ( $\text{J}\cdot\text{kg}^{-1}\text{K}^{-1}$ ) is the specific heat capacity of air,  $\rho_{amb}$  ( $\text{kg}\cdot\text{m}^{-3}$ ) is the air density at the inlet of the dehydrator,  $Q$  ( $\text{m}^3\text{s}^{-1}$ ) is the volumetric flow rate of the operating air stream through the apparatus.

In the case when the air heater of  $\dot{q}$  (W) power is operated in the dehydrator, the Eqn. (8) is replaced with

$$T(t) = T_{amb} + \frac{(dX/dt) \cdot m_s \cdot \lambda \cdot N + \dot{q}}{c_p \cdot \rho_{amb} \cdot Q} \quad (10)$$

For the 6 mm thick rings of Golden Delicious variety apples the dimensionless function  $f$  in Eqn. (5) under the present computing model was approximated as

$$f = \exp[-0.60 \times (X - X_b)] \quad (11)$$

As to another key input value, the value of the mass transfer coefficient  $h_m$ , this was determined in customized experiments with application of the wetted rings fabricated from the porous floral foam material (Spotar, Kopbayev, & Saliyeva 2019).

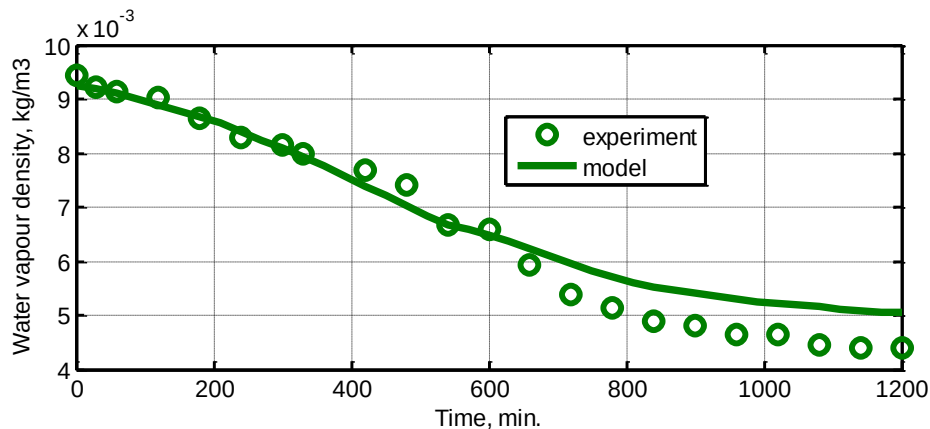
Numerical solution of the described with Eqns. (1-11) has been carried out using the COMSOL Multiphysics® v.5.5 package, ‘the ODE and DAE interfaces’ tool with application of the ‘Time-Dependent Study’ solver.

## 2. RESULTS AND DISCUSSION

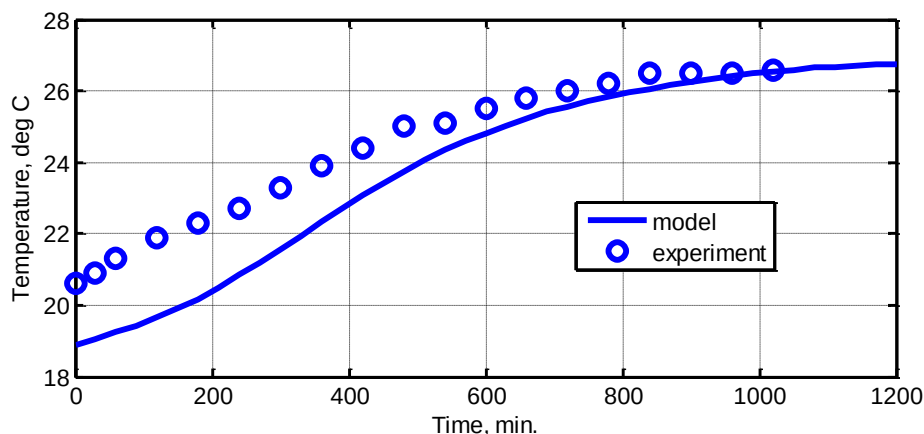
The representative outcomes from the tests and modeling are shown in Fig. 5-8. The temporal change of the air temperature and water vapour density under dehydration is given in Fig. 5 and Fig. 6. Herewith the plotted experimental data represent the readings of temperature and humidity from the *Testo 610* portable humidity meter which was being placed at the fan outflow. Although such observational data are not an accurate measurement of outlet stream temperature and humidity, nevertheless, the behavior

trend of these readings cohere with the models curves, thus concur with the assumption of completeness of mixing in the bulk of the vortex dehydrator.

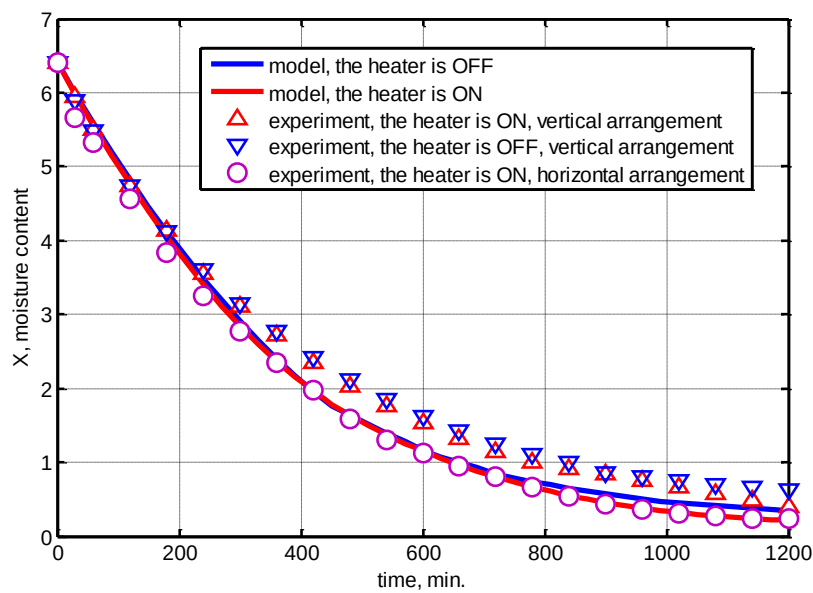
The most important characteristics of the dehydrating process are drying curves  $X=X(t)$ . The typical drying curves of 20 hours dehydration process are plotted in Fig.7. These drying curves are of exponential shape which is typical for the convective drying of apples and many other products. In 4 hours, apple rings are losing about 50% of the free water, in the following the rate of process is retards since increase of mass transfer resistance in delivering the water from the ring interior to the surface. Around here, it is worth to point out the impact of the 'packaging' factor on the rate of the dehydration process. The observed deviation in the drying rate of the rings assembled in the horizontal rows or in the vertical columns appears not at the beginning of drying but after several hours of the process. The explanation of the above difference can be attributed to the channeling effect. At the beginning of the drying the overlapping apples rings prevents a straightforward bottom-top air flow, upon a while, shrinkage of apple rings fixed along the vertical supports leads to formation of vertical channels for the upstream shortcut air paths. When the apple rings are assembled onto the horizontal bars overlapping each other (Fig. 3a) or are placed onto the grating shelves (Fig.4), the above negative 'packing' factor is being neutralized and the regime of a homogeneous air mixing in the apparatus is achieved. In this case the agreement of the modeled drying curve with experimental data is good.



**Fig. 5.** Water vapour density at the exit of the dehydrator operating using air of 20% RH and 26°C

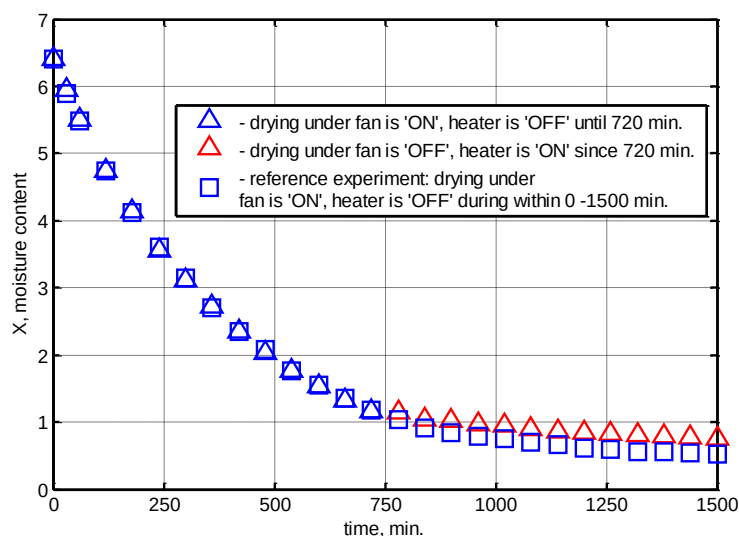


**Fig. 6.** The temperature at the exit of the dehydrator operating using air of 20% RH and 26°C



**Fig. 7.** The characteristic drying curves for dehydration of apple rings

Both modeling and tests data show that the activation of low-power (14W) heater does not exhibit a noticeable impact of the drying rate during the first 6 – 7 hours of drying, but in the following, some intensification of the drying rate is observed (Fig.7). Normally, it is appeared when the moisture content is reduced to the value of 2 and lower. As a matter of fact, the incorporation of this heater into the dehydrator prototype was not motivated by intention to augment the rate of drying, but a want to overcome a well-known complaints of customers on the rather noisy operation of the conventional commercial domestic dehydrator. Indeed, when a typical drying process lasts more than half of day, it is a commonest situation to continue the operation of the utility in the night, but then the noise of the fan becomes a nuisance for humans which is not surprising. The results on Fig. 8 illustrate the mentioned alternative hybrid regime of drying of apple rings, the obtained results correspond to same product load (1.8 kg). The experiments have been carried out at  $\approx 26^{\circ}\text{C}$  ambient air temperature and  $\approx 20\%$  relative humidity; the reference experiment represents the change of the product moisture contents convection air flow driven by the fan, in the second case at the fan was off at 720 min. of operation, but the heater was switched on. In this case drying became slower, but when it comes to domestic application of the vortex dryer, when the fan noise might be a nuisance in the nighttime, a potential customer might prefer to select a noiseless alternative regime. Appositely, it worth be noted that the declared employment of the film heater is a convincing manifestation of a free convection phenomena as a heat engine (Tritton 1988, p.179).



**Fig. 8.** The drying curves showing the effect of the fan replacement with the film heater

It is worth to recall that the drying operation time depends substantially of the apple ring thickness, the results in Fig. 7 and 8 refer to slice of 5mm, whereas 8mm slice thickness require about 30 hours operation. The dimensionless activation energy function (11) is subject to renewal when modeling of the process with a different geometry or physical properties (say, another apple variety). In practice, termination of drying does not imply the removal of all free moisture, moreover the thermodynamics mechanism of natural equilibration is recommended (Defraeye 2017) when the energy saving consideration.

The energy saving estimation of the drying process the with the vortex dehydrator should be considered side by side to the apparatus operation limits, namely, the drying process implies usage of ambient air of low or moderate humidity, the difference of water vapour concentration between the convective flow and the product surface is manifested as a driving force of the process. The following illustrating numbers refer to the 1500 min. drying of 1.8 kg of apples rings using ambient air of 20% humidity, the final weight was  $\approx 0.340$  kg, hence 1.46 kg of water has been removed. The evaporation of 1.46 kg of water requires  $3.6 \times 10^3$  kJ of energy input, whereas the apparatus consumption of mechanical energy to operate the axial fan is  $18W \times (1500 \times 60) s = 1.62 \times 10^3$  kJ only.

### 3. CONCLUSIONS

Drying operation for obtaining the apple rings snacks using the proposed version of vortex dehydrator has been investigated. The addressed vortex dehydrator intakes working ambient air under negative gage pressure developed by the fan, the vortex flow pattern is generated by 4 embodied input ducts located at the bottom of the apparatus. The advantageous performance of the presented apparatus is attained with usage of ambient air of low humidity and an adequate distribution of loaded apple rings. The hybrid version of the apparatus implies a generation of a buoyancy driven convection to ensure a noiseless running.

### ACKNOWLEDGMENTS

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