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Carrageenan drying with dehumidified air: drying characteristics and product quality

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Abstract

Applying dehumidified air is considered as an option to retain quality in carrageenan drying. This work concerns the effects of operational temperature, air velocity, and carrageenan thickness on the progress of drying and product quality when using dehumidified air. Final product quality and progress of drying were measured by experiments, and a two dimensional model was developed to analyze progress of drying for the different operational conditions. The experimental and modeling results showed that air dehumidification with zeolite reduces the drying time the most at low temperatures. Under these conditions the carrageenan qualities whiteness and gel strength are the least affected by the exposure to the drying temperature. The drying time is the shortest at 120°C, but at this temperature the carrageenan quality degrades the most and is not be improved by air dehumidification. Moreover, the quality is improved by increasing the air velocity and by drying thin carrageenan sheets.

KEYWORDS: carrageenan, dehumidified air, quality, zeolite

1. Introduction

Carrageenan is a sulfated polysaccharide isolated from red seaweed, *Euchema cottoni.* Carrageenan is a prominent component for the food and pharmaceutical industry where it is used as stabilizer, edible coating and thickener [1,2,3].

Isolation of carrageenan from sea weed takes four steps: 1) extraction by alkali, 2) filtration, 3) precipitation with isopropanol, and 4) drying [4,5,6]. In the extraction step, the 6-sulfated galactosyl units are converted into the corresponding 3,6-anhydride by hot alkali. The conversion rate depends on temperature, alkali concentration and ionic strength of the medium. The mixture is filtered and the filtrate is precipitated with iso-propanol. After drying of the solids carrageenan is ready for use.

Carrageenan has a strong affinity to water and the final product qualities are formed in the drying step. Thommesa et al (2007) [3] found that the drying time for carrageenan is reduced by drying at higher temperatures, but with this treatment the product quality was also lower. Carrageenan degrades when exposed to temperatures above 70°C [6]. Tari and Pekcan (2007) [7] measured the activation energy of drying (53.9 kJ/mol) and depending on the temperature carrageenan samples shrink up to 70-80% of their initial volume. The drying time of carrageenan at 50°C is about 5 hours [7]. Moreira et al (2011) [8] found that the drying time for biofilms made of starch and carrageenan can be speeded up by using high air flow rates; the drying time is reduced to 2-3 hours at medium temperature drying. However, this method is not yet applied for pure carrageenan [8].

Low and medium temperature drying is important to retain quality. To reduce the drying times under these conditions the driving force for water transfer has to be increased. The driving force is enhanced by: 1) reducing the humidity of air, 2) decreasing air pressure, or by combinations of these two [9]. Drying equipment that operates at low pressure (partial or vacuum) request considerable extra costs for energy and investments [9,10].

Air dehumidification improves the driving force for drying and allows drying at low and medium temperatures at atmospheric pressure [9,10]. The conventional method to obtain dehumidified air is to cool air below dew point where vapor condenses. The cold and dry air is then heated up to the drying temperature. This method is, however, energy inefficient [11].

Adsorption drying with zeolite is another option for air dehumidification in carrageenan processing. In this system, air is dehumidified by passing through a bed of activated zeolite. As a consequence the driving force for drying increases and also the air temperature increases due to the release of adsorption heat. The dried air is fed to the dryer for evaporating water from the product. Djaeni et al. showed that dryers operating at 40-60°C reach an energy efficiency up to 90%,

which is 30-40% above that of conventional dryers [9,11]. These drying temperatures are below the temperatures where carrageenan is subject to gelatinization and caramelization.

This work concerns the application of an adsorption dryer for carrageenan drying with air dehumidification by zeolite. The effect of temperature, air velocity, and carrageenan thickness on drying performance and carrageenan quality is experimentally evaluated. The experimental results are compared by a 2D spatial model for the moisture and temperature profiles in the product, which can be used for analysis. process design and feasibility studies.

2. Materials and methods

2.1. Activation of natural zeolite

Zeolite is an alumino-silicate structure of AlO_4 and SiO_4. SiO_4 is neutral in charge and AlO_4 negative in charge. The negative charge is compensated by positive ions which give the zeolite the ability to adsorp water. The ability for water adsorption is a function of the Si/Al ratio, the surface area, and the pore size [12,13,14]. Zeolite is available as an engineered product but is also available as an natural product (clay and stones). For adsorbing water a pore size of 3-4Å is required. Natural zeolites have an inhomogeneous pore structure, contains organic and an-organic impurities and have a high Si/Al ratio. Therefore the adsorption capacity of natural zeolite is below that of artificial zeolite (0.080 compared to 0.200 gr water/gr zeolite). However, the performance of natural zeolite can be increased by activation [12,13].

To activate natural zeolite, zeolite stones were milled and sieved to obtain uniform particles of 2 mm [14, 15,16]. The particles were mixed with a KOH solution in a ratio of 1 weight unit of zeolite to 4 weight units KOH. The mixture was stirred at $90^{\circ}C$ for 2 hours. The zeolite was separated from the solution by filtration, washed with water and dried at $110^{\circ}C$ for 4 hours. The zeolite was cooled in a desiccator and the water loading capacity was tested for a range of relative humidities. The structure of the activated zeolite was visualized by scanning electron micrograph (SEM). The procedure was applied for KOH concentrations in the range 0.5-2.0 N and temperatures 60-90°C.

The structure of the zeolite before and after activation is given in Figure 1. With the KOH treatment impurity ions are substituted by K+ ions, and a regular structure of the zeolite is obtained. A 2 hour treatment with 1.0N KOH at 70-80°C increased the water adsorption capacity in the natural zeolite to 0.160-0.170 gr water/gr zeolite. This is a significant improvement compared to the water adsorption capacity of 0.080-0.090 gram water/gr zeolite for untreated zeolite.
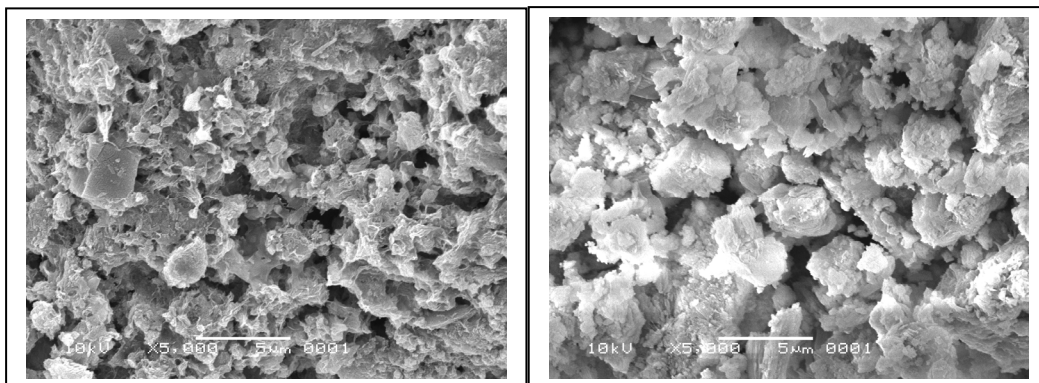
Figure 1: Natural zeolite. a) Before activation with a coarse structure. b) After activation by KOH the zeolite has a regular structure

2.2. Experimental procedure for carrageenan drying

The experiments were performed in a tray dryer equipped with a unit for air dehumidification with zeolite (see figure 2 for a schematic view and photograph). Ambient air with relative humidity (RH) between 70-80% and temperature between 29-33°C passed the adsorber column (suppose A) which contains the activated natural zeolite (1.5 kg/column, particle size 2 mm). About 70-80% of water in air is removed, and the air temperature increases 5-10°C due to the release of adsorption heat. Next, the dehumidified air was heated to the chosen drying temperature. The hot air was fed to the dryer where water evaporates from the wet carrageenan sheets with initial water content of 82%. For the standard experiments carrageenan sheets with 2 mm thickness and 6×6 cm were used. When the zeolite approaches saturation the adsorption function was switched to column B and zeolite in column A was regenerated at 200°C.

Water content in carrageenan, air temperature, humidity and velocity were measured every 15 minutes, The water content in carrageenan was measured by weight measurement, air conditions (ambient air, air at the exhaust of the adsorber, air entering and leaving the tray dryer) were measured by combined temperature and relative humidity sensors (in figure 2 indicated with T-RH1,2,3 ; humidity and temperature sensor KW0600561, Krisbow®, Indonesia), the air flow velocity was measured with an anemometer (in figure 2 represented by F1, thermo-anemometer KW0600562, Krisbow ®, Indonesia). The product quality indicators whiteness and gel strength were analyzed after drying with a brightness and color meter 68-50 (TMI, USA) and texture analyzer type TA1 (LLOYD Material Testing, UK). After about 180 minutes drying was stopped and data was processed. The drying process was repeated for various operational variables: temperature 40,60,80 and 120°C, carrageenan thickness 1, 2 ,3 and 4 mm, and the air velocity in the dryer is 0.1-0.2 m/sec (adjusted by valve VF1)
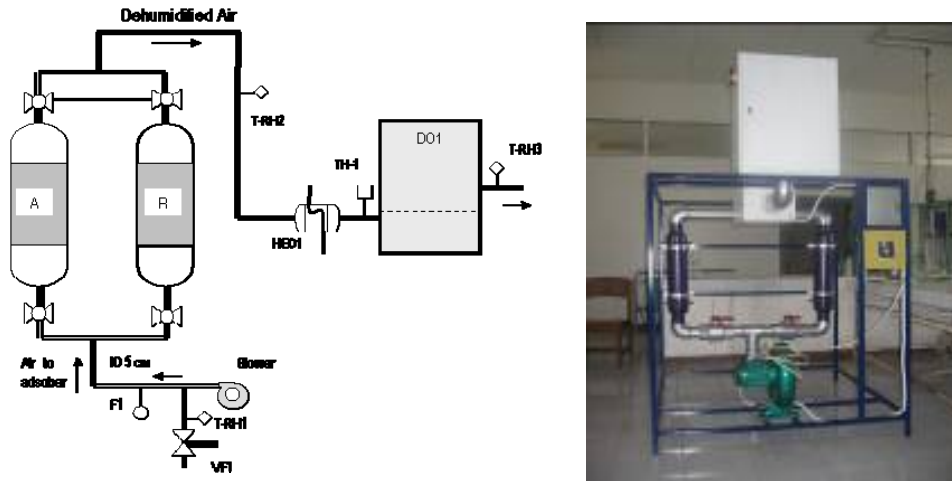
Figure 2: Schematic overview and photograph of the experimental equipment. Internal diameter of columns A and B is 0.12 m, diameter of piping is 0.05 m, tray dryer size 0.40x0.25x0.60 m

2.3. 2-D Modeling carrageenan sheets drying

Carrageenan is dried in tray dryers by placing sheets with a given thickness horizontally at a perforated plate (see figure 4). Drying air, homogenously distributed over the cross sectional area of bottom dryer, flows from the bottom to the top of dryer. Hereby sensible heat is transferred from the air to the product, water evaporates from the surface and water diffuses from the centre of the product towards the surface. Similarly, energy is transferred towards the centre of the product by conduction.
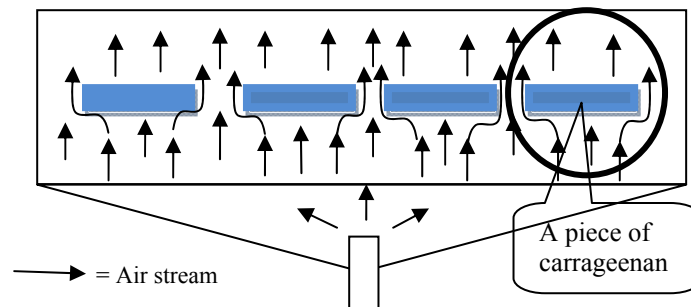

Figure 4: Carrageenan at the drying tray in the experimental dryer. The air flows around the sheets of carrageenan.

Because of the symmetry of the square sheets of carrageenan, mass and heat transfer in the sheets of carrageenan and the drying air are considered as a combined two-dimensional system as illustrated in figure 5. The model is based on the following assumptions:

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1. The distribution of temperature and water content is 2-dimensional (x and y direction)
2. Pressure drop over the equipment is neglected
3. The system is adiabatic; i.e. no heat exchange with the environment
4. Physical properties as density, specific heat, and heat conductivity remain constant
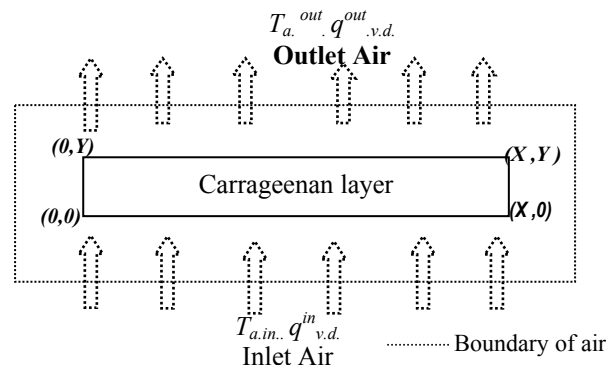5. The air is homogenously distributed

Figure 5: Carrageenan-air system in the dryer, T=Temperature (°C), q= water content. Carrageenan sheet coordinates are defined as: $x=0$ to X and $y=0$ to Y.

Water balance in carrageenan and air

The 2-D model concerns two phases; the product and the air. Both phases are connected by the boundary conditions (see equation 2,4,6 and 8) at the interface of product and air.

Water transport in a sheet of carrageenan is driven by diffusion [17]:

$$\frac{dC_{w,p}}{dt} = D_w\,{}^2C_{w,p} \tag{1}$$

with boundary condition at the surface (x and y directions) of the sheets:

$$-D_w\frac{dC_{w,d}}{dx} = -D_w\frac{dC_{w,d}}{dy} = k(C_{v,surf} - C_{v,a}) \tag{2}$$

Water transport in air is a combination of diffusive and convective transport [17]

$$\frac{dC_{v,a}}{dt} = D_v\,{}^2C_{v,a} - v_a\,C_{v,a} \tag{3}$$

with boundary condition at the surface (x and y directions) of the sheets:

$$- D_v \frac{dC_{v,d}}{dx} = -D_v \frac{dC_{v,d}}{dy} = -k(C_{v,surf} - C_{v,a}) \tag{4}$$

In these equations is D_w the diffusivity of water in carrageenan ($m^2.s^{-1}$), D_v the diffusivity of water in air ($m^2.s^{-1}$), v_a the linear air velocity ($m.s^{-1}$), $C_{w,p}$ and $C_{v,a}$ the water content in product and air (kg water per kg dry material), k the mass transfer coefficient ($m.s^{-1}$), $C_{v,surf}$ and $C_{v,a}$ the water vapor concentration at the carrageenen surface (kg moisture/kg dry air), and t the operational time (s). All values are specified in appendix A.1. The initial condition concerns an equal water distribution throughout the sheet of carrageenan and is given in the appendix table A.2 .

Energy balance

Energy transport in carrageenan is driven by conduction [17]:

$$\rho_p cp_p \frac{dT_p}{dt} = \lambda_p \, ^2T_p \tag{5}$$

At the product surface (x and y direction) energy transfer occurs due to convection and evaporation of water, which results in the boundary condition:

$$- \lambda_p \frac{dT_{p,d}}{dx} = -k_p \frac{dT_{p,d}}{dy} = h_d(T_a - T_p) - \Delta H_v \rho_p D_w \, C_{w,p} \tag{6}$$

The energy balance in the air is a combination of conductive and convective energy transport [17]:

$$\rho_a cp_a \frac{dT_a}{dt} = \lambda_a \, ^2T_a - F_a \rho_a cp_a \, T_a \tag{7}$$

with the boundary condition for air at the product surface:

$$- \lambda_a \frac{dT_{a,d}}{dx} = -k_a \frac{dT_{a,d}}{dy} = -h_d(T_a - T_p) \tag{8}$$

with T_p and T_a the temperature of air and carrageenan ($^\circ$C), F_a the air flow rate ($kg.s^{-1}$), ρ_a and ρ_p the density of air and carrageenan ($kg.m^{-3}$), cp_a and cp_p the specific heat of air and carrageenan ($J.kg^{-1}.^\circ C^{-1}$), λ_a and λ_p the heat conductivity of air and carrageenan ($J.s^{-1}.m^{-1}.^\circ C^{-1}$), ΔH_v the heat of water evaporation ($J.kg^{-1}$), and h_d the heat transfer coefficient ($J.s^{-1}.m^{-2}.^\circ C^{-1}$). All values are specified in appendix

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A.1. The initial condition concerns an uniform temperature distribution throughout the sheet of carrageenan; see appendix table A2.

Additional relations

The equilibrium moisture content for carrageenan is given by the GAB equation [18]:

$$C_{e,p} = \frac{BDKa_w}{(1 - Ka_w)(1 - Ka_w + BKa_w)} \qquad (9)$$

with *B, D, K* the GAB constants for carrageenan [18], a_w is the water activity which is assumed to be equal to the relative humidity (*RH*).

The water diffusivity in carrageenan is related to the product temperature. For a sheet of carrageenan with thickness 1-5 mm the Biot number is in the range 0.2-1.0, which indicates that the product temperature approximates the air temperature. The temperature relation of the water diffusivity in the product is then given by:

$$D_w = D_{Tref} \exp^{\frac{-E_a}{R}(\frac{1}{273.15+T_a} - \frac{1}{273.15+Tref})} \qquad (10)$$

with D_{Tref} the water diffusivity in carrageenan (m^2.s^{-1}) at reference temperature T_{ref} (°C), E_a the activation energy (J.kmol^{-1}), *R* the gas constant (8.314 J.mol^{-1}. K^{-1}), and T_a the air temperature (°C) which is representative for the product temperature.

The Sherwood number for forced convection around square obstacles is [19]:

$$Sh = 0.3 + \left(\frac{0.62 \, Re^{1/2} \, Sc^{1/3}}{(1 + (\frac{0.4}{Sc})^{2/3})^{1/4}} \right) \left(1 + (\frac{Re}{282000})^{5/8} \right)^{4/5} \qquad (11)$$

with *Sc* and *Re* respectively the Schmidt and Reynolds number (see appendix A.3a). Using the vapor diffusivity in air D_v (m^2.s^{-1}) for a range of temperatures (Montgomery [25], see also appendix table A.1) gives the mass transfer coefficient from air to product (k (m.s^{-1})) from:

$$Sh = \frac{kL}{D_v} \qquad (12)$$

with *L* the characteristic length of a carrageenan sheet (m):

$$L = \frac{sample\ volume}{sample\ surface} \tag{13}$$

Estimated values for the mass transfer coefficient are given in the appendix, tables A3a and A3b. The Nusselt number for forced convection around obstacles is linked to the Reynolds and Prandtl number (*Pr*) [20, 21]:

$$Nu = 0.3 + \left(\frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{(1+(\frac{0.4}{\mathrm{Pr}})^{2/3})^{1/4}} \right)\left(1+(\frac{\mathrm{Re}}{282000})^{5/8} \right)^{4/5} \tag{14}$$

With the heat conductivity coefficient for air λ_a (J.s^{-1}.m^{-1}) for different temperatures (Montgomery [25]) follows the heat transfer coefficient h$_d$ from:

$$N_u = \frac{h_d L}{\lambda_a} \tag{15}$$

The estimated convective heat transfer coefficient is given in the appendix table A.4.

3. Results and Discussion

3.1 The effect of zeolite on drying carrageenan

Experimental differences between drying with and without air dehumidification at 40 and 60°C are given in figure 6. The results show that carrageenan dries at both temperatures faster with the dehumidified air. At these temperatures the vapor pressure is effected the most by dehumidification. The advantage is the strongest till 120 minutes. From that time the drying rate is dominated by the difference between actual and equilibrium moisture content which, for both drying methods, don't differ so much in the end phase of drying; the curves approach each other.

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a.

b.
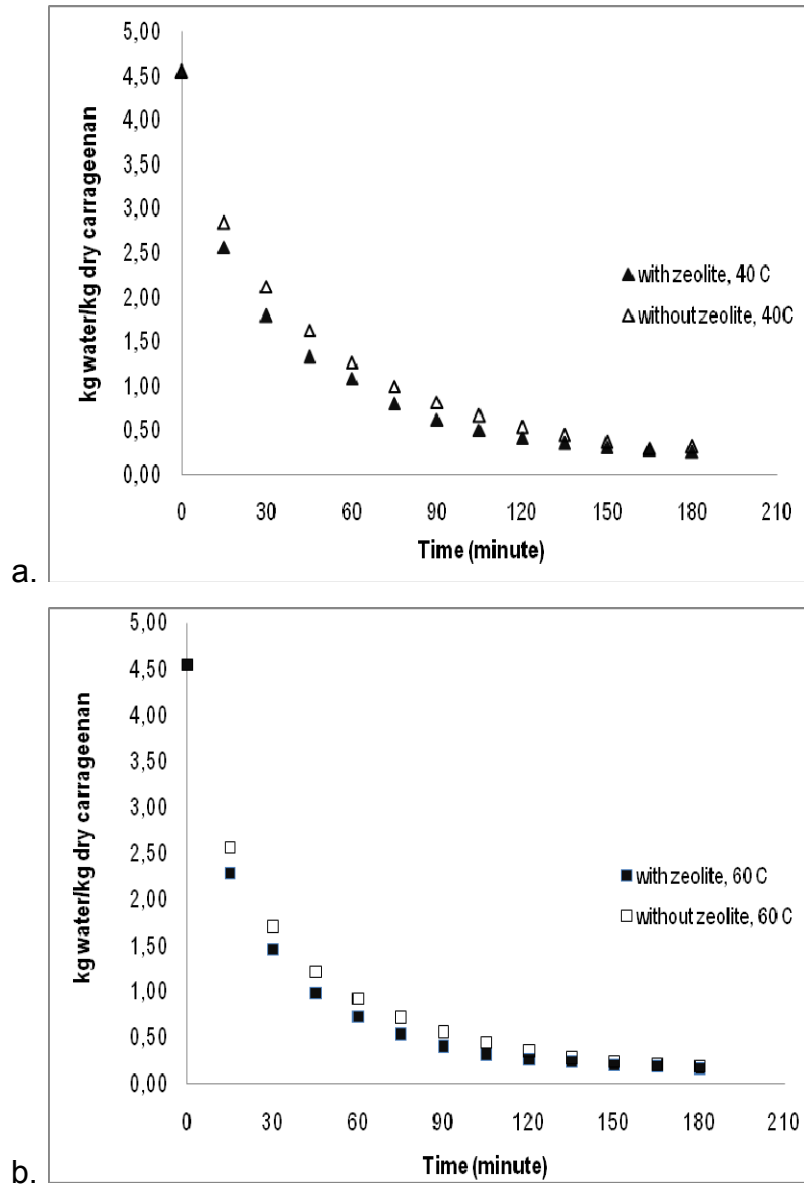
Figure 6: Comparison of progress of drying with and without zeolite at operational temperature. a) 40 ^{o}C, b) 60°C. Air velocity in dryer 0.13 m.s^{-1}, carrageenan sheets of 6×6 cm and 2 mm thickness

3.2 The effect of operational temperature

Experimental results for different operational air temperatures of dehumidified air are given in Figure 7. The results show a significant increase in drying rate and a reduced drying time for the higher temperatures. The time needed to dry

carrageenan with dehumidified air till 10% is shorter than the time for carrageenan drying reported by Tari et al. [7] at 40°C.

Boudhrioua et al. [22] estimated the water diffusivity from succeeding data points by using:

$$\ln(\frac{C_{e,p} - C_{w,p}}{C_{e,p} - C_{e,0}}) = \ln(\frac{8}{\pi^2}) - \frac{\pi^2 D_w t}{l^2} \tag{16}$$

Applying equation 15 for the data in figure 6 and 7 yields the water diffusivity values given in table 1. From the data, equation 10 and using the air temperature as an approximation for the product temperature (Biot-number below 1) follows 5502 J.mol^{-1} as activation energy (E_a). The Sherwood number and the mass transfer coefficient vary with temperature; the values are given in table 1.

Results for quality measurement are also given in table 1. Gel strength is the required load to break the polymer matrix. A high gel strength is preferred for industrial use of carrageenan. Increasing the drying temperature reduces the gel strength from 116 gr.cm^{-2} to 63 gr.cm^{-2}. At the higher temperatures the carbon chains in the carrageenan matrix are split and break down. The whiteness of the product gradually reduces with the operational temperature due to Maillard reactions at medium temperatures and caramelization reactions at higher temperatures [3,23]. Despite the longer drying time low drying temperatures are preferred to keep quality of carrageenan.

Table 1: Water diffusivity, whiteness and gel strength of carrageenan at different temperature. Carrageenan sheets of 6×6 cm, 2 mm thickness.

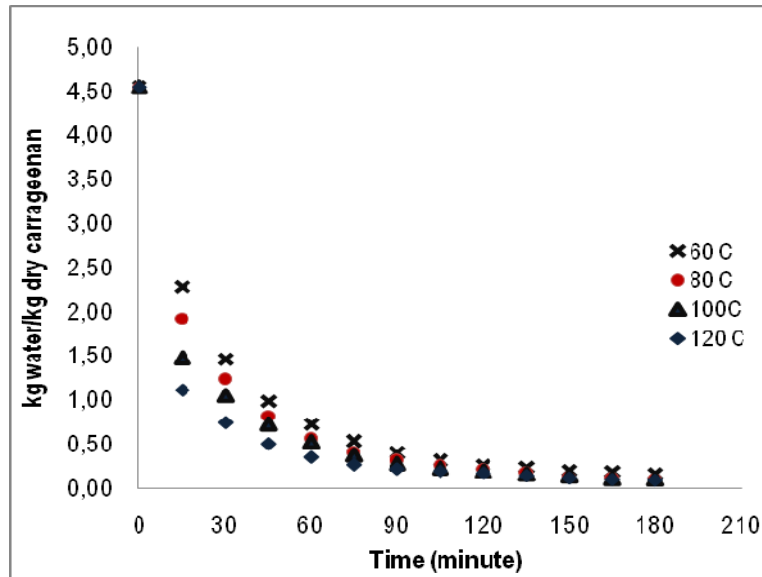| Temperature °C	D_w x10^{-10} m^2.s^{-1}	D_v x10^{-5} m^2.s^{-1}	Sh number	k x10^{-3} s^{-1}		Whiteness	Gel strength gr.cm^{-2}
40	1.14	2.85	10.13	4.83	From equation 10 E_a = 5502 J.mol^{-1}	53	116.0
60	1.47	3.24	9.56	5.16		50	105.1
80	1.53	3.66	9.03	5.51		44	98.8
100	1.63	4.15	8.53	5.89		40	87.5
120	1.74	4.67	8.06	6.31		36	63.0

Figure 7: Water content versus time at different operational temperatures, air velocity in dryer 0.13 m.s^{-1} and carrageenan thickness 2 mm

3.3. Water and temperature profile

Applying equation 1-8, the values from table 1, assuming an uniform water and temperature distribution at time *t=0* and the material properties as given in appendix tables A.1 and A.2, drying is simulated with COMSOL Multiphysics Modeling and Simulation Software. Figure 8 presents the water profile in carrageenan and the water profile in the air at 180 minutes of drying. From the right scale in figure 8 follows that there is hardly a water concentration gradient in the air. So, the conditions around the product are constant, and as drying is diffusion driven moisture distribution in the product is nearly symmetric. The surface of these simulated 1×1 cm pieces carrageenan achieved a moisture content of 0.1 kg water/kg of carrageenan while the moisture content in the centre is around 0.35 kg water/kg of carrageenan. Similar results were obtained for carrageenan sheets of 6×6 cm (but not shown because of the readability of the picture). The simulated average moisture content for 6×6 cm sheets during drying at 40 an 80°C is given in figure 9. Comparison of the simulation results with experimental data (also given in figure 9) show that the model agrees well with the experiments.

Figure 8: Water profile in carrageenan and air after 180 minutes of drying at 40°C and air velocity 0.13 m/s around the sheets of carrageenan. Simulation concerns a piece of carrageenan of 1×1 cm and 2 mm thickness. The left bar presents the scale for the moisture distribution in the central square representing carrageenan, the right bar gives the scale for the water distribution in air in the surrounding square.

Figure 9: Average water content in carrageenan sheets (6×6 cm, 2 mm thickness) obtained from simulations and experiments at 40 and 80°C and air velocity dryer 0.13 m.s^{-1}.

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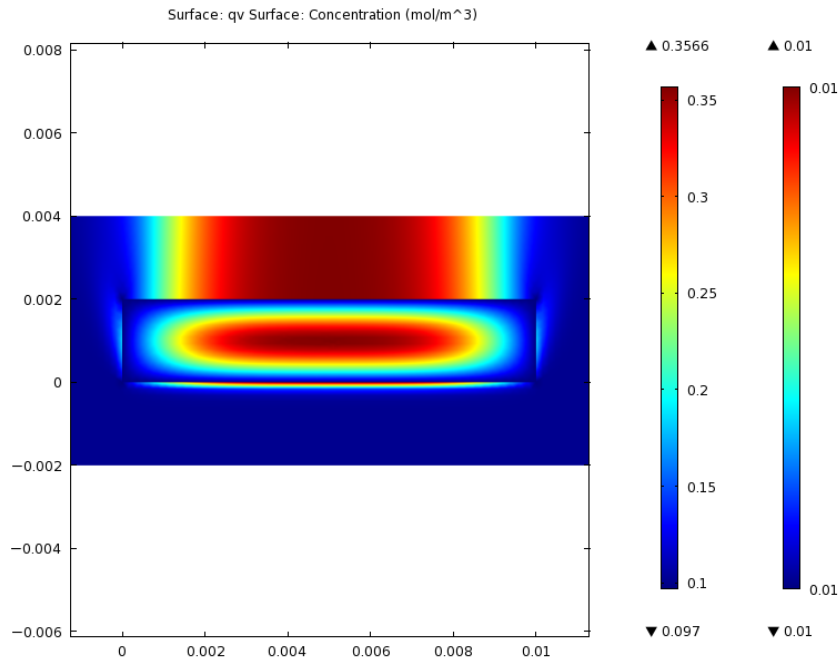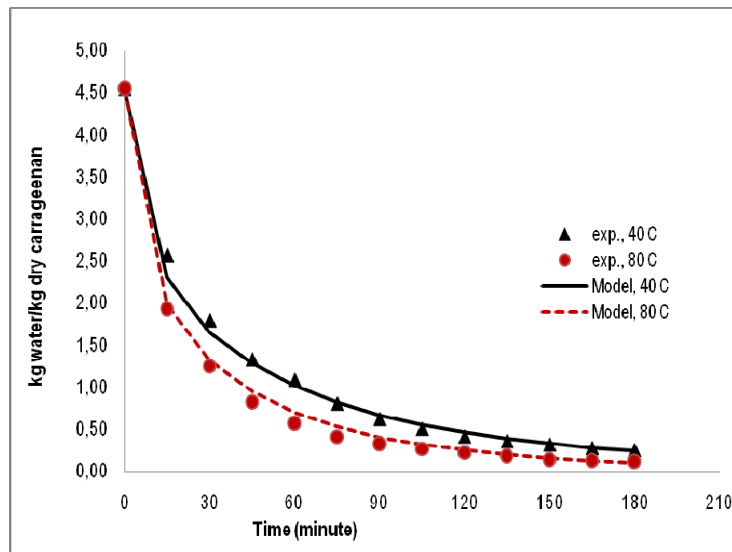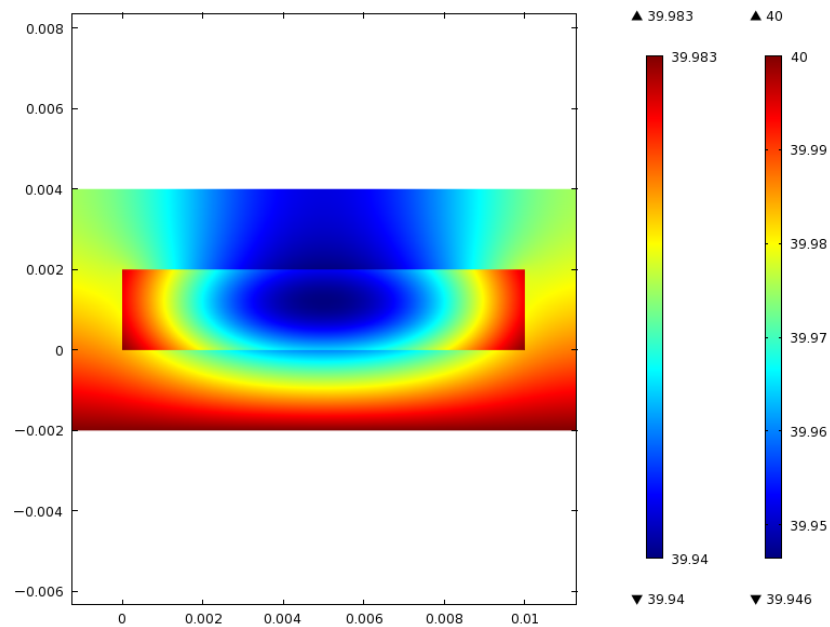**Figure 10**: Temperature profile in carrageenan and air after 180 minutes of drying at 40°C and air velocity 0.13 m/s around the sheets of carrageenan. Simulation concerns a piece of carrageenan of 1×1 cm and 2 mm thickness. The left bar presents the scale for the temperature distribution in the central square representing carrageenan, the right bar gives the scale for the temperature distribution in air in the surrounding square.

Figure 10 presents the temperature profiles in carrageenan and air after 180 minutes of drying. There is only a minor temperature gradient at this moment. This result confirms the statement, derived from the Biot number which is below 1, that the product temperature can be approximated by the air temperature. It indicates that heat transfer and conduction are fast.

3.4 The effect of air dehumidification

The model is used to analyze the impact of air dehumidification by zeolites. Figure 11 presents the average water content in carrageenan as a function of time during drying at different air temperatures and humidity. At low temperatures (40-60°C) drying is enhanced and the drying time can importantly be reduced. At these temperatures dehumidification affects the vapor pressure sufficiently to increase the driving force for drying.

Ambient air heated up till 80-120°C has a decreased vapor pressure and dehumidification has a minor effect on the driving force for drying. The curves for the average moisture content for these temperatures are close for the full drying time.
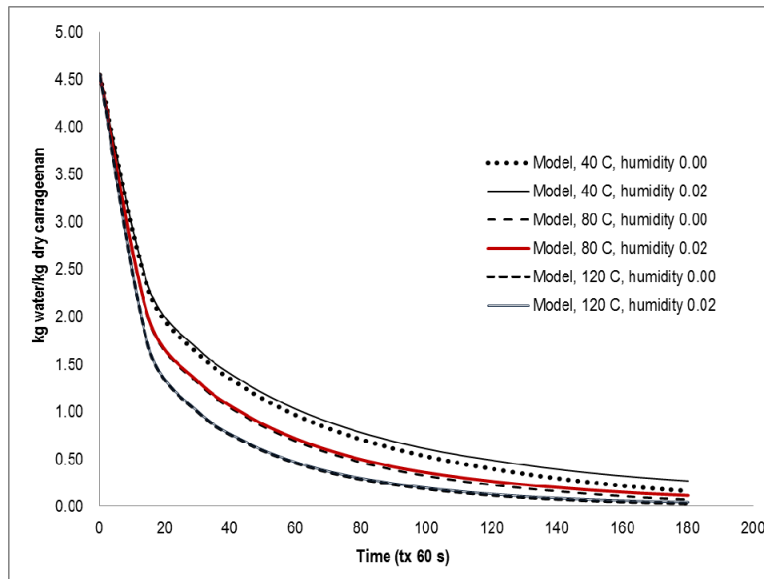
Figure 11: Simulated effect of air dehumidification on drying at various air temperatures and humidity (kg water/kg dry air). Carrageenan sheets of 6×6 cm, 2 mm thickness.

3.5 The effect of air velocity

The effect of air velocity in combination with air dehumidification on drying is given in figure 12 where the experimental average water content is given as a function of time for air velocities in the range 0.11 and 0.18 m.s^{-1}. The mass transfer coefficients for these velocities derived from the Sherwood number and product qualifications are given in table 2. As a validation of the model, figure 12 presents also the simulation results for the average water content. Again there is a good agreement of the model with the experimental results.

Table 2: Mass transfer coefficient and carrageenan quality obtained for drying at various velocities of dehumidified air at 80°C. Carrageenan sheets of 6×6 cm, 2 mm thickness.

air velocity in dryer v_a, m/s	Sh number	k x10^{-3} s^{-1}	Whiteness degree ,%	Gel strength gr.cm^{-2}
0.105	8.09	4.94	45	88.9
0.130	9.03	5.51	48	97.8
0.157	9.88	6.03	49	99.3
0.180	10.66	6.51	50	101.7

A higher air velocity affects the mass transfer at the surface and consequently the internal water transport. The final water content is reached at an earlier moment and therefore carrageenan is exposed for a shorter time to the drying temperature. As a result whiteness and gel strength (see table 2) improve

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for higher air flow rates. Increasing flow rate is thus a realistic option to improve the drying rate, to reduce the drying time and to improve quality[8].
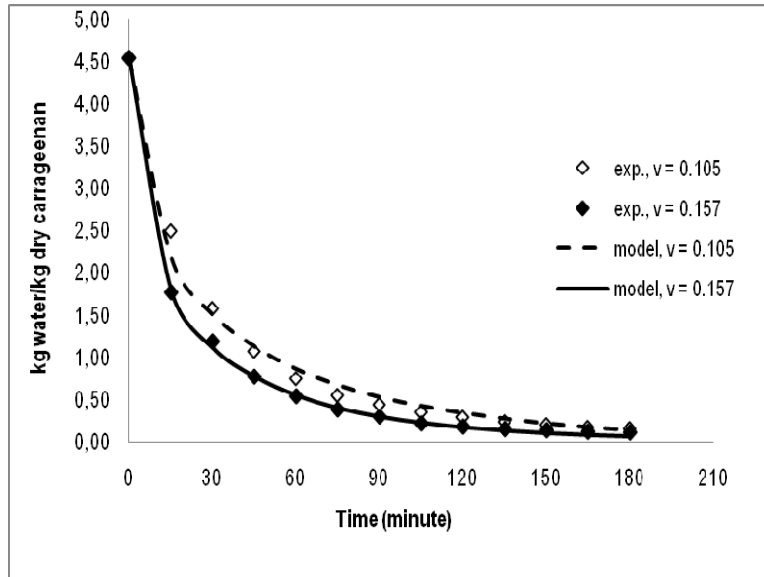

Figure 12: Average water content as a function of time (experimental and model) for velocities of dehumidified air 0.105 and 0.157 m.s^{-1}, temperature 80°C. Carrageenan sheets of 6×6 cm, 2 mm thickness.

3.6. The effect of carrageenan thickness

The total amount of water to be removed increases with the thickness of carrageenan sheets. In addition, the path length for water diffusion increases. Therefore for a given velocity of dehumidified air and operational temperature the time for carrageenan drying increases. Experimental and simulation results are given in figure 13, and product quality results in table 3. Again, product qualities, whiteness and gel strength, reduce due to the longer exposure to the drying temperature.

Table 3: Whiteness and gel strength for different sheet thickness of carrageenan dried with air velocity 0.13 m.s^{-1} and temperature 80°C

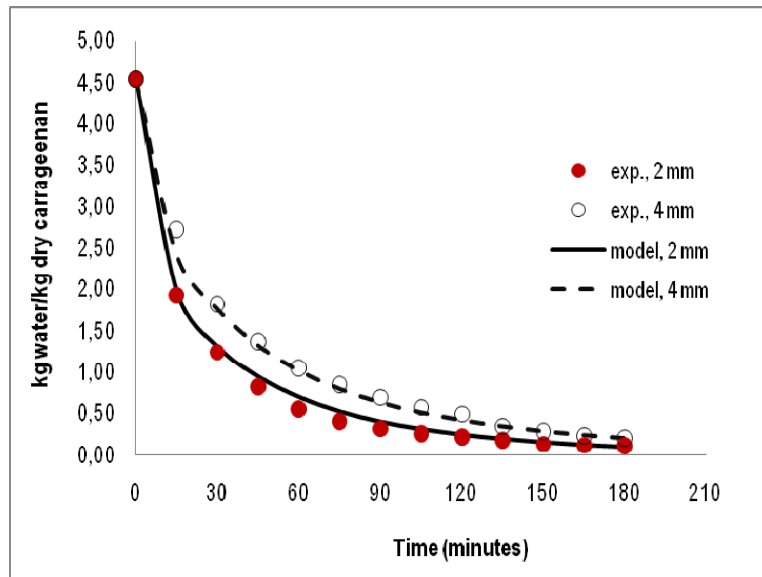| Thickness, m	Whiteness degree	Gel strength, gr.cm^{-2}
1.00x10^{-3}	50	102.0
2.00x10^{-3}	48	97.8
3.00x10^{-3}	46	91.4
4.00x10^{-3}	44	86.9

Figure 13: Average water content as a function of time (experimental and model) for sheets of 6×6 cm with different thickness during drying at air velocity 0.13 m.s^{-1} and 80°C.

4. Conclusion

Retaining quality is an important issue in carrageenan drying. Like in all food product a long residence time at high temperatures has a negative effect on the product quality. To reduce loss of quality it is proposed to dry with dehumidified air. This work considered by experimental work and 2D modeling the effects of air dehumidification with zeolite, air temperature and air velocity and the thickness on the quality of carrageenan sheets to be dried.

The 2D model, based on first principles was fitted to data obtained at 40°C. Extrapolation of the diffusion and mass transfer coefficients to other air temperatures, air velocities and sheet thickness resulted in good agreement with experimental data. Therefore the model is a valid simulation tool to analyze progress of drying, search for the best design of the systems and its operational conditions.

Experimental and modeling results showed that air dehumidification with zeolite reduces the drying time the most at low temperatures. Under these conditions the carrageenan qualities whiteness and gel strength are the least affected by the exposure to the drying temperature. Vapor pressure in air of 120°C is low and is hardly affected by dehumidification. Therefore drying at these temperatures is hardly enhanced by dehumidification. Increasing the air flow rate also enhances drying and contributes to a better quality. More water has to be removed from thick carrageenan sheets and therefore thick sheets require a longer drying time resulting in a quality which is below that of thin sheets.

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Applying air dehumidification with zeolite is a successful method to enhance drying, to reduce the drying time at low temperature drying and to improve product quality. This work was focused on product quality. System improvement with respect to process design, operational conditions and the potential for heat recovery to improve energy efficiency for this product is an additional challenge.

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Appendix

Table A.1: Used symbols and applied values

Notation	Parameter	Expression/value	Source
A_d	Cross sectional area of dryer (m^2)	0.15	
A_p	Cross sectional area of pipe (m^2)	0.002	
a_w	Water activity (-)		
B, D, K	GAB constants	23.3199; 0.1136; 0.8544	[18]
$cp_{a,0}$	Specific heat of dry air, (J.kg^{-1}.$^\circ$C^{-1})	1000	[17]
$cp_{v,0}$	Specific heat of vapor water (J.kg^{-1}.$^\circ$C^{-1})	1930	[17]
$cp_{w,0}$	Specific heat of liquid water (J.kg^{-1}.$^\circ$C^{-1})	4200	[17]
$cp_{p,0}$	Specific heat of dry carrageenan (J.kg^{-1}.$^\circ$C^{-1})	4000	[24]
cp_a	Specific heat of air (J.kg^{-1}.$^\circ$C^{-1})	$cp_{a,0}(1 + q_{v,a}cp_{v,0})$	
cp_p	Specific heat of product (J.kg^{-1}.$^\circ$C^{-1})	$cp_{p,0}(1 + q_{w,p}cp_{w,0})$	
D_v	Vapour diffusivity (m^2 s^{-1})	$0.223x10^{-5}\exp(0,006T_a)$	[25]
ΔH_v	Latent heat of water evaporation (J.kg^{-1})	$2.5x10^6$	
h_d	Heat transfer coefficient in air (J.s^{-1}.m^{-2}.$^\circ$C^{-1})	200	[26]
ID_p	Inside diameter of pipe (m)	0.05	
L_s	width of carrageenan sheets (m)	0.01 and 0.06	
l	Carrageenan thickness (m)	0.001-0.004	
P	Total pressure of air at 1 atm (101325 Pa)	101325 Pa (1 atm)	
RH	Relative humidity (-)		
X, Y	Width and thickness of carrageenan sheets	0.06×0.001-0.004 m in experiments and simulations 0.01×0.001-0.004 m in the graphs	
x,y	coordinates in length and height (m)		
λ_a	Heat conductivity of air (J.s^{-1}.m^{-1}.$^\circ$C^{-1})	0.023	[25]
λ_p	Heat conductivity of carrageenan (J.s^{-1}.m^{-1}.$^\circ$C^{-1})	0.494	[24]
μ_a	Dynamic viscosity of air (kg.m^{-1}.s^{-1})	$10^{-5}(1.85 + 0.003T_a)$	[25]
υ_a	Kinematic viscosity of air (m^2.s^{-1})	μ_a / ρ_a	[25]
ρ_a	Density of dry air (kg.m^{-3}) at 1 atm	$P/(287.05(T_a + 273.15))$	[17]
ρ_p	Density of dry carrageenan (kg.m^{-3})	1000	[24]

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Table A.2: Initial conditions for the calculations

Parameter	Initial value at t=0, for all x and y
Vapour in air dryer (kg vapour per kg dry air)	$C_{v,0} = 0.01$
Temperature of air in dryer (°C)	$T_{a,0} = 80$
Water in product dryer (kg water per kg dry product)	$C_{w,0} = 4$
Temperature of product in dryer °C	$T_{p,0} = 50$

Table A.3a: Estimation of mass transfer coefficient from carrageenan surface to air. Carrageenan sheets of 0.06×0.06×0.002m, air velocity 0.131 m.s^{-1} for various drying temperature

Air Temperature (°C)	D_v x10^{-5}, (m^2.s^{-1}) [25]	μ_a x10^{-5} (kg.m^{-1}.s^{-1}) [25]	υ_a x10^{-5} (m^2.s^{-1})[25]	(Sc)	Re	Sh	k x10^{-3} (m.s^{-1})
40.00	2.85	1.97	1.74	0.61	450.08	10.13	4.83
60.00	3.24	2.03	1.91	0.59	410.53	9.56	5.16
80.00	3.66	2.09	2.09	0.57	376.14	9.03	5.51
100.00	4.15	2.15	2.27	0.55	346.03	8.53	5.89
120.00	4.67	2.21	2.46	0.52	319.50	8.06	6.31

Table A.3b: Estimation of mass transfer coefficient from carrageenan surface to air. Carrageenan sheets of 0.06×0.06×0.002m, drying temperature 80°C for various air velocities.

Air velocity (m.s^{-1})	D_v x10^{-5} (m^2.s^{-1}) [25]	μ_a x10^{-5} (kg.m^{-1}.s^{-1}) [25]	υ_a x10^{-5} (m^2.s^{-1})[25]	(Sc)	Re	Sh	k x10^{-3} (m.s^{-1})
0.105	3.66	1.97	1.74	0.57	300.92	8.09	4.94
0.131	3.66	2.03	1.91	0.57	376.14	9.03	5.51
0.157	3.66	2.09	2.09	0.57	451.37	9.88	6.03
0.183	3.66	2.15	2.27	0.57	526.60	10.66	6.51

Table A.4: Estimation of convective heat transfer coefficient from air to carrageenan surface. Carrageenan sheets of 0.06×0.06×0.002m, air velocity 0.131 m.s^{-1}

Air Temperature (°C)	Air density (m^2.s^{-1}) [25]	μ_a x10^{-5} (kg.m^{-1}.s^{-1}) [25]	υ_a x10^{-5} (m^2.s^{-1})[25]	(Pr)	Re^2	Nu	h_d x10^{-3} (J.s^{-1}.m^{-2}.°C^{-1})
40.00	1.13	1.97	1.74	0.71	450.08	10.77	4.97
60.00	1.06	2.03	1.91	0.70	410.53	10.22	4.96
80.00	1.00	2.09	2.09	0.69	376.14	9.73	4.94
100.00	0.95	2.15	2.27	0.68	346.03	9.28	4.94
120.00	0.90	2.21	2.46	0.67	319.50	8.88	4.93