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Some design parametric considerations of cryogenic pre-cooler for spices grinding

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Abstract

Some design parametric considerations of cryogenic pre-cooler for grinding of spices (fenugreek and coriander seed) were studied. In conventional or ambient grinding of spices, temperature rise causes fat malting and sieve clogging. In grinding operation, spices lose a significant portion of their volatile oil or flavouring components due to rise in temperature. To overcome these drawbacks, cryogenic grinding is employed which is referred as the grinding of spices in the presence of a cryogenic fluid. A Cryogenic spice grinding system consists a pre-cooling unit (cryogenic pre-cooler) and grinding unit (grinder). The cryogenic pre-cooler plays very important role for cryogenic grinding of spices. Some design parameters of cryogenic pre-cooler (e.g. total freezing time, screw length and capacity etc.) were computed for grinding of fenugreek and coriander seed. Total freezing time is a one of the important deciding parameter for screw length. For constant values of screw diameter and pitch, the capacity and screw length of pre-cooler were computed at different speed (3, 6, 9, 12 and 15 rpm) of cooling screw of the cryogenic pre-cooler. It was found that the screw length and capacity of cryogenic pre-cooler for fenugreek and coriander seeds increased linearly with increase in cooling screw speed from 3 to 15 rpm.

Key words : Cooling, design parameters, grinding, spice

Introduction

India is the big house of spices i.e. black pepper, coriander, turmeric and cinnamon etc. The total production and export of spices were 6.17 MT and 1.489 MT, respectively (Anon., 2016). The spices are used in every house hold as the pungent flavour and the medicinal properties of spices. Grinding is an important unit operation in which the size of the particle is reduced and the surface area is increased resulting in increased availability of constituents present in the material (such as oil inside the cells, fragrance and flavouring components). The grinding of spices are age an old tradition for making powder.

Conventional grinding is the most power consuming process as 99% of the input energy is dissipated in rising the temperature of the ground product whereas only 1% is utilized for loosening bond between particles (Meghwal and Goswami, 2010). The temperature may rise to the extent of 42-93°C, which is responsible for loss of volatile oil and flavouring constituents. In case of high oil bearing materials, oil comes out during conventional grinding making the product gummy, sticky and hence choking of sieves through which product passes (Singh and Goswami, 1997; Barnwal *et al.*, 2014; 2015). Thermal damage is reported as one of the main limitations of conventional grinding process (Meghwal and Goswami, 2010), it was suggested to perform the grinding under controlled conditions. It was also suggested that better product can be obtained by reducing the temperature of two rubbing surfaces (Malkin and Guo, 2007). The temperature rise of the product can be minimized to some extent by circulating cold air or water around the grinder (Murthy *et al.*, 1996; Singh and Goswami, 1999). But this technique is not sufficient enough to significantly reduce the temperature rise of the product to a safe level and not affect its quality characteristics. Pruthi (1987) reported that the loss of volatile oil can be significantly reduced by cryogenic grinding technique. Thus, during the conventional grinding, the volatile oil, aroma and medicinal values are reduced, so the need of grinding of such spices at lower temperature using liquid nitrogen to retain the properties of spices.

The terminology 'cryogenics' is related with a Dutch physicist, Kamerlingh Onnes, who wanted to produce a gas in his laboratory that could be refrigerated. As per National Bureau of Standards, UK, cryogenic temperature

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has been defined as -150°C and below. Table 1 represents some thermo-physical properties of liquid nitrogen (LN_2) and liquid carbon dioxide (LCO_2). According to the definition, liquid nitrogen (boiling point -195.6°C) qualifies in cryogenic range, whereas carbon dioxide (boiling point -78.5°C) does not. However, in general, cryogenics is defined as a branch of engineering specializing in technical operations at very low temperature, generally below -50°C. Cryogenic liquids are those which boil at cryogenic temperature and atmospheric pressure. The word 'cryogen' was created to describe a low temperature boiling liquid. Liquid forms of hydrogen, helium, nitrogen, oxygen, inert gases, air, methane, carbon dioxide, etc are common cryogens. Liquid nitrogen (LN_2) and carbon dioxide (CO_2), in liquid or solid form, are the two major cryogens used for food applications.

The cryogenic grinding technique, using liquid nitrogen or liquid carbon dioxide, provides the refrigeration needed to pre-cool the spices and maintain the desired low temperature by absorbing the heat generated during the grinding operation which will significantly reduce the loss of volatile. The extremely low temperature in the grinder solidifies oils so that the spices become brittle, these crumble easily permitting grinding to a finer and more consistent size. Cryogenic grinding reduces specific power consumption, particle size, continuous chocking problem of sieves, fire risk and increases the throughput and overall efficiency as compared to that of traditional or ambient grinding systems (Singh and Goswami, 1999; Barnwal *et al.*, 2014; 2015).). Cryogenic grinding of food materials in atmosphere of liquid nitrogen reduces heat flow, specific power consumption, particle size, continuous chocking of sieves, and risk of fire hazards and dust explosions etc. The cryogenic technique, apart from quality retention of spice, assists in size reduction by the effect of low temperature embitterment through ductile-to brittle transition (Singh and Goswami, 1999). Considerable smaller sizes may be obtained under cryogenic conditions. Finely ground spices spread their flavour uniformly throughout the food product in which these are being used (Goswami and Singh, 2003).

For cryogenic grinding of spices first, the spice will pre-cool in a cryogenic pre-cooler and then send to grinder for its grinding. Secondly, spices and cryogen may be fed directly into the grinder. In first case, some liquid nitrogen may travel to grinder either in liquid and/or gaseous form in grinding zone and hence better ground product obtained. In the present communication, the effort has been made to study some design parametric considerations of cryogenic pre-cooler for grinding of spices (fenugreek and coriander seed) which will be helpful in cryogenic grinding of spices for better ground spice quality.

Some theoretical considerations

The cryogenic grinder is a specially constructed stainless steel heat exchanger designed to optimize heat transfer, using liquid nitrogen as a refrigerant. The feeder is suitable for pre-cooling of spices etc. to their embrittlement temperature for cryogenic grinding operations. Heavy duty material components and simplicity of construction assure a durable and reliable cryogenic cooling system. The cooling conveyor operates with high thermal efficiency resulting in lower nitrogen consumption. The material is cooled to its embrittlement temperature traveling through the cooling conveyor. When the material is passed through the grinder, it is reduced to the required size. Some products can be reduced to as low as 50 micron.

Pre-cooling unit consists of screw conveyor assembly, with vacuum insulation and circulation of liquid nitrogen. Singh and Goswami (1999) developed the cryogenic grinder for spices. The consideration of engineering parameters such as calculation of cooling load, retention/ freezing time of spices, and the size of pre-cooler for optimization of systems were taken and they proposed that the pin mill has more efficient for fine grinding of spices rather than other grinding machines (hammer mill). Chourot *et al.* (2003) also proposed a detailed calculation model to evaluate and compare the technical and economic aspects of different freezing techniques (immersion, air blast and cryo-mechanical freezing). The material to be ground is loaded into a feed hopper. From the hopper, the material enters the cooling conveyor where liquid nitrogen at-195.6°C is sprayed directly on to the food materials. The liquid nitrogen vaporizes to a gas by absorbing the required heat of vaporization from the feed material. To obtain the thermal equilibrium, cold nitrogen gas continues to cool the feed materials below glass transition temperature. The material enters the grinding chamber of pin or hammer mill i.e. where the feed is ground into a powder. During the grinding stage, additional liquid nitrogen may be injected in to the grinder to reduce the rise in temperature.

Cryogenic grinding unit consists of pre-cooling unit and grinder unit. The cryogenic pre-cooling unit consists of screw conveyor assembly, air compressor, liquid nitrogen dewar, control panel and power transmission systems (Singh and Goswami, 1999). In the designing of pre-cooler, the main things are insulation materials because the liquid nitrogen quickly evaporated at ambient temperature. In pre-cooling assembly, the loss of heat is very common due to spices and constructed materials so the outer casing and insulation materials retain the heat losses. Some basic principles were adopted in designing of pre-cooler. Before designing the pre-cooler, some design parameters / data base of cryogenic pre-cooler for fenugreek and coriander seeds were considered.

Assumptions

* There is steady state pre-cooling process.
* The outlet temperature of pre-cooler is -100°C and maintained in grinder is -85°C to -80°C.
* Initial temperature of seed is ambient temperature i.e. 30 °C.
* Vacuum insulation for minimization of heat loss in pre-cooler (appropriate insulation should be used such that the losses to the ambient are minimum).
* 20% losses of heat during the pre-cooling process (Singh and Goswami, 1999).
* Cooling load in liquid zone and gaseous zone will be 70% and 30%, respectively (Singh and Goswami, 1999).
* Various components of the precooler should be arranged in such a manner that dismantling and cleaning becomes easier.

The heat removed from the systems (cooling load) may be expressed as (Singh and Goswami, 1999):

$$q = C_1(T_1 - T_f) + L_f + C_2(T_f - T_2) \quad \text{...(1)}$$

and $$L_f = L_f\,\text{water} \times M_c(\text{w.b.}) + L_f\,\text{oil} \times \text{oil content} \quad \text{...(2)}$$

where, q = Heat removed from seed, J kg^{-1}; C_1= Specific heat of seed above freezing point, J kg^{-1} °C; T_1 = Initial temperature of seed, °C; L_f = Latent heat of fusion of seed, J kg^{-1}; C_2 = Specific heat of seed below freezing point, J kg^{-1} °C; T_f = freezing temperature of seed, °C; T_2 = final temperature of seed, °C; M_c = Moisture Content, % (w.b.) and w.b. = wet basis.

Enthalpy change may be expressed as (Nagaoka *et al.*, 1955)

$$\Delta H = \left[1 + 0.00445\,(T_1 - T_f)\right] \times \left[C_1(T_1 - T_f) + L_f + C_2(T_f - T_2)\right] \quad \text{... (3)}$$

where, φH = Enthalpy change, J kg^{-1}

For freezing time calculations, there are various equations available in published literature such as basic Plank's equations, modified Plank's equations and freezing time calculating models (Mascheroni and Calvelo, 1982; Singh and Goswami, 1999). The following modified form of basic Plank's equation was used for calculation of freezing time of moisture and oil present in spice seed i.e. time required for freezing using liquid nitrogen (Barron, 1972; Singh and Goswami, 1999):

$$t_{fk} = \left[1 + \frac{5C_1(T_1 - T_f)}{8L_f}\right] \times \frac{\rho_s q d_r}{T_f - T_g} \times \left(\frac{1}{h_c} + \frac{Bd}{k}\right) \quad \text{... (4)}$$

Where, ρ_s = true density, kg/m^3; d_r = radius of seed, m; T_g = refrigerant freezing temperature, °C; h_c = heat transfer coefficient, W/m^2-°C; B = constant, which depends on geometry of the seed; d = screw shaft diameter, m and k = Thermal conductivity of the seed, W/m-°C.

Another modification of Plank's equation by incorporating empirical factors based on freezing of fresh fish (Nagaoka *et al.*, 1955) was also considered for calculation of freezing or retention time (Heldman and Singh, 1981):

$$t_{fn} = \frac{\Delta H \rho_s}{T_f - T_g}\left[\frac{Pa}{h_c} + \frac{Ra^2}{k}\right] \quad \text{...(5)}$$

Where, a = Diameter of the seed, m; P and R = Constant, based on geometry of seed (P = R = ¼ = 0.25).

Screw conveyor capacity of cryogenic pre-cooler is calculated by the following equation (Singh and Goswami, 1999):

$$Q = 47 \times \left(D^2 - d^2\right) \times p \times n \times \psi \times \rho_b \times C \quad \text{...(6)}$$

where, Q = capacity of conveyor, kg/h; D = screw diameter, m; p = pitch of the screw, m; n = rotational speed of screw conveyor, rpm; ψ = coefficient of friction of screw cross section; ρ_b = bulk density of coriander seed, kg/m^3 and C = correction factor that depends on angle of inclination of screw

Now conveying velocity, v = (p×n)/60 and then

Screw length = retention time × conveying velocity

Then by rearranging Equation (4), length of screw may be calculated using following formula:

$$L = \left[1 + 0.625\frac{C_1(T_1 - T_f)}{L_f}\right] \times \frac{\rho_s q d}{T_f - T_g} \times \left(\frac{1}{h_c} + \frac{Bd}{k}\right) \times \left[\frac{1}{60} \times p \times n\right] \quad \text{... (7)}$$

Where, L= length of screw conveyor, mm and conveying velocity, v = (p×n)/60 , m/s

Results and discussion

Table 2 presents the values of various design parameters of cryogenic pre-cooler, used for computation purpose, for spice grinding of spices (fenugreek and coriander). These parameters include specific heats of seed (above freezing point and below freezing point), latent heat of fusion of oil of the seed, freezing temperature of the seed, moisture content of the seed, oil content of the seed, true density of the seed, thermal conductivity of the seed, bulk density of the seed, average size of the seed, convectional heat transfer coefficient and refrigerant temperature etc. The specific heat was measured using a differential scanning calorimeter (DSC). True density of seed was determined by using Gas Pycnometer (model2: *Hymipyc,* make IQI make, USA). These data were used in Equations (1), (2) and (3) to compute heat removed from seed, latent heat of fusion of seed and enthalpy change, respectively. These computed values were used in Equations (4) and (5) to calculate the total retention time of seed and tabulated in Table 2 for their comparison. The diameter of cooling screw and pitch of screw (1/3rd of screw diameter) were considered as 120 mm and 40 mm, respectively. Using these values of screw diameter and pitch, the capacity and screw length of pre-cooler were computed by using Equations (6) and (7), respectively at different speed (3, 6, 9, 12 and 15 rpm) of cooling screw of the cryogenic pre-cooler.

Figure 1 shows the variation of screw length and capacity of cryogenic pre-cooler for fenugeek seed (computed by using Equation 4) with cooling screw speed (range 3 to 15 rpm) at constant screw diameter (120 mm) and screw pitch (p= 0.04 m = 40 mm). Both screw length and capacity of cryogenic pre-cooler for fenugeek seed increased lineraly from 466 to 2330 mm and 20.3 to 101.7 kg/h, respectively with increase in cooling screw speed from 3 to 15 rpm (Equation 4; Figure 1). The variation of screw length and capacity of cryogenic pre-cooler for fenugeek seed (computed by using Equation 5) with cooling screw speed (range 3 to 15 rpm) at constant screw diameter (120 mm) and screw pitch (p= 0.04 m = 40 mm) is presented in Figure 2. It was seen that both screw length and capacity of cryogenic pre-cooler for fenugeek seed increased lineraly from 86 to 430 mm and 20.3 to 101.7 kg/h, respectively with increase in cooling screw speed from 3 to 15 rpm (Equation 5 ; Figure 2).

The variation of screw length and capacity of cryogenic pre-cooler for coriander seed (computed by using Equation 5) with cooling screw speed (range 3 to 15 rpm) at constant screw diameter (120 mm) and screw pitch (p= 0.04 m = 40 mm) is presented in Figure 3. It was seen that both screw length and capacity of cryogenic pre-cooler for fenugeek seed increased lineraly from 212 to 1060 mm and 9.55 to 47.75 kg/h, respectively with increase in cooling screw speed from 3 to 15 rpm (Equation 4 ; Figure 3).Figure 4 shows the variation of screw length and capacity of cryogenic pre-cooler for fenugeek seed (computed by using Equation 5) with cooling screw speed (range 3 to 15 rpm) at constant screw diameter (120 mm) and screw pitch (p= 0.04 m = 40 mm). Both screw length and capacity of cryogenic pre-cooler for fenugeek seed increased lineraly from 38 to 190 mm and 9.55 to 47.75 kg/h, respectively with increase in cooling screw speed from 3 to 15 rpm (Equation 4 ; Figure 4).

The Equation (5), as per Nagaoka *et al.* (1955), gives lower value of total retention time than that of using Equation (4), given by Singh and Goswami (1999). Total retention time of fenugreek seed was calculated as 233 second and 43 second using Equations (4) and (5), respectively. Similarly, total freezing / retention time of coriander seed was computed as 106 second and 19 second using Equations (4) and (5), respectively. The computed value of total freezing time, using Equation 5 (Nagaoka *et al.,* 1955), was less as compared to that of using Equation 4 (Singh and Goswami, 1999). Therefore, for same capacity of cryogenic pre-cooler, the calculated screw length was lower (Nagaoka *et al.,* 1955), than that of using Equation 4 (Singh and Goswami, 1999) for fenugreek (Figures 1-2) and coriander (Figures 3-4).

It is reported that if freezing of spice seed was not completed, there may be the accumulation of powder on the sieve surface which might be due to the fact that during grinding at a temperature higher than the brittle point of the seed and freezing point of its oil, the seed was soft and behaved like glue in the grinder. The spice oil might have come out of the cells during grinding which might had sticky characteristics forming a layer over the sieve surface (Li *et al.,* 1991). Singh and Goswami (1999) mentioned that the powder, deposited above this layer, formed a thick layer on the sieve surface which created obstruction in grinding operation whereas the incoming raw material overloaded the grinding surface and stopped the grinder. Singh and Goswami (1999) reported that at the grinding temperature of -70°C, the deposition of cumin powder was least. Below -70°C, grinding was smooth without any deposition and the sieve was very clear. Accumulation of powder at -40°C accounted for about 50% area of the sieve being blocked. At higher temperatures, the grinding experiments could not be completed successfully, because the sieve perforations were blocked soon after running the machine and it stopped due to overloading with the incoming material. The oil gets solidified at temperatures lower than the brittle point and freezing point of spice seed which results in smoother grinding operation. It is further to state that an increase in grinding temperature, from -10°C to 50°C, resulted in a decrease in volatile oil content of pepper (Landwehr and

Table 1. Some thermo-physical properties of liquid nitrogen (LN_2) and liquid carbon dioxide (LCO_2)

Thermo-physical property	LN_2	LCO_2
Density, kg/m^3	808	464
Boiling point, °C	-195.6	-78.5
Thermal conductivity, W/m-°C	0.14	0.19
Specific heat of liquid, kJ/kg-°C	2.05	2.26
Latent heat of evaporation, kJ/kg	199	352
Total usable refrigeration effect, kJ/kg	690	565

LN_2: liquid nitrogen, LCO_2: liquid carbon di-oxide

Table 2. Values of design parameters of cryogenic pre-cooler for fenugreek and coriander, used in computation

Design Parameters	Fenugreek	Coriander
Specific heat of the seed(above freezing point) , J/kg-°C	956.5	1376.0
Specific heat of the seed(below freezing point) , J/kg-°C	317.2	510.1
Latent heat of fusion of oil of the seed , J/kg	28040.0	27190.0
Freezing temperature of the seed , °C	-85.7	-70.9
Moisture content of the seed, % w.b.	8.0	9.0
Oil content of the seed, %	2.2	3.0
True density of the seed , kg/m^3	1102.0	354.2
Thermal conductivity of the seed , W/m-°C	0.056	0.060
Bulk density of the seed , kg/m^3	608.2	285.6
Average size of the seed , mm	4.40	3.76
Convectional heat transfer coefficient , W/m^2-°C	170.7	170.7
B (Constant)	0.25	0.25
Refrigerant temperature , °C	-195.6	-195.6
Coefficient of friction of screw cross-section	0.45	0.45

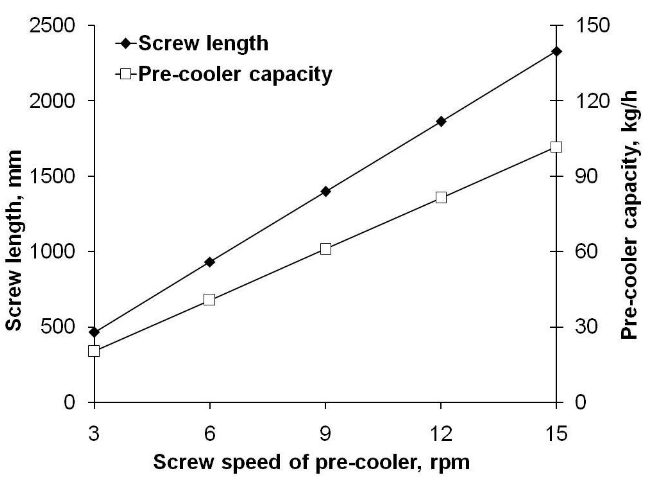

Fig.1: Effect of cooling screw speed on screw length and capacity of cryogenic pre-cooler for fenugeek seed (computed by using Equation 4)

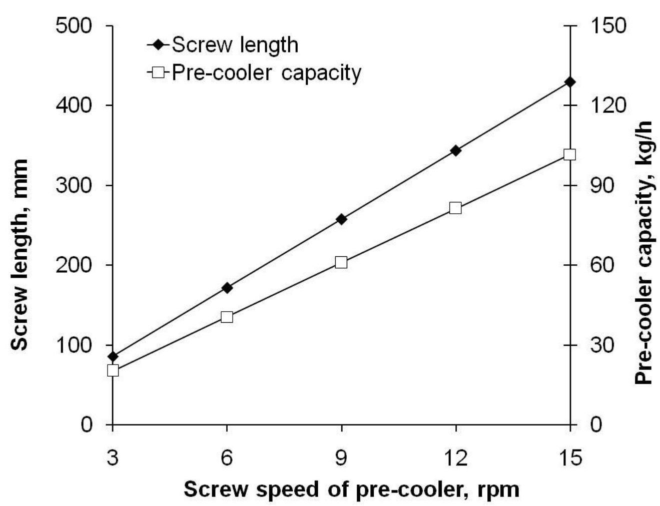

Fig. 2: Effect of cooling screw speed on screw length and capacity of cryogenic pre-cooler for fenugeek seed (computed by using Equation 5)

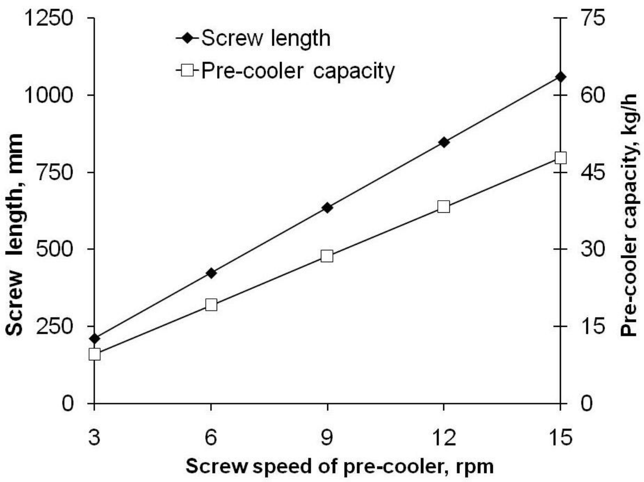

Fig. 3: Effect of cooling screw speed on screw length and capacity of cryogenic pre-cooler for coriander seed (computed by using Equation 4)

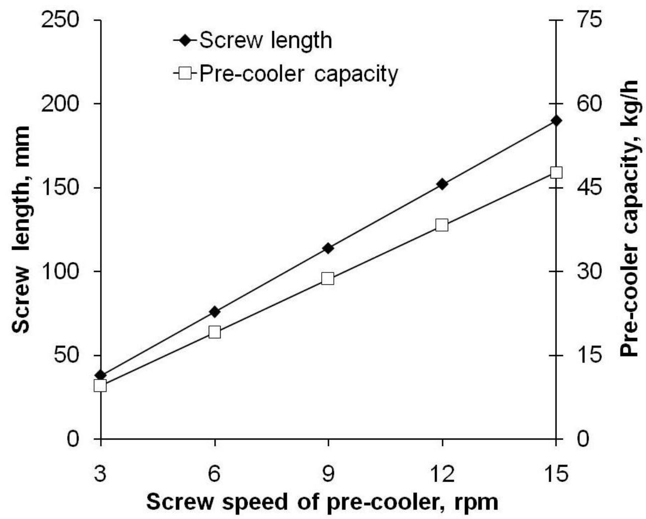

Fig. 4: Effect of cooling screw speed on screw length and capacity of cryogenic pre-cooler for coriander seed (computed by using Equation 5)

Pahl, 1986). To ensure the complete freezing of spice, the higher value of retention time should be used so that during grinding, the temperature should not be more than brittle point of the seed and freezing point of its oil. Therefore, for cryogenic pre-cooler, Equation (4), given by Singh and Goswami (1999), should be preferred over that of Equation (5) proposed by Nagaoka *et al.* (1955) and for cryogenic pre-cooler, design parametric considerations should be used accordingly for grinding of spices.

Summary

Cryogenic pre-cooler is one of the important units of cryogenic grinding system of spices. Some important design parameters (e.g. total freezing time, screw length and capacity etc.) of cryogenic pre-cooler were considered for grinding of spices (fenugreek and coriander seed) and calculated. The capacity and screw length of pre-cooler were computed at different cooling screw speed (3, 6, 9, 12 and 15 rpm) of the cryogenic pre-cooler for constant values of screw diameter and pitch. The screw length and capacity of cryogenic pre-cooler for fenugreek and coriander seeds increased linearly with increase in cooling screw speed from 3 to 15 rpm.

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References

Anon. 2016. Spices Board India, Ministry of Commerce & Industry, Govt. of India (http://indianspices.com).

Barnwal, P., Singh, K.K., Sharma, A., Choudhary, A.K. and Saxena, S.N. 2014. Effect of grinding conditions on physico-chemical, thermal and antioxidant properties of coriander powder. *International J. Seed Spices* 4(1): 25-32.

Barnwal, P., Singh, K.K., Sharma, A., Choudhary, A.K., Zachariah, T.J. and Saxena, S.N. 2015. Selected physical and mechanical properties of black pepper seed (cv. Panniyar-5). *International J. Seed Spices* 5(2):20-25.

Barron, R.F. 1972. Cryogenic food processing. Report No. 72-WA/DE-21.

Chourot, J.M., Macchi, H., Fournasion, L. and Guilpart, J. 2003. Technical and economical model for the freezing cost of immersion, cryomechanical and air blast freezing processes. *Energy Conservation and Management* 44: 559-571.

Goswami, T.K. and Singh, M. 2003. Role of feed rate and temperature in attrition grinding of cumin. *J Food Engineering* 59: 285-290.

Heldman, D.R. and Singh, R.P. 1981. Food Process Engineering, 2nd Edition. AVI Publishing company, Inc. Westport, Connecticut, pp.181-182.

Landwehr, D. and Pahl, M.H. 1986. Cold grinding of spices. *International Journal of Food Technology and Food Process Engineering* 37: 174-185.

Li, S., Ge, S., Huang, Z., Wang, Q., Zhao, H. and Pan, H. 1991. Cryogenic grinding technology for traditional Chinese herbal medicine. *Cryogenics* 31: 136-137.

Malkin, S. and Guo, C. 2007. Thermal analysis of grinding. Annuals of the CIRP 56(2), Connecticut, USA.

Mascheroni, R.H. and Calvelo, A. 1982. A Simplified Model for Freezing Time Calculations in Foods. Journal of Food Science, 47: 1201–1207.

Meghwal, M. and Goswami, T.K. 2010. Cryogenic grinding of spices is a novel approach whereas ambient grinding needs improvement. *Continental Journal of Food Science and Technology* 4: 24-37.

Murthy, C.T., Krishnamurthy, N., Ramesh, T. and Srinivasa, R. 1996. Effect of grinding methods on the retention of black pepper volatiles. *Food Science and Technology* 33(40): 299- 302.

Nagaoka, J., Takaji, S., and Hohani, S. 1955. Experiments on the freezing of fish in air blast freezer. *Proc. IX Int. Cong. Refrig.* 4: 105.

Pruhti, J.S. 1987. Cryomilling- The latest technology of cold grinding of spices and condiments. In Technical Compendium. National Symposium on Spice Industries, 38-47, AFST, April, Delhi Chapter, India.

Singh, K.K. and Goswami, T.K. 1997. Studies on cryogenic grinding of spices. IIT Kharagpur, (India).

Singh, K.K. and Goswami, T.K. 1999. Design of a cryogenic grinding system for spices. *Journal of Food Engineering* 39: 359-368.

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