Strength and Durability of Feed Pellets Influenced by Different Particle Size Distribution, Pellet Volume and Dehydration Techniques

Dejan Miladinovic[1], Mette Sørensen[2], and Birger Svihus[3]

[1] Centre for Feed Technology - FôrTek, Animal Experimental Centre, Norwegian University of Life Sciences, Ås, Norway

[2] Nofima – The food research institute, Ås, Norway

[3] Department for Animal and Aquacultural Sciences, Norwegian University of Life Science, Ås, Norway

ABSTRACT

This article describes the effect of particle size distribution, pellet size and dehydration techniques on the improvement of physical properties of the pelleted feed products. It is shown that dehydration with vacuum has positive effect on durability when compared to air technique. Products volume and particle size distribution also had an effect on physical properties.

INTRODUCTION

In porous feed solids, an internal mass transfer may occur through the solid part or within the void spaces[1]. The dehydration techniques (DT) used on feed solids differs by their heat transfer properties. Moisture-containing solids can be dehydrated by subjecting them to reduced pressures, better known as the vacuum. Vacuum DT (VDT) can be defined as an act to reduce the density of a gas in a vessel to a value adequate for its planned purpose. The first known vacuum dehydration of a commercial product was performed in 1948 for reducing field heat of lettuce[2]. All recent research advances have confirmed that vacuum technique is a method to shorten processing time and improve product quality[3,4,5]. Factors affecting the speed and efficiency of the product being dehydrated might influence the product quality also. These factors are: the surface area exposed to the atmosphere[5], specific heat of the product prior the dehydration[6], density[7,8], porosity[4,9,10] and particle size of the product[8]. Different moisture removal rates observed between conventional air DT (ADT) and VDT are caused by differences in the dehydration mechanisms[11]. ADT is achieved by heat transfer, while VDT by mass transfer. VDT is caused by pressure difference between the saturation pressure on the walls of the micro pore and flow of water vapor through the pore spaces to the surface of the moist-solids and surrounding atmosphere[12]. In VDT the porous structure plays an important role in determination of water flow[3] during dehydration. The steam and the water are the important ingredients for manufacturing the feed product. One of the reasons is the given hydrogen bonds which are connecting various particles of mixed ingredients with the help of an adhesion process[13]. Water state and its type, bonded or free water, play an important role in these processes[14]. Close contact between the wetting adhesive molecules and the solid surface of the feed particles give rise to attractive forces known as physical intermolecular interactions (Van der Waals forces). In this way macromolecules of different sizes in the feed solids inter-diffuse and create an interpenetration layer in the capillary microstructure capable to bear mechanical load[15]. In such microstructures there are some driving forces for the transfer of water molecules defined as pressure gradients and capillary forces. The exchange of a gas or liquid in a vacuum environment is driven by a pressure difference[16]. The mobility of water[17] in porous solids is dependent of the pore structure[18]. Moisture removal by VDT can presumably decrease the time for such requiring operation in the feed production. Also, it might influence positively on intermolecular bonding, thus assumable better physical properties of the feed pellets might occur. Advantages of the feed dehydration by VDT might meet the quality control requirements much easier than ADT[3]. So far, no detailed experimental study has yet been done for determining the influence of VDT on the quality of feed solids and its final moisture. The current experiment was undertaken to test the assumption that different texture, volume and surface area[4,7,8,9] of the feed products have an influence on the water transfer and the physical quality by VDT and ADT.

MATERIALS AND METHODS

Experimental design

The experimental design was made considering a full-factorial design. The different parameters are described as: three different hammer-mill grinding of the wheat grain (1, 3 and 5 mm screen hole size), three different pellet die-hole diameters (2, 3 and 5 mm) and two different dehydration techniques (VDT and ADT).

Preparation and production

Nine experimental diets were prepared and produced by a pelleting technique at the Norwegian University of Life Sciences (UMB), Ås. The major ingredient of the diets was wheat, milled in a hammer mill (HM) (Bliss, Oklahoma, U.S.A., E-22115-TF) fitted with 1, 3 and 5 mm screen holes. Mixing was done in a Dinnissen twin-shaft paddle mixer (Pegasus 400 l, Sevenum, Holland) for 180 seconds. The diets were conditioned with the addition of 2.5 bar steam for 30 seconds prior to pelleting. The pelleting output for all diets was 1100 kg h^{-1}. The conditioning temperature was set to 75 °C in a continuous conditioner. A ring-die pellet press (Munch, 350, Germany) was used for pelleting. Three different pellet die diameters of 2, 3 and 5 mm were used, respectively. Different dehydration techniques, VDT and ADT, were used immediately after the pelleting. ADT was used for all the diets with the same volume of feed pellets in the batch cooler with the average air flow of 1.5 m s^{-1} created by the axial fan (EBM, W-160, Germany) with the air volume capacity of 2550 m^3 h^{-1}. For ADT the air flow was stopped by switching off the fan after five minutes. The research vacuum moisture removal apparatus (Fig. 1) was used for moisture removal by VDT. In the vacuum chamber a residual pressure of 200 mbar was used. Vacuum chamber wall was heated up to 75 ºC for all the diets in order to avoid condensation of water on the inner-walls. Temperature was measured by a digital thermometer (Arnitsu-M, HA-250k, Japan). The dwell time for dehydration of all pellet samples was five minutes. After the moisture removal by VDT the vacuum pump was switched off and the air was re-admitted into the chamber very fast in order to avoid the back-return of any potential remaining condensate from chamber into the pellets. All experimental representative pellet samples were placed into sealed plastic bags and stored immediately at a constant temperature of -18 °C for 30 days prior to analysis. Dry-matter analysis was performed by drying the sampes in the oven (Termaks, Norway) with the standardized procedure (EU 71/393). Duplicate samples were used. Durability (PDI) of each 100 g sample was measured as a triplicate using the automatic pellet durability tester (TekPro, LTD, NHP 200, UK) with the automatic adjustments for each pellet diameter. Hardness analyses, defined as the maximum force needed to crush a pellet, were performed by a hardness cylinder tester (Amandus Kahl Gmbh Co.). Methods have been described in detail by Thomas and Van der Poel[19]. The uniform feed pellets were chosen prior the hardness analysis by measuring the same length for the same diameter with an electronic caliper (Würth Group Int., type 0-150 mm).

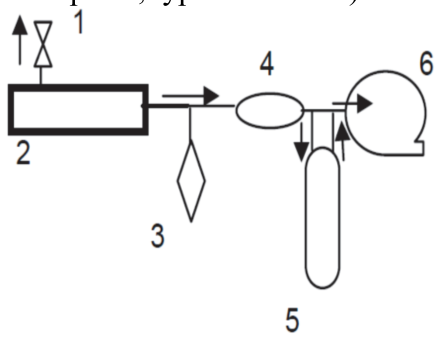

Figure 1. The schematic diagram of the research vacuum moisture removal apparatus: 1-Pressure release valve; 2-Vacuum chamber; 3-Pressure control valve and barometer; 4-Steam condenser; 5-Air filter, 6-Vacuum pump.

The experimental data were partially subjected to t-test analysis to examine possible effects of the dehydration methods on the responses, feed moisture and the physical pellet properties. Software used for descriptive and inferential statistics was SAS (SAS Institute Inc., 1999). Significant differences between treatments were determined by using the generalized linear model (GLM procedure), Fisher's Least Significant Difference (LSD) t-test with 0.05 levels of significance.

Partial Least Squares (PLS) regression was carried out using the software Unscrambler X (Camo AS, version 10.1, Oslo, Norway) to study the relationships between particle size distribution, pellet diameter and drying method (X-variables) versus moisture, durability and hardness (Y-variables). Differences between the Y-variables were also observed. All variables used in PLS regression were centred and scaled to unit variance prior to the analyses. Full cross-validation was performed to determine the number of significant principal components (PC) in the model. Significant variables were detected by using the "Jack-knife" [20]. The level of significance used for these analyses was 0.05.

RESULTS AND DISCUSION

<u>Influence of the feed structure, DT and volume of the feed pellets on dehydration rate and physical quality of feed pellets</u>

For the PLS regression, the three PC's were explaining the variation in the Y and the X variables. The moisture component is presented as PC 1 and physical quality component as PC 2 (Fig. 2). The drying method was explained as PC 3 (Fig. 3). In PC 2, coarser grinding was negatively associated with PDI and hardness (Fig. 2). However, fine grinding was positively correlated with PDI and hardness, where it gave the hardest and more durable pellets. The opposite influence was observed for coarse grinding.

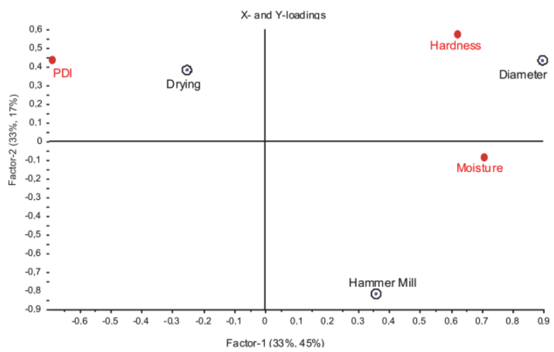

Figure 2. Loading plot of PC1 vs PC2. The X variables are presented as PDI, moisture and hardness and the Y-variables are presented as diameter, DT and grinding.

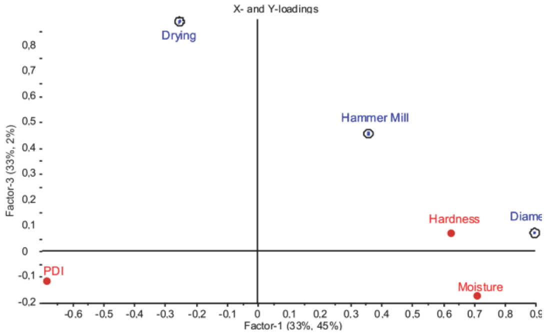

Figure 3. Loading plot of PC1 vs. PC3 showing that PC3 mainly was associated with the drying method and moisture content of the pellets.

Combination of coarse grinding and small pellet diameter had the most adverse effect, while fine grinding gave the favourable hardness for the same pellet diameter (table 2).

<u>Influence of the DT, structure and the volume of the product on dehydration of product</u>

The dehydration rate during the ADT is initially dependent on the evaporation rate of unbound water at the surface of the feed solids where water needs to diffuse between the feed particles to its dry surface in order to be removed. Yet, during the VDT critical moisture content was easily reached in the vacuum conditions where the moisture loss was balanced within the entire volume of the product (table 1).

The results from this research suggest that VDT might be faster compared to ADT which was also suggested by Sun and Wang11. Milling size showed to have an influence on the mobility of water molecules. The flow of water in feed pellets is dependent of the pore structure within product (table 1) which is in agreement with Van Brakel and Heertjes18.The mechanism of VDT showed to be influenced by the milling size and larger pellet diameter. The moisture content was significantly affected by diameter of pellets while this was not the

Table 1. Influence of dehydration techniques on moisture content, PDI and hardness in the feed product 5 min after dehydration (means and *p* values), P<0.01 in a GLM procedure - LSD t-test.

Test name	*2 mm **HM 1	*2 mm **HM 3	*2 mm **HM 5	*3.5 mm **HM 1	*3.5 mm **HM 3	*3.5 mm **HM 5	*5 mm **HM 1	*5 mm **HM 3	*5 mm **HM 5
PM (%), VDT	11.5	11.61	11.8	12.43	13.03	13.34	13.6	12.67	13.58
PM (%), ADT	12.44	12.49	13.25	13.49	13.54	13.7	13.25	12.92	13.51
PM (%) – *p*-value, ADT VS VDT	0.002	0.035	0.011	0.003	0.018	0.049	0.75	0.108	0.431
PDI %, VDT	91.79	89.3	91.11	93.22	91.67	84.69	90.42	85.5	78.83
PDI %, ADT	89.6	86.13	88.12	92.08	89.6	82.7	89.13	83.31	72.77
PDI % - p-Value, ADT VS VDT	0.041	0.015	0.0001	0.022	0.0001	0.026	0.046	0.043	0.01
Hardness (kg), VDT	3.32	3.33	3.3	5.11	4.84	4.16	7.71	6.17	6.05
Hardness (kg), ADT	2.67	3.09	3.09	4.95	5.03	4.2	7.07	5.8	4.93
Hardness (kg) p-Value, ADT VS VDT	0.002	0.108	0.347	0.748	0.687	0.944	0.074	0.299	0.477

PDI and moisture means are derived from the diet and its replica statistically analyzed (P<0.01) in a GLM procedure - LSD t-test
PM – Product Moisture; PDI (%) indicates Pellet Durability Index % (a predictor of pellet fines produced during mechanical handling);
* 2; 3.5 & 5 mm indicates the pellet diameter;
** HM 1, 3 & 5 indicates hammer mill grinding with the screen hole size of 1, 3 & 5 mm.

case for the DT (Fig. 6). DT had an important impact on durability (Table 2). Large pellets had in average the highest moisture content. However, it is shown that DT and particle size of the mash did nothave more important effect on moisture content than diameter (Fig. 6). Infect, the drying method had the greatest negative regression coefficient on moisture (Table 2). The lowest moisture content was obtained with VDT.

Water in pelleted products exists as the vapour which takes part in diffusion process between particles. In this experiment, high moisture was associated with high pellet diameter. However, a clear pattern for ADT in this case was not observed. Pellets with fine grinding had possibly smaller void space between particles and hence a lower water quantity compared to less dense feed pellets such as HM 3 and HM 5 mm. This is however not in correspondence with the findings from Waananen and Okos[21].

Table 2. The weight regression coefficients of PLS-1 analysis, estimating the most important factors for variation in pellet durability index (PDI), hardness and moisture of pellets.

	Drying*	HMSS*	Diam*	HMSS vs. Diam	Diam vs. Diam	RMSE*	Variance (%)
PDI*	0.23 *S*	-0.67 S	-0.43 S	-0.44 *S*	-0.22 *S*	1.56	92
Hardness*	0.12 *NS*	-0.21 S	0.812 S	-0.17 *S*	0.04 *NS*	0.83	75
Moisture*	-0.37 *S*	0.24 S	0.59 S	0.096 *NS*	-0.03 *S*	0.43	67

*PDI = Pellet Durability Index; HMSS = Hammer mill screen size; Diam = Diameter of pellet; RMSE = Root mean square error of prediction; S = Significant; NS = Not significant

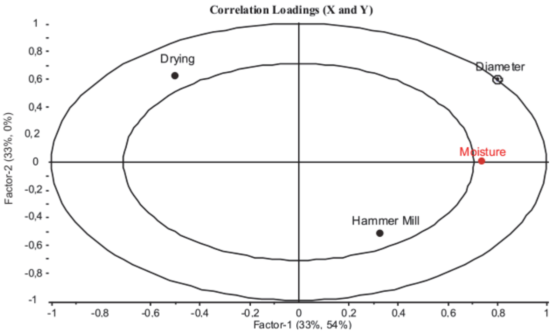

Figure 6. Correlation loading Moisture: Moisture content was mainly influenced by diameter.

<u>Influence of the DT, dehydration rate, structure and volume of the product on physical characteristics of the product</u>

As Xiong et al. [22] have postulated, the binding energy at high moisture levels is small and increases as the moisture content decreases. This was also shown in our experiment (Table 1, Fig. 2). However, the results have shown negative correlation between moisture content and PDI which is in contradiction to results reported by other researchers investigating effect of moisture as a binder in steam pelleted products[23, 24,25].

In GLM (LSD t-test) the relation of pellet hardness towards the main factor such as DT was not observed, thus the score plot for hardness was run towards all factors. DT had no effect on hardness (Fig. 3). The hardness of pellets was mainly influenced by pellet diameter and grinding screen size of the hammer mill (Fig. 9). The largest pellet diameter gave the hardest pellets and small pellet size gave lowest hardness. Earlier study has reported similar results[26].

Considering that PDI and hardness have described different quality properties of the pellets, PLS-1 regression was carried out in order to identify and rank the important X-variables and how they affect the Y-variable (PDI, hardness and moisture content). The loading of PDI, hardness and moisture content are presented in Fig. 9 and Fig. 10. In addition, the scaled regression coefficients for the most important X-variables are presented in Table 2. The physical characteristics of pellets such as PDI and hardness have placed themselves in the correlation loading opposite to each other in PC 1, suggesting that PDI was negatively associated with diameter of the pellet and positively on hammer mill grinding settings (Table 1, Fig. 10). In this case the PDI was mostly associated with small pellet diameter.

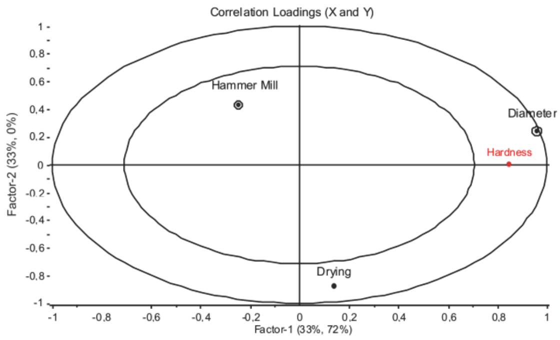

Figure 9. Correlation loadings Hardness: within each cluster, the samples followed the same order with regard to drying method and screen size of hammer mill.

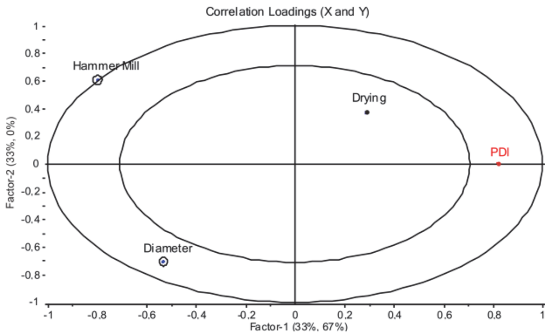

Figure 10. Correlation loading PDI: Moisture content was mainly influenced by particle size distribution and diameter of pellets

The results from Table 1 suggest that the moisture was removed faster with VDT. Also, faster moisture removal with VDT enhanced the durability of feed pellets. In order to acknowledge that moisture content did not have any influence on higher or lower PDI the PLS-1 regression test with jack knifing was performed and correlation loading presented (Fig. 10). The Unscrambler model for X-variable (DT, grinding, pellet diameter, interaction between grinding, DT and diameter) was used against the outputs, Y-variable (PDI and moisture). This enhanced durability with VDT can be explained by allowance of rapid flow of moisture in the gaseous state to vacuum environment where structural collapse is prevented as suggested by Lin et al.[27]. During the ADT the increase of porosity was hypothetically influencing weakening of the inter-particle links inside the feed pellets, thus lower PDI.

Considerably better durability of feed pellets after using the VDT presumably can be explained by rapid decreasing of the moisture content where vapor is no longer in equilibrium with the liquid and the rate of vapor desorption becomes rate-controlling which is a consequence of high binding energy at low moistures. Second assumption is that polymerized network among the feed components and its complexes were set by VDT from chaotic into the organized network. Therefore the greater durability of feed pellets was observed. This phenomenon was explained by Bistac and Galliano[15], when the arranged network increases, macro-friction decreases due to chain orientation phenomena. Therefore, the effects of elastic contact and bulk dissipation are minimized and the interfacial adhesive behaviour of feed components is magnified. Molecular orientation during the adhesive interactions at the surface must be mentioned, where the cracks on pellets might be recovered by VDT and hence better physical properties achieved through formation of attractive properties within the cracks in the polymerized feed structure. Also, better physical properties occurrence by usage of VDT might be explained on the molecular level where the adhesion on polymer fibre interface can be improved by static generation of the low-stress matrix, which will all potentially lead to high-bond strength. Considering that the durability of pelleted feed was increased by VDT, it can be concluded that vacuum has assisted mechanical and chemical adhesion of feed components after the pelleting process with dispersive (van der Waals) forces and diffusive adhesion where the surface pressure of the liquid vapour was decreased and surface energy increased. On the other side, the physical properties defined by hardness analysis did not seem to be influenced by DTs when statistically analyzed by LSD t-test derived from the GLM procedure.

Comparison of the results obtained from usage of different DTs and its influence on physical properties of feed pellets with the results from the literature was difficult due to differences in product composition, production technology, treatment and the structure of the product. No notable changes were seen in process parameters during the feed production to rationalize the differences in moisture content and physical properties for all the diets. That should be addressed to pellet diameter, pellet length, particle size distribution and dehydration techniques.

CONCLUSION AND SUGGESTION

Shown results indicate that a VDT can be used for the moisture removal from the animal feed pellets. Most important advantage of VDT is faster dehydration of the feed product. VDT has already demonstrated to provide many benefits to the food processing industry as shortening product hold up time, increasing production throughput, reducing energy consumption and minimizing microbial growth. This makes itself a much more advantageous method for products of high water content, especially in the extruded fish feed and pet food where the product is subjected to the high air temperatures where the thermo-labile components, as vitamins E and C, as well as the pigment astaxantine, with the excess water content, might be damaged. VDT might be used here as a hybrid DT composed of complementary drying which donate advantages of dehydration of extruded fish pellets on lower temperatures where vitamins and pigments can be preserved. However, modelling of VDT for the feed pellets is still largely unexplored and requires further research. Optimal method should be selected according to a few factors, such as: the economy, convenience, utilization of equipment, operating conditions, personal preference and product requirement. The VDT might make a significant contribution to better quality and easier feed manufacturing.

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