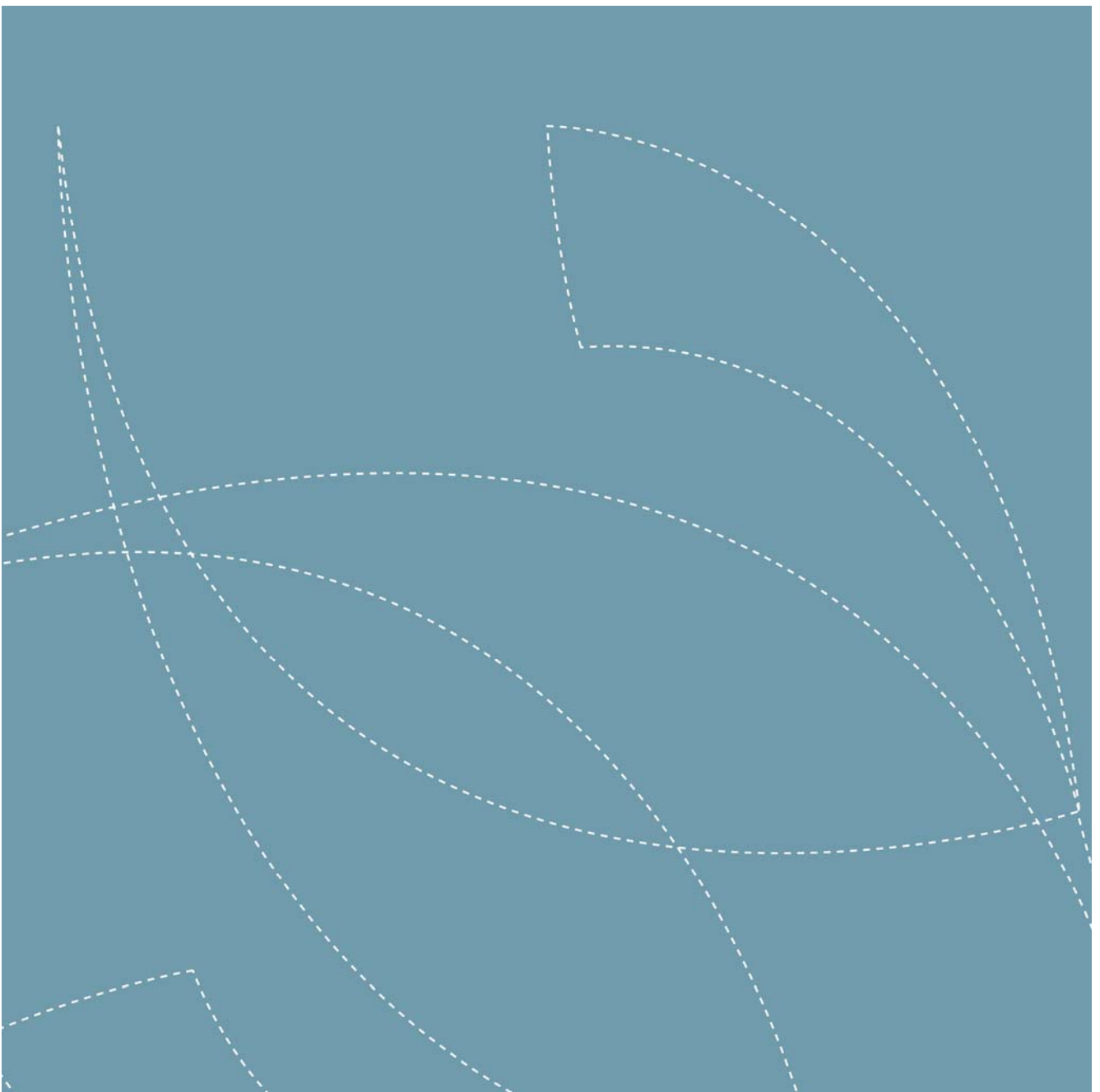


## **Feed pellet durability in pneumatic conveying systems for fish farming**

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# Report

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<i>Summary:</i> <p>This report is based on Gaojie He's master thesis, which was completed in June 2008 at the Department of Animal and Aquacultural Sciences, Norwegian University of Life Sciences, supervised by Mette Sørensen and Trond Storebakken.</p> <p>The degradation of three commercial diets (denoted A, B and C) during pneumatic conveying at different air speeds and feeding rates was investigated in the present experiment. The experiment was arranged in a three by three by three factorial design, with physical quality (Doris value of feed A, B and C was 30.6, 23.7 and 16.5, respectively), airspeed (25, 39 and 35 m/s) and feeding rate (9, 18 and 36 kg/min). Degradation during pneumatic transportation was investigated using the research facilities of a company producing computer-controlled pneumatic feeding systems (AkvaMarina CCS Feed System, Akvasmart, AKVA group, Bryne, Norway). Feed samples of 2 kg were pneumatically conveyed through a 400 m pipeline. The samples were collected at the outlet of the pipeline and sieved in order to determine total degradation as well as amount of fractures and dust. Durability and hardness of the pellets were also evaluated by use of Ligno tester and texture analyzer. The results showed that degradation of pellets during pneumatic conveying was affected by physical quality of feed, airspeed and feeding rate. All three different diets showed different degradation patterns during pneumatic conveying. Pneumatic conveying of feed A showed the least degradation, generating the lowest amount of small particles. Feed B was ranked in between feed A and feed C in terms of degradation, but generated a relatively high amount of dust (particle size &lt; 2.36 mm). Feed C showed the highest degradation during pneumatic conveying, and formed a higher amount of fracture (particle size 2.36-10 mm) than dust. The formation of dust and fracture during the pneumatic conveying did not significantly correlate to the Doris value. Feed A had the highest Doris value and feed B the lowest. As airspeed increased, the generations of both fractures and dust were increased. Increasing the feeding rate had the opposite effect, causing a reduction in formation of dust and fracture. The overall conclusion from the experiment was that the three diets varied in degradation pattern during pneumatic transportation. No good correlation was found between Doris, hardness, durability index or bulk density and degradation during pneumatic conveying, but in general, degradation of pellets increased as airspeed increased, whereas high feeding rate appeared to protect the pellets from degradation.</p>	



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# 1 Introduction

Use of automatic feeding devices has developed along with intensification of the aquaculture production. Pellets are susceptible to generation of fractures and dust upon handling. The physical quality of the pellet used in automatic feeding devices should therefore be good enough to keep the structure throughout transportation and feeding without generating excessive amounts of small particles and dust.

Hand feeding is still the most common and simplest method to feed the fish, commonly used in countries around the world where labor cost is low, such as Asia and Africa. When feeding by hand, the feed is taken directly from storage and thrown into the water, and thus the quantity of feed and the feeding schedule can be adjusted at each feeding. Hand feeding is the best way to train fish to use demand feeders or to administer medicated feed to sick fish (Andrew et al., 1996). However, it is labor intensive and may not be practical for large commercial fish farms.

Automatic fish feeding devices have been broadly developed recently. It can be divided into two main categories (Lau and Glenn, 1990). One category includes continuously operable, electrically-powered mechanisms which deposit feed into the water at a predetermined rate. However, this type of automatic feeding devices have the primary disadvantage that as the feeding habit of fish varies because of the weather conditions, growth rate and any other factors, the amount of feed allotted is not changed accordingly. Thus, the continuously operating devices may deposit too much feed which causes waste and pollution of water, or too little feed which influences the growth of the fish. The other category is systems in which the distribution of feed is triggered by the feeding activity of fish, which is known as "demand-responsive feeding devices" (Lau and Glenn, 1990) or "self-feeding" (Paspatis et al., 1999). These feeding devices have a triggering mechanism located under the surface of water so that feeding is induced by the fish. Obviously, this type of feeding devices and methods are more effective than the former because of its flexibility and sensitivity. The disadvantage of self-feeder is the possibility of mechanical failure due to its complexity of machine. Besides, it may not be very efficient when a large number of fish is to be fed.

Automatic feeding devices vary in construction and operational characteristics. Lau and Glenn (1990) invented a type of automatic feeder with a container for the feed, which floats on the surface of water and dispenses the pellet-like feed from the barrel periodically by gravity. Other feeding devices have been developed using either air or water to convey the feed from a holding bin to the fish. Pneumatic feeding systems have gained higher market shares over the last years in large commercial fish farming due to its flexibility, simplicity and environmental compatibility (Chapelle, 2004). Pneumatic feeding devices can either utilize positive pressure (compressed air) to convey the pellet, or it can utilize a negative pressure conveying pellets by suction. Most pneumatic conveying systems applied in aquaculture farming use positive pressure. Four basic pneumatic conveying modes exist: Solid dense phase, discontinuous dense phase, continuous dense phase and dilute phase. The dilute phase, which is characterized by large amounts of transport gas with no upper limit to velocity but little solids to be conveyed in a suspension, is by far the most prevalent type of conveying in practical application (Klinzing, 2001).

A well designed pneumatic conveying system can usually transport fish feed fast and reliably to the pen. Moreover, it can be designed to support many transport routes to different cages and minimize the pellet degradation upon delivery. The computer-controlled pneumatic conveying system Akvasmart (AKVA group, Bryne, Norway) consists of the pipelines and a main part including blower, storage bins and feeder located on a ship that can move between different cage areas. The transport routes can easily be selected, and the feeding capacity adjusted by changing the airspeed and feeding rate. Feeding rate and delivering time is

controlled by software. The Akvasmart system closely monitors appetite and feed intake by the fish using a video camera.

One challenge with dilute phase pneumatic conveying of feed pellets is formation of dust and small particles as pellets are conveyed through the pipeline (Salman, 2002). Degradation of pellets will not only cause contamination of pipelines but may also decrease the quantity of feed available for fish. Fine powders or oily/sticky products will stick to and accumulate inside pipelines (Wypych, 2001), and may therefore result in blocking.

Degradation of pellets during pneumatic conveying of pellets is affected by several factors. First of all, length and diameter of the pipeline, as well as its wall roughness (Sommerfeld, 2004) affects generation of small particles. Long pipeline coupled with small diameter and coarse wall could increase both opportunity and intensity of collision or attrition between feed and pipes, and thus induces generation of dust and fracture. Airspeed and particle pick up velocity (Norambuena, 2005; Aarseth, 2004) are also associated with fractures and dust. High airspeed generates high drag force between air flow and feed particle surface, which increases the attrition, therefore more dust. Increasing the feeding rate may give a “friendly protection” effect, meaning that the pellets protect each other from collisions, thus reducing the generation of dust and fracture.

Physical quality of pellets varies a lot. Hence, to survive pneumatic conveying, the pellet quality should be high to begin with. Production of a stable pellet quality is a major challenge to the feed industry since it is very much affected by variation in ingredient quality (Behnke, 1996). Furthermore, the physical quality of a feed may affect its biological value, and the digestibility may be reduced if the pellet is too hard. On the other hand, pellets with low physical quality are expected to give more dust and small particles since they are expected to break more easily during conveying.

The design of the pipeline is also of importance to reduce generation of fracture and small particles. Aarseth (2004) showed that bend design was important to reduce pellet degradation. Flexible long radius bends made of rubber generates much lower attrition compared to rigid short radius bends made of steel (Kalman and Goder, 1998).

The aim of this study was to investigate the effect of air speed and feeding rate on degradation of three extruded fish feeds of different physical quality during pneumatic conveying. A main goal was, if possible, to find a value for physical pellet quality that can serve as a steering parameter to adjust the settings of the conveying system.



## 2 Materials and methods

### 2.1 Experimental diets

Three extruded commercial fish feeds were supplied by Skretting AS, Stavanger, Norway. The diameter and length of the pellets were approximately 12 mm. All feeds were packed in big plastic bags (500 kg) and stored at an average temperature of 16.5 °C during the experimental period. The three feeds were labeled feed A, feed B and feed C. Table 1 shows the Doris values given by the manufacturer of all three feeds.

*Table 1 Doris values and fracture of three commercial fish feed (values given by the manufacturer).*

<b>Feed (commercial name)</b>	<b>Doris value(%)<sup>1</sup></b>	<b>Fracture(%)<sup>2</sup></b>	<b>Label</b>
SELECT LR 70MR 3000-50A 12	30.6	25.8	A
OPTILINE V 2000-40A 12	16.5	13	B
OPTILINE V 3500-20A 12	23.7	21.4	C

<sup>1</sup> Doris value is the sum of fracture and dust (%) after the Doris test (described in Materials and Methods). Skretting used shaker with amplitude 1.5 for 30 seconds, coupled with sieve group of 9.6 mm, 2.37 mm and dust pan.

<sup>2</sup> In Skretting's Doris values, fracture is the percentage of materials passing through 9.6 mm sieve but staying above 2.37 mm sieve after Doris test. Dust is the fraction collected in the dust pan.

### 2.2 Pneumatic conveying system

A pneumatic conveying system (AkvaMarina CCS Feed System, Akvasmart, AKVA group, Bryne, Norway), was the main test equipment. In brief, this is a positive pressure pneumatic conveying system, consisting of a blower, cooler, feeder/doser, feed selector and collector. In addition, a computer was connected to the blower, doser and selector to control airspeed, feeding rate and transportation routes. This system was designed to convey pellets with diameter from 1.2 to 25 mm. The complete structure of pneumatic conveying system is outlined in Fig. 1.

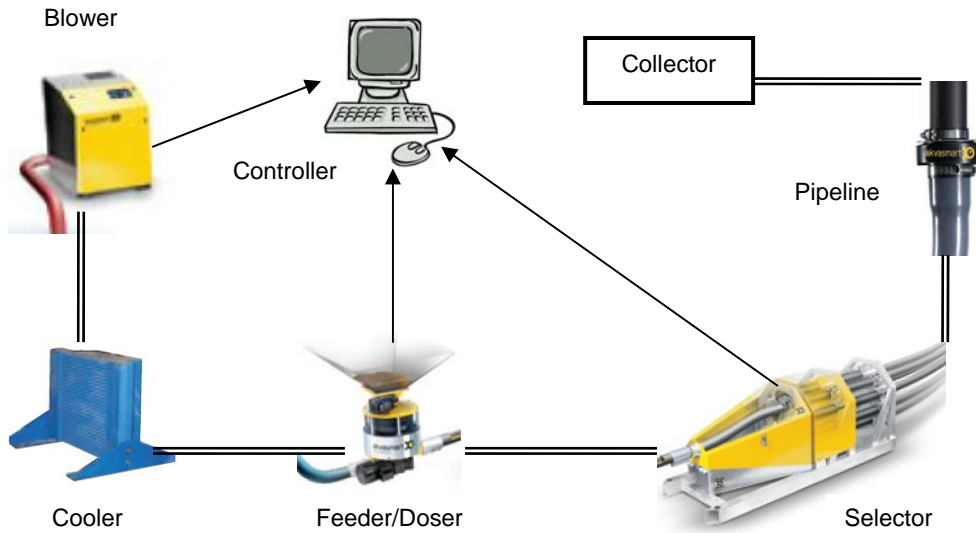


Figure 1 Structure of the pneumatic conveying system.

## 2.3 Blower

A rotary blower (Kaeser CB 130 C, Akvasmart), with a maximum performance of 20.4 KW, able to generate 0 ~ 10.97 m<sup>3</sup>/min airflow with high speed to convey the feed through the pipeline, was used to compress the air. The maximum inlet pressure and outlet pressures were 1.88 bar and 1 bar respectively. The air speed was regulated by changing the motor speed of the blower.

## 2.4 Cooler

The air temperature of the air after the blower was higher than the ambient temperature, and increased as the airspeed generated by the blower increased. High temperature of air flow may affect physical quality of the pellets, and may also cause oil leakage of pellet, which not only may reduce pellet nutritional quality but also pollute the pipelines. Therefore, in practical application, the pipe between blower and feeder/doser go deep into the water to cool the air. In this experiment however, a cooler (Akvasmart), having maximum capacity to cool the air temperature by 30 °C, was adopted for the same purpose. There were two temperature sensors located in the position just before and after cooler to register the temperature of the air flow.

### 2.4.1 Feeder/Doser

In this experiment, the transport of feed started at the feeder/doser. The capacity of the feeder was from 0.6 kg/min up to 87 kg/min. Through the computer software, the feeding rate can be changed within the given limits.

### 2.4.2 Feed selector

The Akvasmart feed selector could lead 10 conveying routes. In this experiment, only one conveying route was used.

### 2.4.3 Pipeline

The pipeline had a total length of 400 m and was composed of PEHD (high density polyethylene) pipes with 76.2 mm inner diameter. Every 100 m there was an aligned joint to minimize the degradation of pellets during conveying.

### 2.4.4 Collector

In order to collect the pellets at the outlet after the pneumatic conveying, a cotton stretch bed sheet (Fig. 2) was used. The bed sheet was attached to a wooden pole. The pipeline and collector were placed outdoor with mean ambient temperature 5.0 °C.

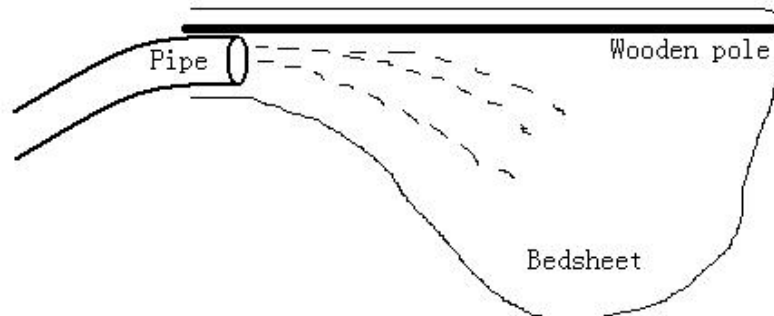


Figure 2 Sketch of the collector.

### 2.4.5 Controller

A computer program, AkvaControl Feed System Software, Akvasmart, AKVA group, was connected to the blower, feeder/doser and feed selector, and was utilized to change the settings of the pneumatic conveying system.

### 2.4.6 Sieving process

Quantification of the amount of dust and fracture in the samples was carried out by using a sieving procedure. A shaker (HAVER EML 200 Digital plus T, HAVER & BOECKER, Germany) was used to separate the differently sized pellet particles. The sieving procedure was run with amplitude 2.3 (Level 7 vibration intensity of the shaker, Level 9 for the maximum) for 2 minutes. For the pellet size used (12 mm), a set of 10 mm, 8 mm and 2.36 mm sieving screens as well as a dust pan was chosen (Fig. 3) Pellet particles larger than 10 mm was considered as intact pellet. Pellet particles from 2.36-10 mm was denoted “fracture”, whereas particles <2.36 mm was denoted “dust”.

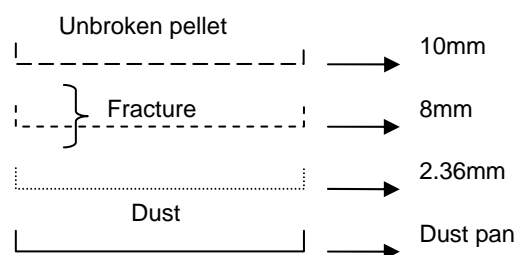


Figure 3 Rack of sieves used to measure small particles and dust.

After sifting the samples, some obviously broken pellets staying above the 10 mm sieve were picked up by hand and included in the fracture part. The upper limit for material for efficient separation was 300 ~ 350 g pellets. Thus, the sample was divided into several sub-samples. After all sub-samples were sieved, the materials collected on the sieves were weighed and the percentage of fracture and dust was calculated.

## 2.5 Pellet degradation during feed conveying

### 2.5.1 Standardization of the method

Feed B was selected to be the test diet for establishing the experimental design for the main experiment. Samples of both 2 and 5 kg were fed into the pneumatic conveying system (two replicates). No difference in pellet degradation (Doris value, fracture and dust) between the 2 and 5 kg sample was observed, and it was therefore decided to use 2 kg sample. The airspeeds and feeding rates chosen are shown in Tables 2 and 3, respectively.

*Table 2 Range of airspeeds used.*

Airspeed setting (%)	Real airspeed (m/s)
90	35
75	30
59	25

*Table 3 Range of feeding rates used.*

Feeding rate setting (%)	Real feeding rate (kg/min)
40	36
20	18
10	9

The pneumatic conveying system had a 400 m pipeline located outdoor. Temperature differed between the air in the pipeline and the ambient outdoor temperature, which resulted in condensation in the pipeline. In order to reduce error, sponges were conveyed through the pipeline 6 ~ 12 times to wipe off the water. Thereafter, 1 ~ 3 runs of feed samples were made before the drying procedure had to be repeated.

The feed sample was weighed and placed in the hopper above the feeder. Airspeed of the blower as well as feeding rate was adjusted by using AkvaControl Feed System Software. The blower was run for 30 seconds to clean the pipeline for dust and small particles. After that, the feeder was started and the pneumatic conveying of the feed begun. The feed collected after each run was transferred to a bucket and then taken indoors for sieving. The bedsheet was thoroughly cleaned by shaking. For each sample, the following parameters were recorded:

- 1) EptSheet\_B: The weight of empty bed sheet before collecting pellets.
- 2) FullSheet: The weight of bed sheet together with pellets.
- 3) EptSheet\_A: The weight of empty bed sheet after unloading pellets.
- 4) Pellets: The weight of pellets collected in the bed sheet.
- 5) 10 mm: The weight of particles > 10 mm.
- 6) 8 mm: The weight of particles > 8 mm.
- 7) 2.36 mm: The weight of particles > 2.36.
- 8) Dust: The weight of material in the dust pan.

### 2.5.2 Main experiment

The experiment was run as a 3 x 3 x 3 full factorial design with two replicates. The three diets were tested at three airspeeds, and three feeding rates were used per airspeed level (Table 4). There were 54 runs in the final experiment, and the run order was randomized using SAS 9.0 software.

Table 4 Experimental design.

Feed	Airspeed (m/sek)	Feeding rate (kg/min)	Replicate
A, B, C	25	9	1
			2
		18	1
			2
		36	1
			2
	30	9	1
			2
		18	1
			2
		36	1
			2
35	9	1	
		2	
	18	1	
		2	
	36	1	
		2	

## 2.6 Measurement of physical quality parameters of feeds

### 2.6.1 Measurement of bulk density and specimen weight

The bulk density was measured by filling a columned container of 1 L with pellets. The top of the pile was scraped once to remove the redundant pellets that exceed container edge level. The weight of the pellets was recorded. Three replicates were measured for each feed.

The specimen weight was calculated by counting the number of pellets in a sample of approximately 200 g of mass. This was done with 3 replicates.

### 2.6.2 Doris Test

Doris fracture, Doris dust and Doris value were investigated on pellets directly from the big bags by control sieving (sieving of pellets without any pneumatic conveying).

Approximately 350 g of sample was put into DORIS tester (Akvasmart). The DORIS tester is made up by an Archimedes screw that feed pellets into a vane, simulating stresses that pellets are exposed to during pneumatic conveying in feeding systems. Thereafter the sample was sieved, using the sieving procedure described previously. The DORIS value is sum of the percentage of fracture (pellet size 2.36 – 10 mm) and dust (pellet size < 2.36 mm). The test was carried out in three replicates for each feed and pellets from the upper and middle layer of the big bags were tested.

### 2.6.3 Ligno test

Approximately 120 g of sample was sieved according to the sieving procedure described previously, using the amplitude 1.5 for 30 sec in order to ensure that the sample was free of dust and breakage. From the pre-sieved sample, approximately 100 g of pellets were put into Ligno tester (LignoTester Serial N° LT 110, BORREGAARD LIGNOTECH, Sarpsborg, Norway). The Ligno tester was stopped after 2 min. Subsequently, the sample was collected and the same sieving process was executed. Three replicates for each kind of feed are required. The pellet durability index (PDI) was calculated by Eq1.

$$PDI (\%) = \frac{\text{The Mass of pellets above 10 mm sieve after sieving (g)}}{\text{The Mass of pellets before sieving (g)}} * 100 \dots\dots \text{Eq1}$$

### 2.6.4 Texture analysis

The diameter, breaking force and breaking distance of sample were measured by TA-XT2<sup>R</sup> Texture-Analyser, Arrow Scientific, Sydney, Australia, with 30 replicates for each feed. The length of the pellets was measured with a caliper before the pellets were placed into the texture analyzer.

## 2.7 Calculations and statistical analysis

The amount of whole pellets, fracture and dust was measured coupled with control sieving for all three feeds. These values were used to correct for already broken pellets and dust, so that we were able to measure broken particles and dust during pneumatic conveying. The same sieving procedure was used as already described. Table 5 shows the control sieving results, "existing quality", for all three feeds.

Table 5 Result of control sieving (sieving of feed samples directly from the bag, without prior conveying)

Feed	10mm(%)	8mm(%)	2.36mm(%)	Dust(%)
A	99.3	0.4	0.1	0.2
B	99.4	0.3	0.1	0.2
C	98.9	0.8	0.1	0.2

The fraction of the 'existing quality' was subtracted from the corresponding fraction after the pneumatic conveying as shown in Eq.2. The calculation of fracture and dust were the same.

$$InPipe_{10mm} = U_{10mm} - (PWA * P_{10mm} / 100) \dots \text{Eq. 2}$$

Where

- InPipe<sub>10mm</sub>= The weight of unbroken pellets above 10 mm sieve purely generated by pneumatic conveying.
- U<sub>10mm</sub>= The weight of uncorrected unbroken pellets above 10 mm sieve.
- PWA= Total weight of pellets after pneumatic conveying.
- P<sub>10mm</sub>= Percentage of unbroken pellets above 10 mm sieve at control sieving.

Principle components analysis (PCA) was performed using the statistical analysis software The Unscrambler 9.7, Camo AS, Oslo, Norway. A large number of original variables were reduced into a fewer number of un-observable variables called principle components (PC) that were linear contributions of the original ones. The first few PCs gave information about the most important interactions and phenomena in the dataset. Tukey's studentized range test (Honestly Significant Difference, HSD) and the Pearson correlation analysis between several physical quality parameters like bulk density, specimen weight and PDI, were performed using The SAS System 9.0 for Windows, SAS Institute Inc., Carey, RA, USA.





## **3 Results**

### **3.1 Pellet degradation during pneumatic conveying**

#### **3.1.1 Fracture and dust in pneumatic conveying**

Degradation of pellets during pneumatic conveying and how the degradation was affected by physical quality of feed, airspeed and feeding rate is shown in the loading plot (Fig. 4). Variation in degradation was described by use of PCA (Principle Component Analysis). Approximately 76% of the variation in the data was described by use of two principal components (PC's), of which PC1 explained 49% and PC2 explained 27% of the variation. The first PC described variation in whole pellets (pellets above 10 mm) and fractures (smaller than 8 mm and 2.36 mm) respectively. The second PC explained variation in dust.

Positive correlation between two variables exists if they are located on the same side of the coordinate axis, and negative correlation exists if they are located on opposite sides. Therefore, for PC1, feed C had a positive correlation with the generation of fractures and was negatively associated with whole pellets. Feed A was positively correlated with whole pellets but negatively associated with small particles. Feed C had a higher loading than feed A in PC1 indicating that this feed contributed to a higher variation in small particles. Feed B had a high loading in PC1 and PC2. The loading was higher in PC2 than PC1 suggesting that feed B was positively correlated with dust. The generation of dust and the increased weight of the bedsheet were positively correlated to airspeed and temperature before and after cooler, but negatively correlated with feeding rate. Increased weight of the bedsheet where pellets were collected suggested that there were still some small particles left after the feed samples were collected in the buckets.

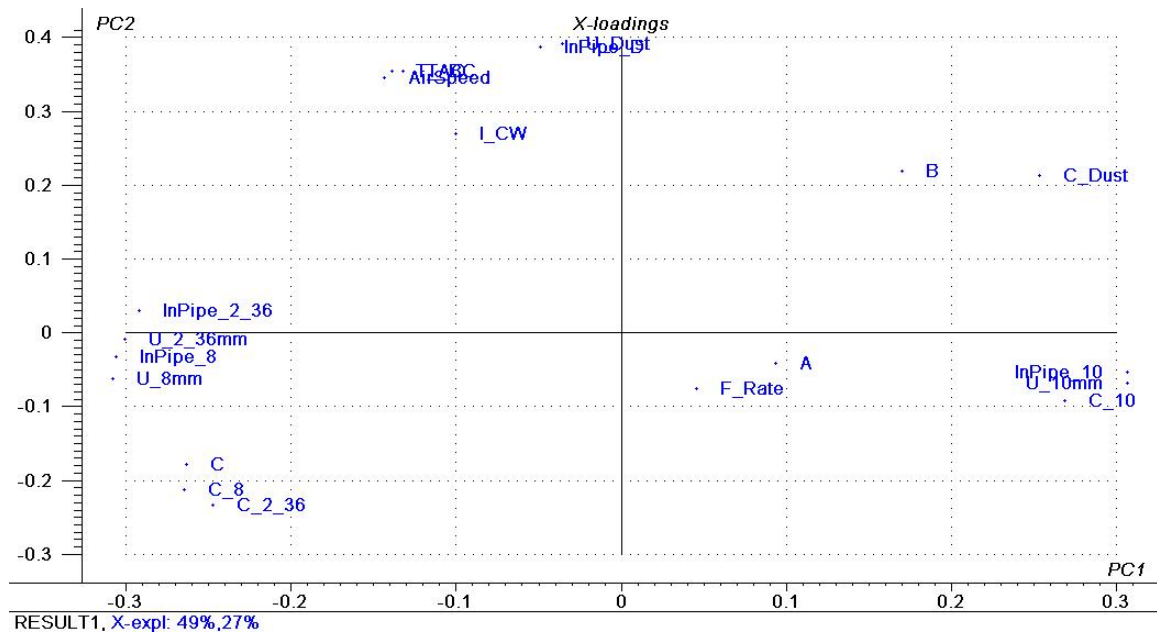


Figure 4 Loading plot showing whole pellets and generation of small particles and dust among diets A, B and C at different feeding rates (F\_Rate) and airspeeds. The corresponding score plot is presented in Fig. 5. InPipe\_10, InPipe\_8, InPipe\_2\_36 and InPipeD are the weights of the 10mm, 8mm, 2.36mm and dust fractions, respectively, after conveying, corrected for the amount of each fraction present in the existing quality, see Eq.2. U\_10mm, U\_8mm, U\_2\_36mm and U\_Dust are the corresponding uncorrected values. Different fractions generated among the three diets are labeled A, B or C\_10; A, B, or C\_8; A, B or C\_2\_36 and A, B, C\_Dust, respectively.

The score plot (Fig. 5) showed that feed samples were organized in three main clusters according to pellet quality. However, within each main cluster, the samples were arranged in sub-clusters according to airspeed; highest airspeed on top and lowest airspeed in the bottom. Feeding rate contributed to lowest variation, but increasing the feeding rate indicated higher amount of whole pellets. Interestingly, decreasing airspeed and increasing feeding rate followed the same pattern within each main cluster with respect to whole pellets. The score plot thus corresponded to the loading plot showing that airspeed was positively correlated to the generation of dust, while feeding rate was positively correlated with whole pellets. The effect of feeding rate on the generation of both dust and fractures was quite small.

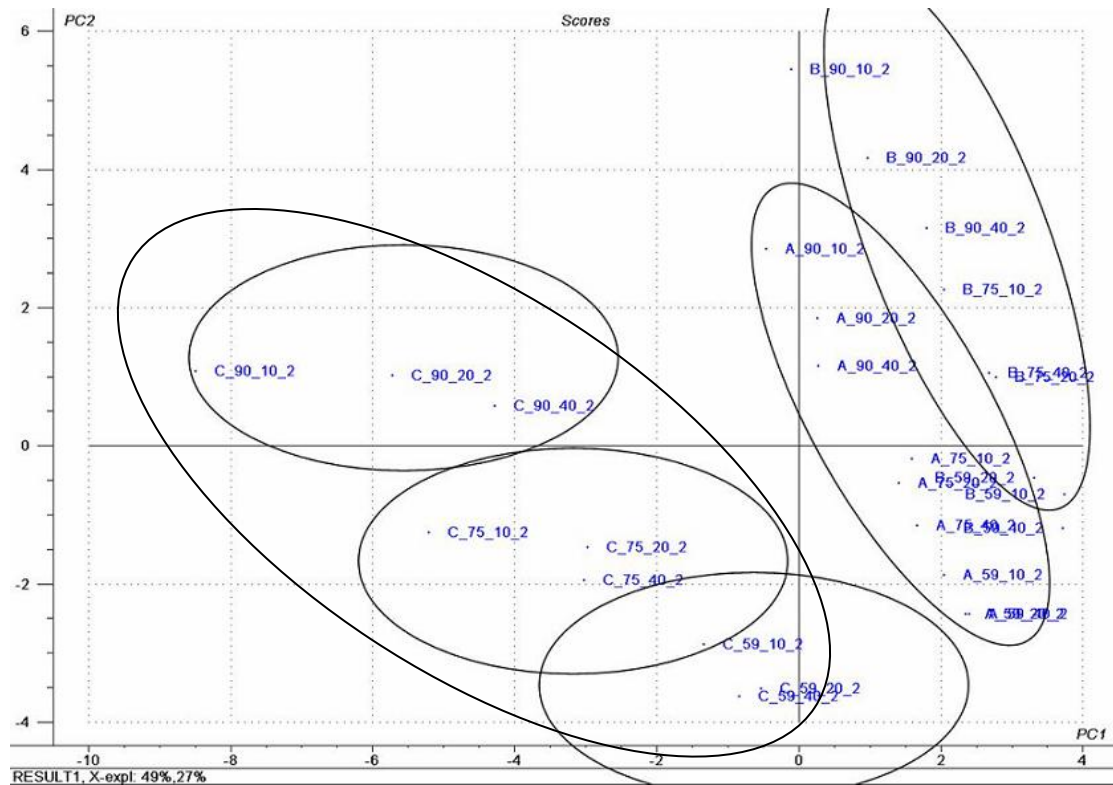


Figure 5 Score plot showing the samples corresponding to the results presented in Fig. 4. The samples are labeled as Feed\_Airspeed (%)\_ Feeding rate (%)\_Replicate.

Feed A was positively correlated to whole pellets (Fig. 4), and had the highest physical quality, measured by generation of the smallest amount of damage including dust and small particles (Fig. 6)

Feed B was positively associated with the generation of dust (Fig. 4), and it was ranked in between feed A and feed C in terms of physical quality. This was, however, the feed that had the highest proportion of dust in its total damage and the highest amount of dust as well during pneumatic transportation (Fig. 6).

Feed C was positively correlated to the generation of fractures (Fig. 4). The score plot (Fig. 5) also showed that feed C also was most affected by airspeed and feeding rate. As shown in Fig. 6, after pneumatic conveying, feed C generated the largest amount of damage, of which the amount of dust was the smallest though. The proportion of fracture in its total damage was the highest among all three feed. However, most of the broken pellets of feed C had a pellet size 8-10 mm (Fig. 6), which is probably edible for the fish.

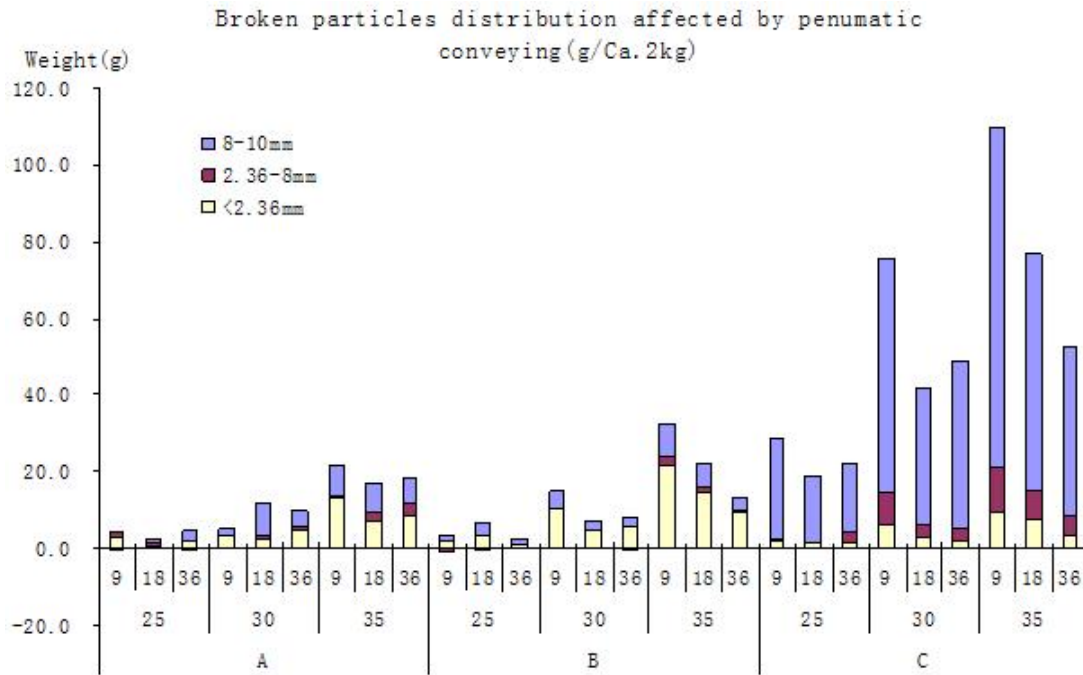


Figure 6 Generation of dust and small particles during pneumatic conveying. The number 9, 18, 36 in x-axis direction is the real feeding rate (kg/min). The number 25, 30, 35 is the real velocity of air flow (m/s).

### 3.1.2 Effect of airspeed on pellet degradation of three different feeds

The generation of dust for all three diets increased as airspeed increased (Fig. 7). Feed B generated more dust than feed A and C at the same airspeed (Fig. 7), i.e. airspeed affected feed B the most in generation of dust. Although feed C appeared to have the lowest physical quality, it generated the least dust. The smallest slope found in feed C (Fig. 7) suggested that airspeed affected feed C the least in the generation of dust.

As airspeed was increased, generation of fracture also increased for all three diets (Fig. 8). Feed C had the highest amount of fractures and the highest slope, suggesting that airspeed affected feed C the most in generation of fractures. This was consistent with results presented in the loading plot (Fig. 4). Feed A and B only slightly increased the amount of fracture with increasing airspeed suggesting that they were not susceptible of creating particles of this size during pneumatic conveying.

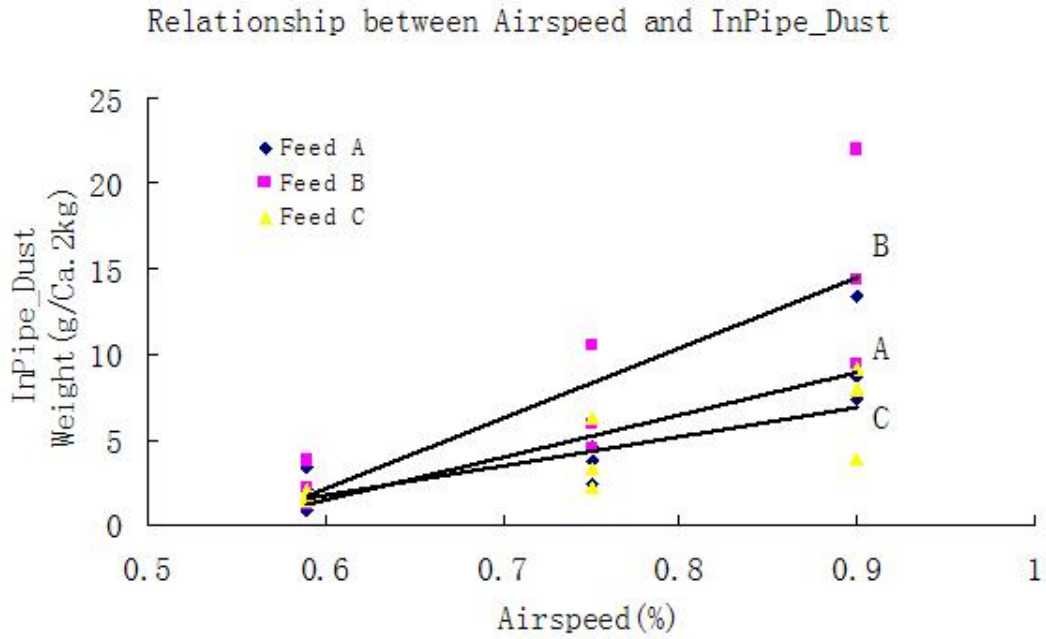


Figure 7 Effect of airspeed on generation of dust. *InPipe\_Dust*: The weight of dust purely generated by pneumatic conveying, and the weight of dust generated by sieving process was subtracted.

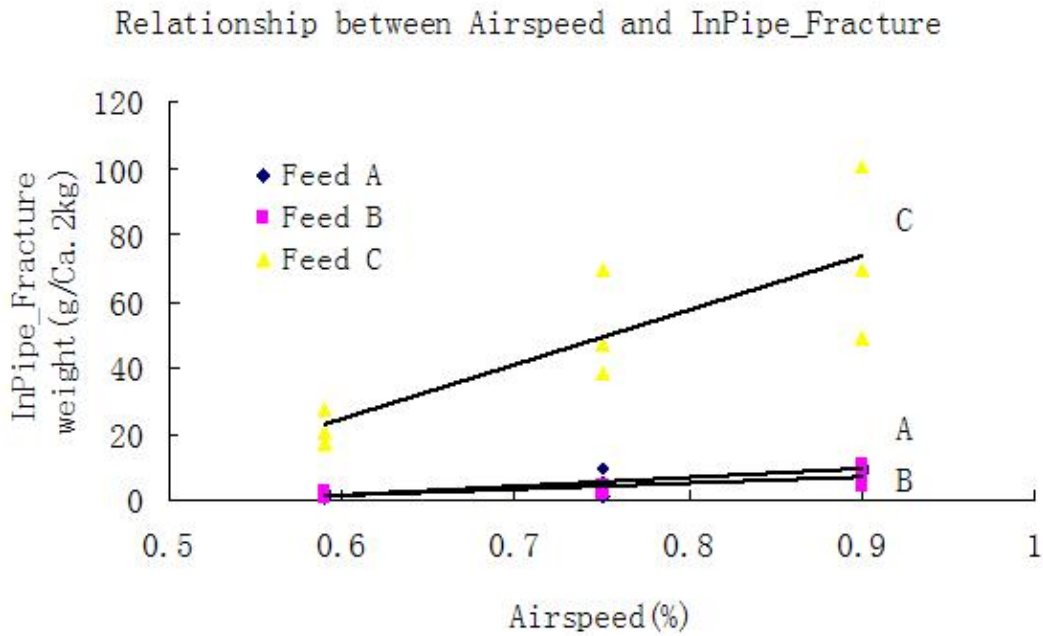


Figure 8 Effect of airspeed on generation of fracture. *InPipe\_Fracture*: The weight of materials above 8 mm and 2.36 mm sieves purely generated by pneumatic conveying.

### 3.1.3 Effect of feeding rate on pellet degradation of three different feeds

Increasing the feeding rate resulted in less dust for diets B and C (Fig. 9). At the same feeding rate feed B generated most dust and feed C generated least. The slopes of feed B and feed C lines were rather similar suggesting that increased feeding rate reduced formation of dust for both diets. The slope of feed A was nearly horizontal, suggesting that feed A was neutral to feeding rate in terms of forming dust. Although feeding rate was negatively correlated with the generation of dust, the loading plot (Fig. 4) suggested that the impact of feeding rate was still quite small.

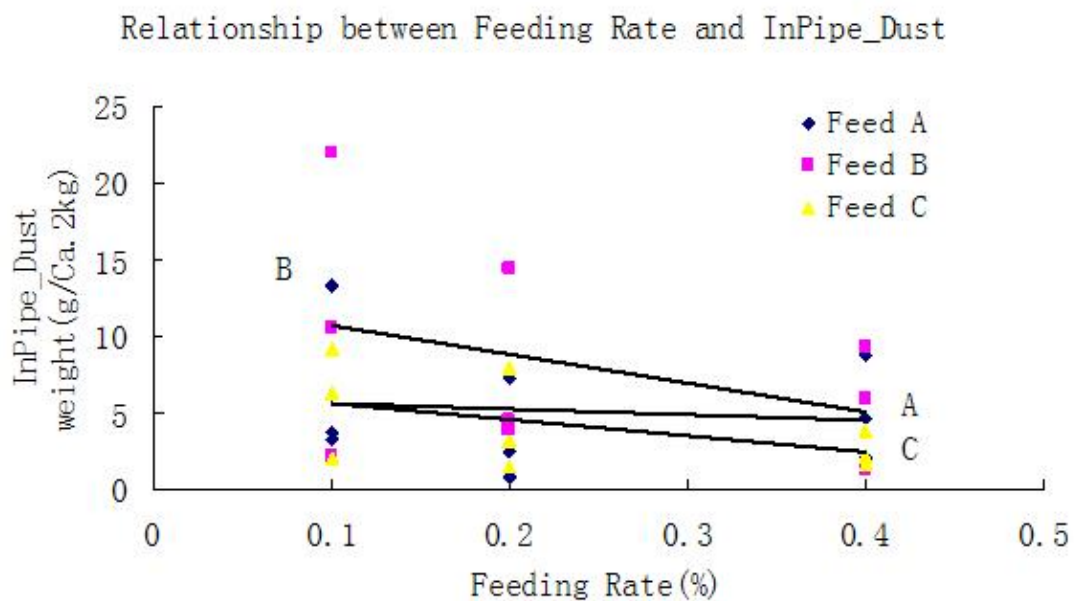


Figure 9 Effect of feeding rate on generation of dust.

The generation of fracture for feed C and feed B decreased as the feeding rate increased (Fig. 10), but for feed A, as the feeding rate increased, the generation of fracture increased. Feed C generated most fracture at the same feeding rate compared with feed A and B, thus feeding rate affected feed C the most in generation of fractures. But the effect of feeding rate for feed A and feed B was quite small.

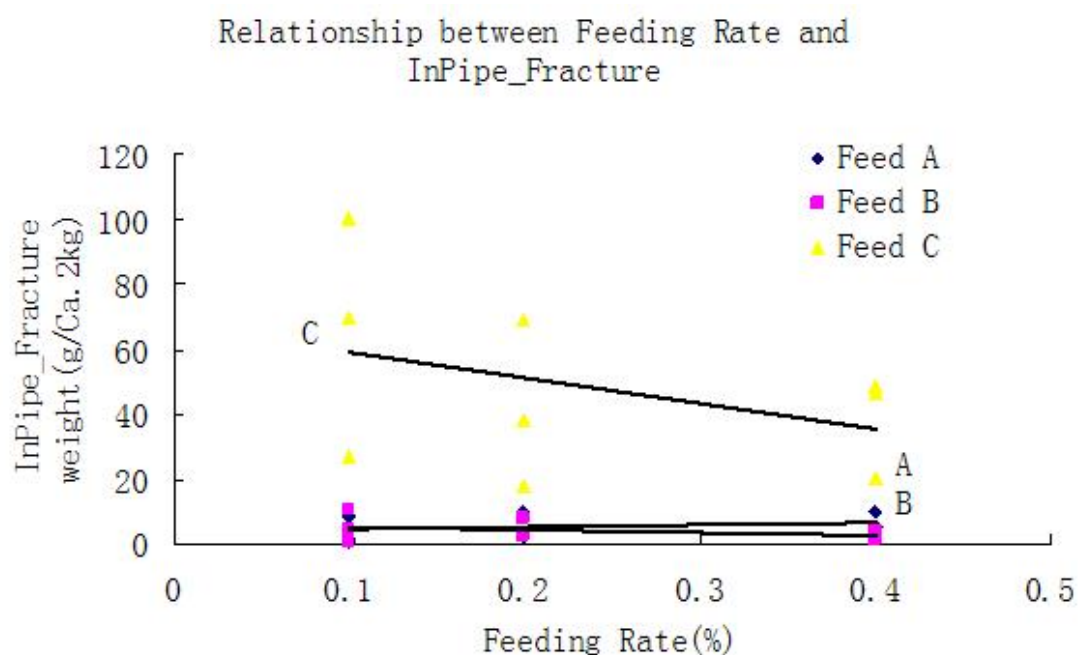


Figure 10 Effect of feeding rate on generation of fracture.

### 3.2 Physical quality of feed

#### 3.2.1 Doris values of samples from top and middle layer

There was a big difference between Doris value and fracture value among feed samples taken from the top and middle layer (Table 6). The Doris value and the percent fracture of sample from the middle layer were higher than the ones from top layer, suggesting that there were more broken pellets and dust as you went from the top to the bottom of the big bag. Feed A had the highest Doris value and Fracture at both top and middle layer, whereas feed C had the smallest Doris value and Fracture. Feeds B and C were rather similar in Doris value and Fracture value at the top layer.

Table 6 Doris and fracture values of feed sample from different layers of the big bag (Mean±Standard Deviation).

Feed	Top		Middle	
	Doris Value (%)	Fracture (%)	Doris Value (%)	Fracture (%)
A	32.6 ±3.15	27.9 ±2.64	50.7 ±1.13	44.8 ±1.04
B	19.1 ±2.43	16.5 ±2.26	48.1 ±3.40	43.3 ±3.00
C	19.0 ±3.44	17.9 ±3.14	35.7 ±2.14	33.7 ±1.74



Table 7 Correlation analysis result of main experiment and Doris test.

Pearson Correlation Coefficients, N = 8  
Prob > |r| under H0: Rho=0

	Doris_S	Frac_S	Doris_T	Frac_T	Doris_M	Frac_M	InPipe_D	InPipe_F
Doris_S	1.00000	0.98622 0.1058	0.85654 0.3452	0.91184 0.2693	0.15005 0.9041	0.11234 0.9283	-0.72904 0.4799	0.03794 0.9758
Frac_S	0.98622 0.1058	1.00000	0.75934 0.4510	0.83135 0.3751	-0.01560 0.9901	-0.05362 0.9658	-0.83224 0.3741	0.20276 0.8700
Doris_T	0.85654 0.3452	0.75934 0.4510	1.00000	0.99290 0.0759	0.63876 0.5589	0.60904 0.5831	-0.27120 0.8252	-0.48321 0.6789
Frac_T	0.91184 0.2693	0.83135 0.3751	0.99290 0.0759	1.00000	0.54272 0.6348	0.51038 0.6590	-0.38376 0.7493	-0.37565 0.7548
Doris_M	0.15005 0.9041	-0.01560 0.9901	0.63876 0.5589	0.54272 0.6348	1.00000	0.99926 0.0242	0.56733 0.6160	-0.98227 0.1200
Frac_M	0.11234 0.9283	-0.05362 0.9658	0.60904 0.5831	0.51038 0.6590	0.99926 0.0242	1.00000	0.59824 0.5917	-0.98869 0.0958
InPipe_D	-0.72904 0.4799	-0.83224 0.3741	-0.27120 0.8252	-0.38376 0.7493	0.56733 0.6160	0.59824 0.5917	1.00000	-0.71164 0.4959
InPipe_F	0.03794 0.9758	0.20276 0.8700	-0.48321 0.6789	-0.37565 0.7548	-0.98227 0.1200	-0.98869 0.0958	-0.71164 0.4959	1.00000

- Doris\_S: Doris value of sample supplied by Skretting.
- Fract\_S: Fracture value of sample supplied by Skretting.
- Doris\_T: Doris value of sample from top layer, Akvasmart.
- Fract\_T: Fracture value of sample from top layer, Akvasmart.
- Doris\_M: Doris value of sample from middle layer, Akvasmart.
- Fract\_M: Fracture value of sample from middle layer, Akvasmart
- InPipe\_D: The weight of dust purely generated by pneumatic conveying, corrected with values from the control sieving.
- InPipe\_F: The weight of materials above 8 mm and 2.36 mm sieves purely generated by pneumatic conveying, corrected with values from the control sieving.

A correlation analysis among Doris value, Fracture, InPipe\_Dust and InPipe\_Fracture (Table 7), showed that only Doris\_M was significantly correlated with Frac\_M, of which the R value was 0.99926 and P value was 0.0245. There also existed correlation between Doris\_T and Frac\_T, InPipe\_F and Frac\_M, of which the P value was less than 0.1.

### 3.2.2 Physical quality measurements

As shown in Table 8, feed A had the highest durability and feed C the lowest. Feed C had a significant difference in PDI compared to feeds A and B, while there was no significant difference between feeds A and B. In diameter, the difference was significant between feeds A and B, and feed C had no significant difference neither to feed A nor to feed B. In length, the difference was significant between feeds B and C. According to Force/Distance, feed C was numerically ranked as the hardest and feed A was ranked numerically as the easiest to crack, but there were no significant differences among any of the three feeds. In bulk density and fracture, feed A was significantly different from feeds B and C, which were not significantly different. All three feeds were significantly different in Doris value and specimen weight.



**Table 8** Physical characteristics of feed A, B and C measured as pellet durability index, pellet diameter and length, hardness, bulk density, Doris value, fracture and specimen weight (Mean±Standard Deviation).

	Feed	A	B	C
<b>Ligno Test</b>	<b>PDI (%)</b>	<b>99.3<sup>a</sup> ±0.57</b>	<b>99.1<sup>a</sup> ±0.31</b>	<b>97.5<sup>b</sup> ±0.20</b>
Texture Analysis	Diameter (mm)	11.2 <sup>b</sup> ±0.17	12.0 <sup>a</sup> ±0.24	11.6 <sup>ab</sup> ±0.18
	Length (mm)	11.8 <sup>ab</sup> ±0.21	11.4 <sup>b</sup> ±0.20	12.2 <sup>a</sup> ±0.19
	Force/Distance <sup>1</sup> (N/mm)	35.5 <sup>a</sup> ±0.92	40.5 <sup>a</sup> ±24.26	51.5 <sup>a</sup> ±36.75
Bulk Density	Bulk density (g/L)	668.7 <sup>b</sup> ±2.73	660.0 <sup>a</sup> ±2.62	682.3 <sup>a</sup> ±5.27
Doris Test (AVG)	Doris value (%)	41.7 <sup>a</sup> ±2.02	33.6 <sup>b</sup> ±2.90	27.4 <sup>c</sup> ±2.18
	Fracture (%)	36.3 <sup>a</sup> ±1.75	29.9 <sup>b</sup> ±2.63	25.8 <sup>b</sup> ±1.95
Specimen Weight	Specimen weight (g)	1.2 <sup>c</sup> ±0.02	1.3 <sup>b</sup> ±0.01	1.4 <sup>a</sup> ±0.01

<sup>1</sup> Force/Distance equals to the breaking force of the pellet divided by the distance of distortion to start breakage.  
<sup>a,b,c</sup> Different superscripts express significant differences (P<0.05).

As shown in Table 9, PDI was correlated to all other measured physical quality characteristics except Force/Distance. Specimen weight was negatively correlated to Doris value, fracture and dust, and there were positive correlation among Doris value, fracture and dust. Bulk density was negatively correlated to dust, but positively correlated to length.

**Table 9** Pearson correlation analysis among different physical quality characteristics.

Variable 1	Variable 2	R value	P value
PDI	Length	-0.73387	0.0244
PDI	Bulk density	-0.75187	0.0195
PDI	Doris value	0.72515	0.0271
PDI	Fracture <sup>1</sup>	0.67777	0.0448
PDI	Dust <sup>2</sup>	0.83671	0.0049
PDI	Specimen weight	-0.80673	0.0086
Length	Bulk density	0.91961	0.0004
Bulk density	Dust	-0.60562	0.0839
Doris value	Fracture	0.99656	<0.0001
Doris value	Dust	0.96856	<0.0001
Doris value	Specimen weight	-0.94061	0.0002
Fracture	Dust	0.94460	0.0001
Fracture	Specimen weight	-0.92232	0.0004
Dust	Specimen weight	-0.95642	0.0001

<sup>1</sup> Fracture equals to the amount of small particles formed during doris test.

<sup>2</sup> Dust equals to the amount of dust formed during doris test, Dust = Doris value – Fracture.



## 4 Discussion

### 4.1 Effect of airspeed on degradation of pellet

In dilute phase pneumatic conveying, airspeed is the most important factor that determines the effectiveness of conveying and the degradation of pellets (Norambuena, 2005). A low airspeed may not provide enough force to ensure proper conveying of the pellets. Feeding the fish to satiation will take longer time, or even worse, cause blockage of the pipeline if the conveying airspeed is lower than the minimum velocity. On the other hand, too high airspeed can generate turbulent flow, which may give more degradation of pellets and higher wear and tear of the pipeline.

Airspeed had high correlation with airflow temperature before and after cooler (Fig. 4). The compressor increases the pressure on the air so that the air can be transported through the pipeline. Air is compressible and as the compressor reduces the volume, the temperature increases. Increased airspeed was brought about by increasing speed of the rotary blower, hence higher airspeed raised the pressure and the airflow temperature.

As shown in the loading plot (Fig. 4), airspeed was obviously associated with the generation of dust for all three different feeds used in this experiment. The pellet velocity during suspended pellet flow is slightly more than half the air velocity, about 55% (Aarseth, 2004). Air flow exerts thrust force on the cross section of pellets and the drag force on their surface (Salman, 2002), which accelerates them to move forwards. The surface attrition of pellets caused by drag force of air is one of the most important factors generating dust during pneumatic conveying. Increased drag force with increased airspeed may result more surface attrition and thus more dust.

Another reason for generation of more dust with higher airspeed is due to increased surface attrition among pellets caused by the frictional force between pellets and pipe wall. The collision between particles can be neglected in dilute phase pneumatic conveying (Salman, 2002). In dilute phase pneumatic conveying, high airspeed will generate more or less turbulent flow of pellets, even if the pellets are of big size and high density. Turbulent flow increases the attrition not only between pellets, but also between pellets and pipe wall, therefore generates more dust.

The loading plot (Fig. 4) also presented the relationship between airspeed and the generation of fracture (small particles on 8 mm and 2.36 mm sieves). Although the variation in airspeed was more correlated to PC2, and thus more associated with formation of dust, it also affected formation of fractures in PC1. As shown in Fig. 8, the generation of fracture increased as airspeed was increased. However, the effect of airspeed was rather low except for feed C. Feed C made the highest amount of fracture regardless of airspeed. The generation of fracture during pneumatic conveying was mainly explained by PC1 and variation in feed quality, and not so much explained by airspeed.

In general, there are three fragmentation mechanisms (Aarseth, 2004): (1) chipping fracture; (2) cleavage fracture; (3) destructive fracture or fragmentation. Although high airspeed may increase the collisions of pellets, joint or bend construction are the most important factors for generation of fractures. Most of the fragmentation is expected to have taken place in the bend of pipe (Salman, 2002; Kalman, 1999). The response to impact velocity is significantly influenced by the particle size (Salman, 2002).

High airspeed increases pellets velocity, hence the retention time of pellets is reduced in the pipe. The present result suggested that in a dilute phase pneumatic conveying, the retention time didn't affect the degradation of pellets significantly.

#### 4.2 Effect of feeding rate on degradation of pellet

Feeding rate adjusts the mass of pellets conveyed through the pipelines and may decide the mode of pneumatic conveying. Usually the fish farmers require a high feeding rate in order to satisfy that a high number of fish in a pen with a minimum of time. However, higher feeding rate require a higher power consumption of the blower to generate high airspeed to move the pellets forwards, and may in worst case cause blockage of the pipe.

Increased feeding rate indicates that more pellets are conveyed at the cross section of pipe instantaneously (Fig. 11). The loading plot (Fig. 4) showed that feeding rate had equal contribution to explaining variation in fracture (PC1) and dust (PC2), however, the loading was rather small. Thus, less dust and fracture was created during pneumatic transportation when the feeding rate was high. This seemed to be most important for feed B (generating the highest amount of dust) and feed C (generating the highest amount of fracture).

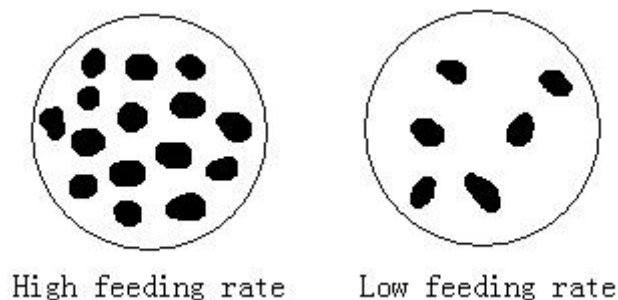


Figure 11 Distribution of pellets at the cross section during conveying at high and low feeding rate.

As shown in Fig. 11, the fact that more pellets will be conveyed at the cross section of pipe instantaneously reduces the air space in the bulk pellets, which minimizes the effect of turbulent flow. The pellets stay at a relatively stable status during pneumatic conveying, and a friendly protection by pellets themselves is formed. Under this protection, the frictional force is reduced and therefore less dust is generated. The generation of fracture is also reduced due to the same mode of action.

#### 4.3 Effect of feed physical quality on degradation of pellet

The most important variation in physical quality was described by PC1 (Fig. 4), which moreover was mostly explained by variation in whole pellet, thus physical quality. This indicates that variation in physical quality of the feed was more important to prevent degradation of the pellets during pneumatic conveying than airspeed or feeding rate. Several factors affect physical quality of feed, however, we do not have detailed information about ingredient composition or processing conditions.

Feed C showed the highest degradation during the pneumatic conveying (Fig. 6), and this feed made a higher proportion fracture than dust, indicating that the effect of crash exceeded abrasion during pneumatic conveying. In fracture generation, feed C is the one affected by

airspeed and feeding rate most among all three feeds (Fig. 8 and Fig. 10). It was also found that feed C had the lowest PDI in the Lingo test (Table 8), which indicated that feed C had the lowest pellet durability.

Feed B generated the largest amount of dust but the smallest amount of fracture, and the highest proportion of dust in its total damage as well (Fig. 6), which indicated that feed B was more susceptible for abrasion than crash during pneumatic conveying. In generation of dust, the effects of airspeed and feeding rate for feed B were the biggest (Fig. 7 and Fig. 9), but in generation of fracture, the effects of airspeed was the smallest (Fig. 8).

Feed A generated both fracture and dust in the middle level among all three feeds (Fig. 6 and Table 5). But it generated the smallest amount of total damage, which indicated that it had the highest physical quality and was the most suitable for pneumatic conveying. Evaluating physical quality by use of lingo confirmed the result (Table 8).

#### **4.4 Difference between the Doris values and some physical quality characters**

Differences were observed between the Doris values measured by the feed producer and the values measured at Akvasmart, Bryne. The values measured at Akvasmart by sampling from both top and middle layer were all higher than the ones supplied by Skretting, except feed C at top layer (Table 1 and Table 6).

One explanation is that different sieve sets and sieving procedure were used by Skretting and Akvasmart, respectively. Skretting sieved the samples with amplitude 1.5 for 30 sec with sieve set of 9.6 mm, 2.37 mm and dust pan. At Akvasmart samples were sieved with amplitude 2.3 for 2 min with sieve set of 10 mm, 8 mm, 2.36 mm and dust pan. Another plausible explanation may be that the pellets when arriving at Akvasmart had formed small particles and dust during bagging and transportation.

Representative samples are of critical importance since fracture and dust generation of pellets considerably depend on which layer the sample was taken from. Doris values were measured on samples from the top layer at the very beginning and from the middle layer of the big bag. Samples from the middle layer were analyzed when the main experiment was finished. The different results shown in Table 6 clearly demonstrated that the results were affected by the sampling procedure. The main experiment, however, was executed using a completely randomized design ensuring that samples were taken from all over the package when investigating the degradation of pellets during pneumatic conveying.

The Doris test is supposed to simulate the pneumatic conveying. We therefore expected to find a high correlation between the Doris value and generation of dust and fracture during pneumatic conveying. In this experiment, as shown in Table 7, the correlation was low, but tended to be significant when feed samples were taken from the middle layer in the big bag.

All three feeds were nearly the same in diameter (Table 8), but feed C was the longest. Since feed C generated more fracture during pneumatic conveying, the result may suggest that length affect formation of fracture during pneumatic conveying.

Although no significant correlation was observed between Doris test and hardness of the pellets (texture analysis), the numeric values appeared to have an inverse relationship (Table 8). When hardness increased, the Doris values decreased. The negative correlation between the Doris value and the bulk density suggest that low expansion of the pellets may be a reduce formation of dust and small particles during pneumatic conveying. The correlation between the PDI measured with the lingo tester and the Doris value as well as length and

bulk density should be interpreted with care (Table 9). In general, the PDI values were very high and showed low variation among the three diets. Besides, the PDI from the lingo test showed the opposite result of the hardness and the Doris test. Thomas and van der Poel (1996) described that the attrition of pellets comprises two phenomena, fragmentation and abrasion. Fragmentation involves the fracture of pellets into smaller particles and fines at the fracture area, which is generally in connection with the hardness of pellets. Abrasion involves the fracture on the edges or surface of particle, and is generally associated with the durability of pellets. The Ligno test mainly focuses on the effect of abrasion, and therefore measures the durability of sample, whereas texture analysis and Doris test mainly focus on the effect of fragmentation, which present the hardness of sample. Due to the different work principles of the Ligno test, Doris test and texture analysis, and also different physical quality parameters, it is quite possible that the results of the different measurements are correct although they not necessarily are highly correlated.

Physical quality of extruded fish feed is affected by several variables, among which formulation (Refstie, et al., 2007; Øverland et al., 2007; Sørensen et al., 2008) and extruder parameters (Aarseth et al., 2006; Barrows et al., 2007; Sørensen et al., 2008) are recognized as having great influence. However, since we don't have details regarding ingredient composition or processing parameters from the production of the diets, a discussion about causative factors for the differences in physical quality beyond the scope of this investigation.

#### **4.5 Practical consideration of pneumatic conveying conditions**

Besides considering the degradation of feed during pneumatic conveying, conveying time and the mass of feed to be spread to fish at the same time are also quite important to satisfy the fish farmers' needs. In general, shorter conveying time and bigger mass of feed spread to fish instantaneously are demanded by most customers. But shorter conveying time means that the airspeed should be increased, which will cause more degradation of feed. The longer the feeding rate, the higher the airspeed required keeping the same conveying time. Therefore, it is quite important to compromise among all these factors.

The feeds with different physical quality need to be pneumatically conveyed in different conditions. Because of the positive effect of airspeed and the negative effect of feeding rate on degradation of pellets, it is better to convey feed of high physical quality at higher airspeed, and the feeding rate can be set by considering the requirement of feed amount that needs to be spread instantaneously. For the feed of low physical quality, it is better to decrease airspeed but increase feeding rate to minimize the degradation of pellets.

## **5 Conclusion**

The three different diets varied in degradation during pneumatic conveying. Low correlation between Doris test and degradation during the pneumatic conveying suggested that it is difficult to predict which feed that is most susceptible to form small particles and dust during pneumatic conveying. Airspeed was highly associated with formation of dust and small particles: the higher the airspeed was, the more dust and fractures were formed. A higher feeding rate seemed to reduce formation of fines and small particles, in particular for the diets that formed the highest amount of fines. The overall conclusion from the experiment was that pellets with high quality generate low amount of dust and small particles during pneumatic conveying, regardless of feeding rate and air speed. Pellets with a low quality should be conveyed with a lowest possible airspeed in combination with a high feeding rate. One of the main challenges for future research is to find methods to evaluate physical quality that has a higher correlation to formation of dust and small particles during pneumatic conveying of feed.





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