The United Nations University
FISHERIES TRAINING PROGRAMME
P.O. Box 1390, Skulagata 4
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Final Project 2004

STUDY ON HEAT PUMP DRIED SHRIMP AND FISH CAKE

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ABSRACT

Peeled, headed and whole shrimp as well as fish cake of 50 mm (diameter) × (7-9) mm (thickness) and 50 mm × (14-18) mm were dried in a heat pump dryer at -2~0°C and 20°C. Physical and sensory properties as well as the stability of the dried products were evaluated. The desorption isotherms of shrimp and the adsorption isotherms of shrimp and fish cake were investigated. The results show that the drying time decreased greatly and the degree of shrinkage became higher as drying temperature increased from -2~0°C to 20°C. Higher shear force was required to cut the dried shrimp samples when the drying temperature was increased. Drying temperature (-2~0°C or 20°C) has no measurable effect on the sorption isotherms of the headed and whole shrimp and has little influence on peeled shrimp, but it affects significantly the adsorption characteristic of fish cake. The drying and drying rate curves display that the drying process of shrimp and fish cake could be well described by the diffusion model ($MR = A \exp(-kt)$). The results demonstrate that the Oswin model ($X = a\,[a_w/(1-a_w)]^n$) is suitable for predicting the desorption isotherms of shrimp and the adsorption isotherms of shrimp and fish cake. The hysteresis phenomenon between desorption isotherms and adsorption isotherms of frozen peeled shrimp has been observed in the range of $a_w>0.85$ and $a_w = 0.75\text{-}0.88$ when dried at -2~0°C and 20°C, respectively. A strong hysteresis existed in thawed peeled shrimp at $a_w>0.65$. Frozen headed shrimp dried at 20°C (B-2) had the best synthetic performance compared with all the shrimp samples, and thin fish cake dried at -2~0°C (D-1) is the best of the fish cake samples.

Keywords: Heat pump drying; Shrimp (*Pandalus borealis*); Fish cake; Shrinkage; Colour; Rehydration; Texture; Water activity; Stability; Sorption isotherm.

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1 INTRODUCTION

Fish and shrimp represent major sources of protein for human consumption. Preservation is an important issue as fish and shrimp products are perishable. Drying has been shown to be an efficient and cheap method for food preservation. It has been used to preserve fish and shrimp for a long time in most parts of the world. On the other hand, besides the preservation purposes, the demand for dried fish and shrimp has also been driven by the flavour of the products. For example, dried and seasoned squid products are popular as snack foods in Japan (Mauricio and Satoshi 1998). Dried salted codfish is a popular food in Southern Europe, West Africa, Canada and the Caribbean (Sankat and Mujaffar 2003, Doe 1998). Shark is commonly used in the production of dried salted fish in Trinidad and Tobago (Sankat and Mujaffar 2003). Dried shrimp has a long tradition in the Orient and is gaining wide acceptance in the US and European markets (Lin *et al.* 1999). In recent years, the annual world production of dried, unsalted fishery products has been 350,000 tons, and the world production of dried fish has been estimated above 3 million tons (Arason 2003).

Dried fish and shrimp are consumed in many countries but because most of the fish and shrimp are sun dried or hot air dried, severe deterioration in quality often occurs during the drying process (Skonberg *et al.* 1998, Cho *et al.* 1989). However, there is increasing demand for high quality food products today. Recent trends towards more functional and healthier food products have been strengthened in the European Community (Dirk and Markus 2004). In order to solve this problem, some new drying methods and techniques have been used in fish and shrimp drying such as vacuum freeze drying and microwave drying. But this raises some other problems, namely, increase in energy consumption and cost (Bala 2001, Chua 2002).

A heat pump could play a key role in fish and shrimp drying. Improved quality of dried fish and shrimp products can be achieved with this innovative technology due to its low drying temperature and independency of outdoor air. Also, energy consumption is reduced because of the high coefficient of performance of the heat pump and the high thermal efficiency of a properly designed dryer (Dirk and Markus 2004, Braun *et al.* 2002, Wang and Chang 2001).

In this project, some drying experiments of shrimp and fish cake have been carried out with heat pump drying equipment. The heat pump drying characteristics of shrimp and fish cake as influenced by drying temperature and the types of materials (peeled shrimp, headed shrimp, whole shrimp, thin or thick fish cake) were investigated. At the same time, the physical and sensory properties of dried shrimp and fish cake such as shrinkage, colour, rehydration, texture and water holding capacity (WHC) were studied. In order to evaluate the quality of dried shrimp and fish cake, chemical and microbiological analysis were carried out. Moreover, desorption and adsorption isotherms of dried shrimp and fish cake were determined. On the basis of these studies, the effect of heat pump drying on the quality of dried shrimp and fish cake were evaluated, and the application of a heat pump in drying production was also appraised.

2 LITERATURE REVIEW

2.1 Progress in fish and shrimp drying

Drying means that water is extracted from a substance. The conventional methods for fish and shrimp drying are sun drying and hot air drying. Open-air sun drying is still the most common method used to preserve fish and shrimp in many developing countries due to its low price (Ichsani and Dyah 2002, Bala and Mondol 2001, Wall *et al.* 2001, Hollick 1999, Lin *et al.* 1999, Esper and Muhlbauer 1998). But, open-air sun drying can not dry fish on rainy days and can lower significantly the quality of dried fish and shrimp in uncertain weather. Moreover, contamination by dust, over drying and insect infestation is typical in open-air sun drying. Some reports indicate that losses from insects, animals and weather may be up to 30-40% (Wall *et al.* 2001, Hollick 1999).

Because of the problems associated with sun drying, indoor hot air drying has been widely used in fish and shrimp drying for many years (Teeboonma *et al.* 2003, Konishi and Kobayashi 2003.). It is a great advantage to be able to dry fresh fish and shrimp all year round and not be dependent on weather conditions. Furthermore, drying time is reduced from several weeks of outdoor sun drying to a few days of indoor hot air drying (Arason 2003).

Nevertheless, no matter which method is used to dry, two things are of primary importance during drying, i.e., the heat transfer that causes the evaporation of water and the mass transfer of the evaporated water through the substance and subsequently the removal of moisture away from the surface of the substance itself. Usually the drying process is divided into two periods, a period of constant drying rate and a period of falling drying rate. The first period is characterized by the surface of the substance being entirely saturated with moisture at the wet-bulb temperature of the air; air velocity, temperature and the level of humidity control the drying rate. During the period of falling drying rate, the surface of the substance is already dry but the evaporation occurs inside the fish flesh. Now, air velocity has less effect and the speed of the drying process is mainly dependent upon the resistance against the water flow to the surface of the substance and the force which pushes the water to the surface. The former is mainly dependent on the nature of the material, but the air temperature has a great effect on the latter (Wallace *et al.* 1973(a)). That is to say, the higher the temperature the faster the drying rate. However, higher drying temperature usually causes lower quality of products (Doe, PE *et al.* 1998 and Burt 1988). So in hot air drying of fish and shrimp, the air temperature can not be too high and the drying time is longer. For example, the hot air drying time of sardine (30g) is 50-110 hours at a temperature of 35-50°C (Bellagha *et al.* 2002). Using air at a temperature of 40-60°C to dry shark fillets (10cm×5cm×1cm), the drying time needed was about 70 hours (Sankat and Mujaffar 2003).

In recent years, some new drying technologies have started to be used in fish drying, such as vacuum freeze drying and microwave drying. Vacuum freeze drying, in which the moisture is sublimed from a frozen product in a vacuum, has certain advantages over other means of drying: there are no major changes in the size, shape and colour of the fish and the products rehydrate rapidly when soaked in water (Sablani *et al.* 2001, Wollf and

Gilbert 1990). Generally speaking, vacuum freeze drying can attain high quality products. But the cost of vacuum freeze drying is very high and the production price is several times that of air drying (Chua *et al.* 2002). Vacuum freeze dried products also need to be properly packaged and stored, otherwise they will deteriorate rapidly. Another disadvantage is that vacuum freeze dried products do not have the same flavour as other dried products (Wallace *et al.* 1973b).

Microwave and vacuum microwave drying offer an alternative way to improve the quality of dried products (Drouzas *et al.* 1999, Kiranoudis *et al.* 1997). Microwave drying can provide a rapid heat transfer. Evaporation of moisture within the food is fast during microwave drying because water boiling in the food results in a large vapor pressure difference between the center and the surface of the products. Thus, food can be dried quickly without exposure to high temperature. But, because the drying rate is so fast in microwave drying, it is important to determine and control the end point of the drying process, otherwise the products are easily overdried (Mallikarjunan *et al.* 1996).

A heat pump dryer is a device that can take the thermal energy from a lower temperature source, and then release it at high temperature (Dirk and Markus 2004). Unlike in hot air drying, a heat pump dryer can utilize the latent energy of evaporation, and most of the energy can be reused. At the same time, because most of the air used for drying is reused, the products can be dried relatively independently of the outdoor air (Dirk and Markus 2004, Wang and Chang 2001). Meanwhile, a heat pump dryer is suitable for working at lower temperatures. Therefore, it is possible to achieve a high quality of dried fish and shrimp products at a low price with a heat pump dryer.

2.2 Development of heat pump technology and the application in fish drying

2.2.1 Principles of a heat pump dryer

Heat flows naturally from a higher to a lower temperature. In order to transport heat from a heat source to a heat sink, external energy is needed to drive the heat pump. The great majority of heat pumps work on the principle of the vapour compression cycle. In such heat pumps a volatile liquid known as the working fluid and a refrigerant circulate through four main components (evaporator, compressor, condenser and expansion valve) (Dirk and Markus 2004, Bert 1995, Hans *et al.* 1981). The flow chart of this kind of heat pump is shown in Figure 1 (Bert 1995).

A heat pump dryer consists of two parts: the heat pump system and the drying chamber. Figure 2 shows the principle of a batch heat pump dryer. The operating principle of heat pump drying is such that hot air passes through the drying chamber and extracts the moisture from the damp material by convective transfer to the air. The air which now contains more moisture, is led pass the evaporator, where the moisture in the air will condense into water, and the working fluid (refrigerant) at low pressure is vaporised into the evaporator by the latent energy of the moisture from the dryer exhaust air. At the same time the air becomes dryer. The compressor raises the enthalpy of the working fluid of the heat pump and discharges it as superheated vapour at high-pressure. At the condenser, the work liquid condenses and releases energy to heat the dried air. The reheated dry air goes into the drying chamber and extracts the moisture from the damp material again.

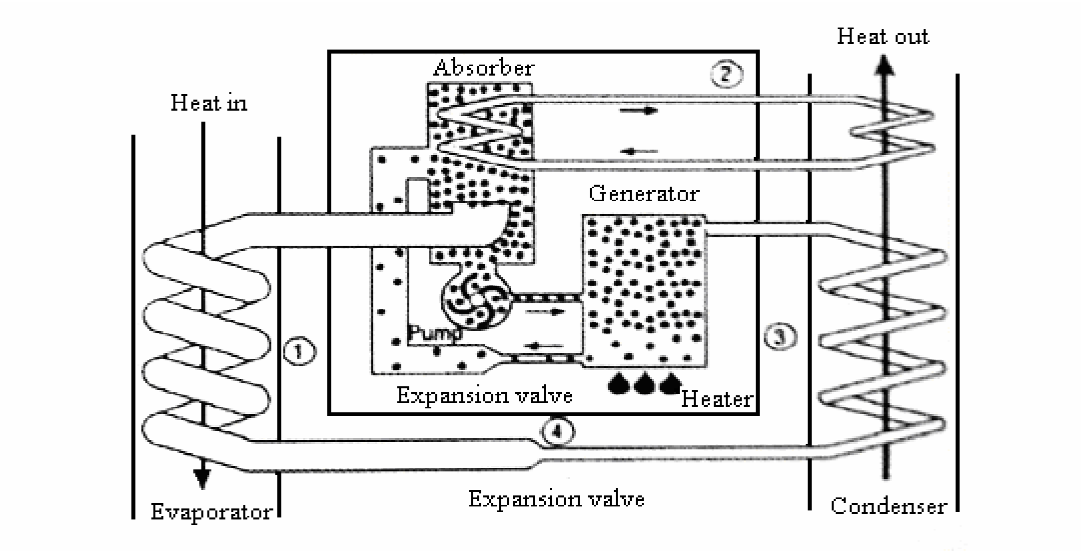

Figure 1: Diagram of a heat pump dryer.

(①: Evaportor; ②: Compressor; ③: Condenser; ④: Expansion valve**)** (Bert 1995).

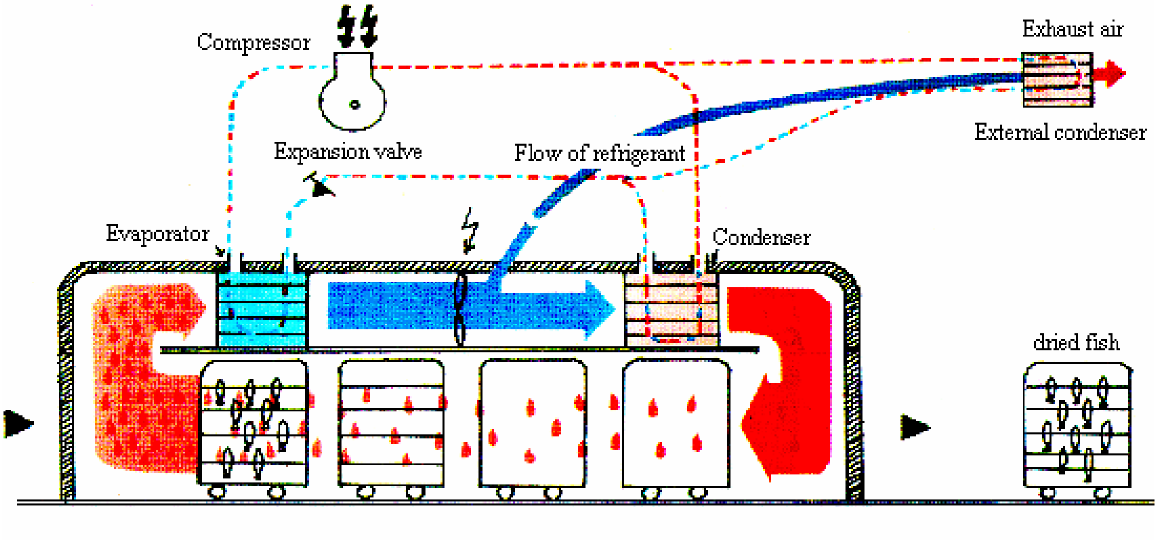

Figure 2: The structure and principle of batch heat pump dryer (Arason 2004).

2.2.2 Development of heat pump drying and its application in fish drying

Traditional drying is an energy consuming procedure. In most industrialised countries, the energy used in drying accounts for 7-15% of the total industrial energy used often with a relatively low thermal efficiency ranging from 25% to 50% (Dincer 1998, Mujumdar 1987). Some highly industrialised countries use over one third of their primal energy for drying operations (Dirk and Markus 2004). These figures clearly indicate why most studies have been focused on examining potential energy savings in the drying processes. Heat pump drying is one of the most efficient methods for drying.

Heat pump dryers (HPD) have been in widespread commercial use since the 1970s, particularly in the timber and food drying industries (Paul *et al.* 2004). The studies on HPD can be classified in three groups. The first group includes studies in which the performance of these systems has been investigated, while the second group covers studies on developing simulation models. The investigations on the application of HPD to drying specific materials belong to the last group. Meyer and Greyvenstein (1992) proved that HPD were more economical than using electrical heaters and fuel burners. Arason (2003) compared the costs for different types of energy for drying cod head, indicating that except for using geothermal hot water, the price of using HPD was the lowest (Figure 3).

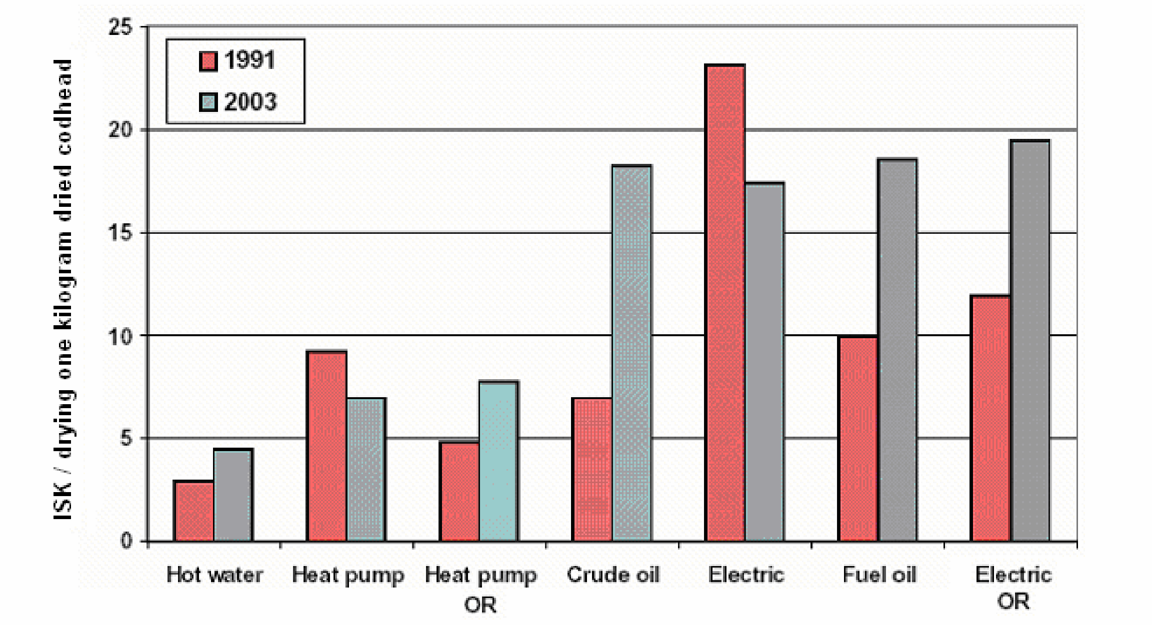

Figure 3: Comparison of costs for different types of energy for drying.

OR: Reykjavik Energy and Rarik. (Arason 2003).

Along with the development of heat pump drying technology, it has become important to establish empirical thin layer drying models by experimental studies. In the past two decades, many experimental studies on HPD dried agricultural materials have been carried out. Based on the three major models (compressor, evaporator and condenser models), some experimental models have been developed (Teeboonma *et al.* 2003, Achariyaviriya *et al.* 2000, Jolly *et al.* 1990, Chen and Pei 1989). In the application studies of HPD, it has been found that the colour and aroma qualities of dried agricultural products using HPD were better than when using conventional hot air dryer (Prasertsan *et al.* 1998 Soponronnarit *et al.* 1998, Strommen 1994). To maximize specific moisture extraction rates, Clement, Jai, and Jolly (1993) recommended that the evaporator bypass air ratio (BP) should be around 60-70%. To minimize energy consumption, Soponronnarit *et al.* (1998) suggested that the evaporator BP should be around 86-90%.

In Scandinavia there is a well established fish drying industry based on the application of heat pump drying technology. The special low temperature and low humidity capabilities of heat pump dryers are significant here. This is possibly the most successful application of heat pump drying (Paul *et al.2004*). There are two rack cabinet dryers with a heat pumping system which is used for cod head drying in Iceland. In these rack cabinet dryers, the air is heated in the condenser and then blown through the cabinet. In the evaporator, the air is cooled and the moisture, which was absorbed in the cabinet, is condensed before the air is heated again in the condenser. About 40% of the energy needed for heating is supplied by electricity, but the other 60% comes through the reuse of the condensing heat, which is released in the evaporator.

Generally speaking, heat pump dryers are an alternative method for drying fish and shrimp with low energy consumption, at low temperature and independently of outdoor air. But until recently few studies on fish and shrimp drying using heat pump dryers have been carried out. The objective of this research is to study the drying characteristics of shrimp and fish, investigate the effect of heat pump drying on the quality of dried shrimp and fish cake as well as to evaluate the application of heat pump drying in fish and shrimp drying production.

3 MATERIALS AND METHODS

3.1 Materials

3.1.1 Shrimp

Northern shrimp (*Pandalus borealis*), quick frozen on board (size 98-104 counts/kg) and frozen peeled northern shrimp (size 538-570 counts/kg) were purchased from the Icelandic Export Center Ltd.

Four different types of shrimp were used in this project, frozen peeled shrimp, thawed peeled shrimp, frozen headed shrimp (size 196-200 counts/kg) and whole shrimps. The headed shrimp were attained by removing the heads of the same shrimp under frozen conditions. All the samples were kept in frozen storage (-18~-20°C) before starting the experiment except the thawed peeled shrimp. Thawed samples were got by putting frozen peeled shrimp into flowing water of 5°C at the workshop temperature of 5-8°C for 30 minutes and then placing them on a grid until no water dripped off.

3.1.2 Fish cake

Fish cake was made from small fresh fish muscle by using an extruder. After being extruded, the fish cakes were frozen and stored in frozen storage (-20°C). The fish cake used in this project was in the shape of a cylinder and with a diameter of about 50 mm. Before the drying experiment, the fish cakes were cut into pieces manually under semithawed condition and divided into two groups. One with the thickness of 7-9 mm, the other group had the thickness of 14-18 mm.

3.2 Methods

3.2.1 Experimental design

Drying experiments of shrimp and fish cake were carried out with a batch heat pump dryer (designed by IFL and Seafood Bureau of Iceland, produced by Cooltech) at the Gullfiskur Company. The heat pump dryer is mainly used for the production of dried haddock fillets and its production cycle is 7 days. The working temperature of this dryer is divided into two steps in the whole drying process (Figure 4). During the first step, the temperature is kept at -2-0°C and lasts for 4 days. The temperature during the second step is 20°C and the duration is approximately 3 days.

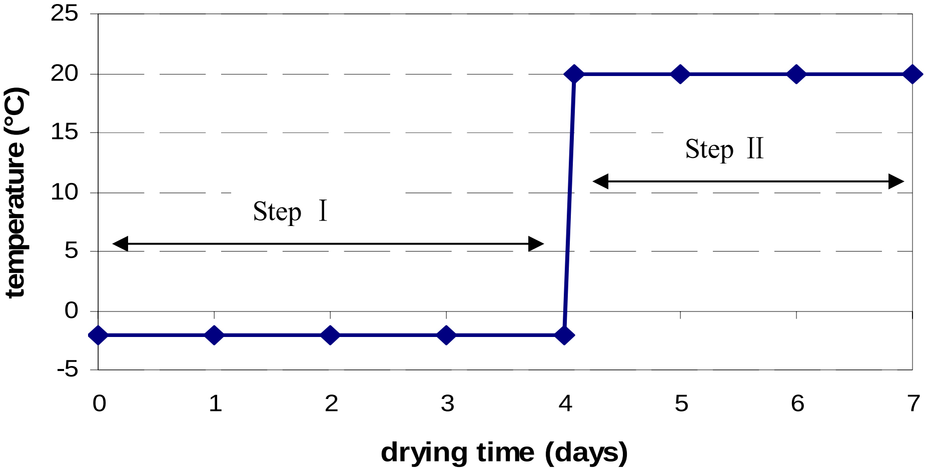

Figure 4: The two temperature steps of the heat pump drying process used for drying fish fillets. Step I: 4 days, drying temperature of -2~0°C; Step II: 3 days, drying temperature of 20°C.

In this project, a first batch of samples were placed in the first step of the drying cycle at a temperature of -2~0°C and a second batch of samples was put into the dryer when the drying temperature was increased to 20°C (see Table 1). In each experiment, approximately 300~400g of samples were put on a small grid (30×30 cm) and about 3kg~4kg samples were put on a large grid (100×120 cm). The samples were spread in a single layer both on small and large grids. During the experiments, the small grids were taken out at regular intervals (every 2 hours at -2~0°C or 1 hour at 20°C), weighed with a digital balance (accuracy of ±0.5g) and then returned to the dryer. Approximately 50 g samples were taken from the large grid and put into plastics bags and sealed as fast as possible. All the intermediate samples and final dried samples were stored in frozen storage (-18°C~-20°C). The initial water content of the samples was determined by drying in an oven at 102°C to 105°C for 4 hours. The water content changes were calculated according to the initial water content and the weight change of the samples. The final water content was 15-18% (wb). The temperature and relative humidity (RH) in the heat pump dryer were determined and recorded automatically every 5 minutes by

HOBO U12 Temp /RH Data Logger. The air flow rate in the heat pump dryer was measured with an anemometer (type: testo 452).

Table 1: The design of heat pump drying experiments

Group	Drying temperature*	Sample condition before drying	Symbol
1	-2~0°C	Frozen peeled shrimp	A-1
		Frozen headed shrimp	B-1
		Frozen whole shrimp	C-1
		Frozen thin fish cake	D-1
		Frozen thick fish cake	E-1
2	20°C	Frozen peeled shrimp	A-2
		Thawed peeled shrimp	A-3
		Frozen headed shrimp	B-2
		Frozen whole shrimp	C-2
		Frozen thin fish cake	D-2
		Frozen thick fish cake	E-2

3.2.2 Water content measurements

Water content was determined according to the ISO 6496 (ISO1990) method. About 5 g of sample was weighed accurately (±1 mg) in a pre-weighed clean and dry metal dish with a lid. The sample was heated in an oven at 102°C to 105°C for 4 hours. The lid was then placed on top of the dish with the lid cooled in a desiccator and then weighed. The water content of the sample corresponded to the weight loss observed and results were given as percentage of the weight of dried material (wb).

$$X = (\text{initial total weight} - \text{dried material weight}) \times 100 / \text{dried material weight}$$

3.2.3 Water activity (a_w) measurements

The Novasina AW-Center (AWC503 RS-C, Axair AG, Switzerland) used in this study can measure three samples simultaneously in a temperature controlled heating chamber. The instrument used sensors that had previously been calibrated with saturated salt solutions at six humidity reference points: RH =33%, 53%, 75% and 90%, offering a measuring range of a_w from 0.06 to 1.00. The sensors in the measuring chamber indirectly registered the humidity change in the conductivity of a hygroscopic electrolyte. Measurements were done at 25°C ± 0.2°C. The samples were placed in a clean and dry plastic sample cup. The analysis was done in triplicate.

3.2.4 Shrinkage measurements

The measurement of shrinkage was performed by measuring the thickness of the shrimp's body before and after drying using a Vernier. Thirty samples were measured for each experiment. The degree of shrinkage was defined as the ratio of the difference in diameter of the samples ($\Delta D = D - D_0$) to its initial diameter D_0 (Tein M. Lin *et al*. 1999).

$$r\ \% = (\Delta D / D_0) \times 100$$

3.2.5 Rehydration measurements

Before starting the rehydration, colour, water holding capacity and texture measurements, the samples of dried headed shrimp and dried whole shrimp were peeled manually.

The rehydration potential of dried samples was evaluated by immersing about 10 g samples in 100°C water. Samples were drained and weighed after 2, 4, 6, 8 and 10 min of rehydration (Tein M. Lin *et al*. 1999, Namsanguan *et al* 2004 BOTH MISSING). The samples were taken out of the boiling water and put on a grid until dripping stopped. The water absorbed (g) divided by the dry sample weight (g) was expressed as the rehydration ratio. The slope of the rehydration ratio vs. rehydration was defined as the rehydration rate. The samples after rehydration at 100°C for 10 min were then used to measure colour, water holding capacity and texture.

3.2.6 Colour measurements

Colour of the samples was measured with Minolta Chroma Meter CR-300, portable tristimulus colorimeter (Tein M. Lin *et al*. 1999, Prachayawarakorn Somkiat *et al*. 2002, Namsanguan *et al*. 2004). The colour space used was the L*a*b (also referred to as CIELAB) that is used in virtually all fields of colour measurement. L shows the lightness and a represents the redness (-a implies greenness) whereas b represents yellowness (-b implies blueness).

The dried headed shrimp and whole shrimp were deshelled before measuring the colour and rehydration ability. Colours of both dried and rehydrated samples were measured. A cylindrical plastic dish (8.5 cm diameter ×1.4 cm depth) was used for the colour measurement of shrimp. The plastic dish containing dried or rehydrated peeled shrimp was placed at the light port. For each treatment, twenty colour measurements were taken at random locations of the plastic dish and the average calculated. Evaluated values were the average of 20 measurements. For the colour measurements of dried or rehydrated fish cake, five pieces of fish cake were measured at 5 points on each side and the average of 50 measurements calculated. All the measurements were done in triplicate.

3.2.7 Water Holding Capacity (WHC) determination

Water Holding Capacity (WHC) was determined by a method that is built on a method described by Børresen T. 1978. The samples were centrifuged at 210*g and 0-5°C for five minutes in special sample glasses made from plexi-glass. Water removed during centrifuge was drained through a nylon membrane in the sample glasses. The rotor used was SS-34 for Sorvall centrifuge, type RC-5B (Dupoint, USA). Samples were prepared by chopping them in a Braun Mixer (Type 4262, Germany) for 10-15 seconds (until homogenous). The sample glass was weighed empty and then approximately 2 g of the sample were weighed into the sample glass. After centrifugation, the sample glass was weighed again with the sample in it.

The water holding capacity of the sample was then calculated using the following formula:

$$\%\text{Weight loss, } \Delta r = \frac{\text{Weight loss in centrifuge (g)}}{\text{Sample original weight (g)}} \text{x}100$$

$$\text{WHC} = \frac{\text{Water in the sample before centrifuge (\%) - } \Delta r}{\text{Water in the sample before centrifuge (\%)}}$$

3.2.8 Texture determinations

The texture of dried and rehydrated shrimps was evaluated by the shear resistance measured with a TA-XT2I Texture Analyzer (Stable Micro System, Surrey, England). The shear force required to cut through an individual shrimp was measured using a Warner-Bratzler (WB) device with an angular triangular shear blade and slot cutting edge (Tein M. Lin *et al*. 1999, Prachayawarakorn Somkiat *et al*. 2002, Namsanguan, *et al*. 2004). The crosshead speed used was 0.5 mm/s and the distance travelled by the blade was 30 mm. The maximum shear force was recorded automatically. The values of the shear force were the average of 30 measurements.

3.2.9 Protein measurements

Protein content of all the samples was determined by a standard method for analysing protein in fish or fish meal (ISO5983-1997). A 5 g sample was digested in sulphuric acid in the presence of copper (as a catalyst). The sample was then placed in a distillation unit (2400 Kjeltec Auto Sample System). The acid solution was made alkaline by a sodium hydroxide solution. The ammonia was distilled into boric acid and the acid was simultaneously titrated with diluted H_2SO_4. The nitrogen content was multiplied by the factor 6.25 to get the ratio of crude protein.

3.2.10 Fat measurements

Fat content of all the samples was determined by the method for analysing total fat in fish and fish meal (AOCS Official Method BA 3-88 and application note Tecator no. An 301. 1997 IS THIS A REFERENCE?).The sample was extracted with petroleum ether, boiling range 40-60°C. The extraction apparatus was the 2025 Soxtec Avanti Automatic System.

3.2.11 Salt measurements

Salt content of all the samples was determined by the method for measurement of salt in fish meal w/Titrino (AOAC 16th ed. 1995 no. 976.18). Soluble chloride was extracted from the sample with water containing nitric acid. The chloride content of the solution was titrated with silver nitrate and the end point was determined potentiometrically.

3.2.12 Total viable count (TVC) measurements

Total viable count (TVC) was determined by the pour-plate method (American Public Health Association (APHA): Compendium of Mehtods for the Microbiological Examination of Foods, 3. ed 1992.

25 g of minced samples were mixed with dilution buffer (225 ml) and then stomached for 1 minute. Further decimal dilutions were made and then 0.1 ml of each dilution was transferred with pipettes onto the surface of Petri plates. Iron agar melted at 45°C was poured on the plates and the content was mixed. After solidification the plates were covered with a thin layer of iron agar. Then the plates were incubated at 22°C for 48 hours. The values were the mean of the counts of two plates multiplied with the corresponding dilution factor.

3.2.13 Determination of stability and water sorption isotherms

Samples were placed on a grid in a container over the saturated salt solution and then the sealed cover was put on the container (Figure 5). Three different kinds of saturated salt solutions (K_2SO_4, KCl and NaCl) were made in three containers. The equilibrium relative humidity (ERH) in these environments could reach 97%, 85% and 75% respectively at room temperature (25°C). Before starting the experiments, the initial weight and initial water activity of all the samples were measured accurately. Two groups of experiments were carried out in this part. In the first group, the weight changes of the samples were measured every day and for a period of one week. During the second group of experiments, the first measurement was taken after 6 days and then measured once every two days. At the same time as measuring the weight changes, the changes in water activity were measured using the Novasina AW-Center. The temperature and relative humidity (RH) in the container were determined and recorded automatically by HOBO U12 Temp /RH Data Logger in 10 minute intervals.

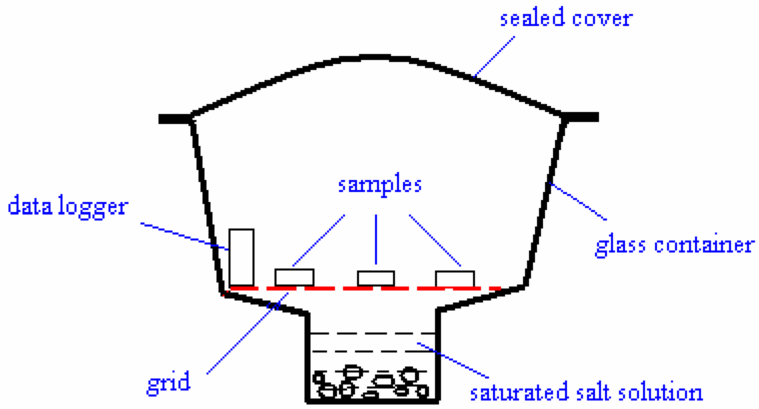

Figure 5: The structure of the vessels and the data determining method for measuring the stability of dried samples.

3.3 Data analysis

Microsoft Excel 2000 was used as the main method for data analysis in this study.

4 RESULTS

4.1 Characteristics of shrimp and fish cake in heat pump drying

4.1.1 The drying experiments of shrimp and fish cake

Eleven drying experiments of shrimp and fish cake were carried out in one drying circle at different periods of the heat pump dryer (see Figure 6). Experiment A-1 (frozen peeled shrimp) was dried in step I entirely (at -2~0°C). Experiments A-2 (frozen peeled shrimp), A-3 (thawed peeled shrimp), B-2 (frozen headed shrimp), C-2 (frozen whole shrimp) and D-2 (thin fish cake) were dried entirely in step Π (at 20°C). Most part of the drying process of E-2 (thick fish cake) was in step Π except the initial 6 hours which was in step I. The drying of B-1(frozen headed shrimp), C-1(frozen whole shrimp), D-2 (thin fish cake) and E-1 (thick fish cake) were started in step I and ended in step Π, but most part of the drying process was conducted in step I. The changes of drying temperature and RH in the whole drying process are shown in Figure 6 simultaneously.

4.1.2 Drying and drying rate curves

The initial water content of frozen peeled shrimp, thawed peeled shrimp, frozen headed shrimp, frozen whole shrimp and frozen fish cake was 84.2%, 74.5%, 71.1% and 81.4%, respectively. The air speed in the heat pump dryer was fixed in the range of 1.8~2.2 m/s. The RH varied from 40%~60% depending on the drying temperature (Figure 6). The drying curves of peeled shrimp (A-1, A-2, A-3), headed shrimp and whole shrimp (B-1, B-2, C-1, C-2), thin and thick fish cake (D-1, D-2, E-1, E-2) at different drying temperatures are shown in Figures 7 through 9. The drying rate curves (difference of water content between consecutive sampling times divided by the drying time interval) of these samples are shown in Figures 10 through 12, respectively.

The drying of peeled shrimp at 20°C was much faster than that at -2~0°C. It took only 9 and 10 hours to dry thawed peeled shrimp and frozen peeled shrimp to a final water content of 0.21 and 0.23 (kg water/kg dry solid) at 20°C respectively. Whereas the drying of frozen peeled shrimp at -2~0°C required 48 hours (Figure 7). The same trends are evident in the drying of other samples. For example, the drying of headed shrimp and whole shrimp at 20°C required nearly the same drying time of 32 hours, but 72 and 92 hours were needed respectively to dry the same samples at -2~0°C (Figure 8). The drying of thin fish cake required 32 hours at 20°C, compared with 68 hours at -2~0°C (Figure 9). Contrasting different types of shrimp samples, it is obvious that the drying time of peeled shrimp was shorter than that of headed shrimp and whole shrimp, especially at 20°C (Figure 7 and Figure 8). Similarly, the drying of thin fish cake was faster than thick fish cake (Figure 9). Figure 10 shows that for the drying process of frozen peeled shrimp at -2~0°C there exists both a constant drying rate period (from 1 hour to 8 hours) and a falling drying rate period (after 8 hours). The drying of frozen and thawed peeled shrimp at 20°C has a much high drying rate (2.27 and 1.34 kg water/kg dry solid·h) during the first two hours but no constant drying rate period exists in the whole drying process.

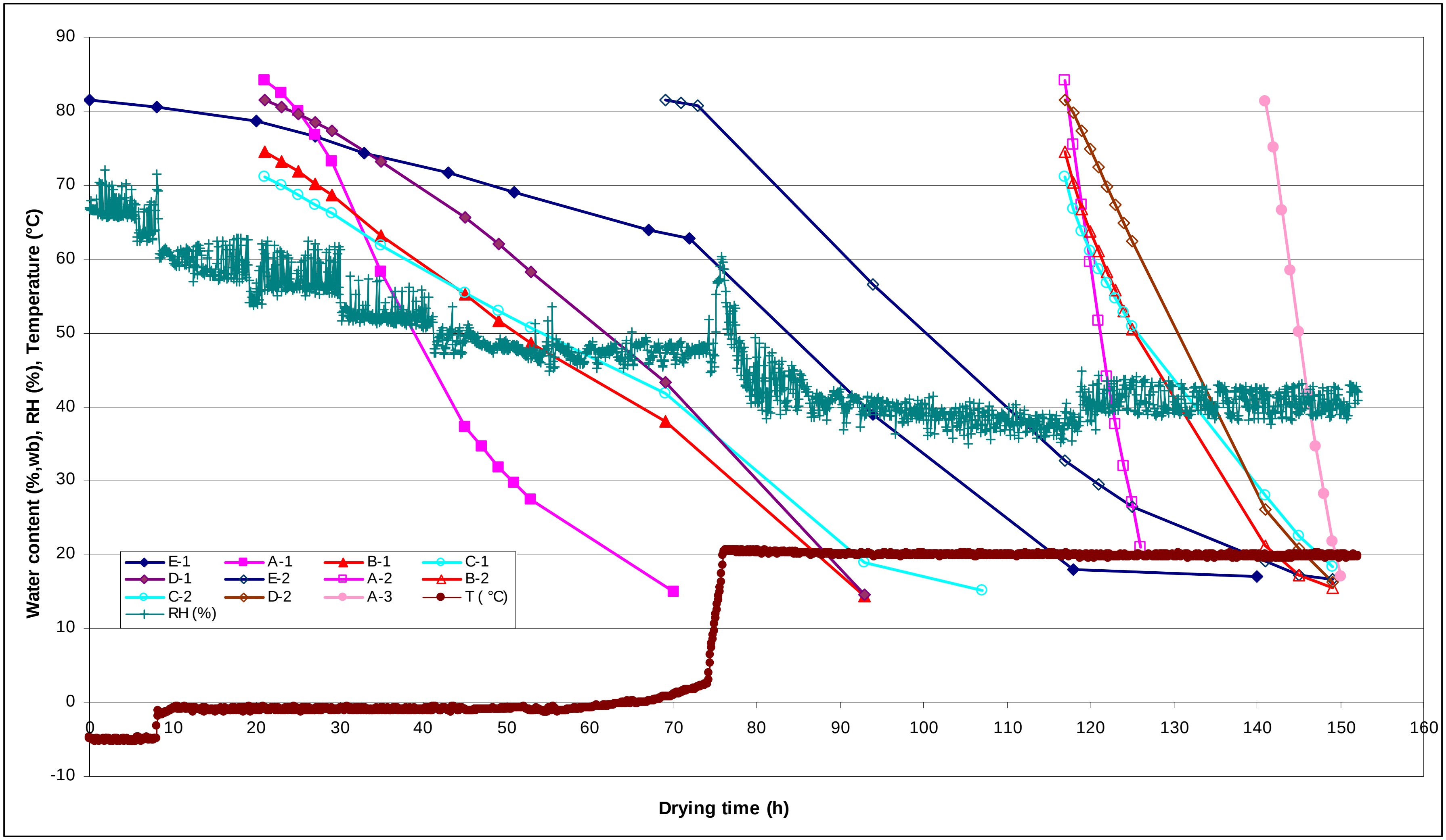

Figure 6: The drying experiments of shrimp and fish cake in the heat pump dryer.

(A-1 and A-2 are frozen peeled shrimp; A-3 is thawed peeled shrimp; B-1 and B-2 are frozen headed shrimp; C-1 and C-2 are frozen whole s hrimp; D-1 and D-2 are frozen thin fish cake (7~9 mm); E-1 and E-2 are frozen thick fish cake (14~18 mm); T (°C) is drying temperature; RH (%) is relative humidity).

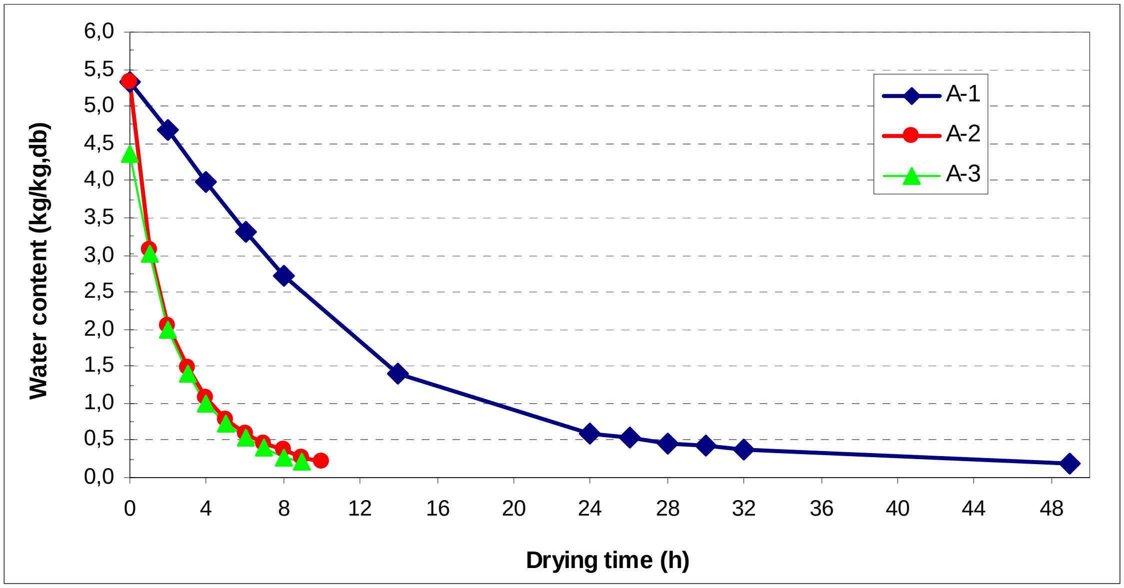

Figure 7: The drying curves of peeled shrimp under different treatments.

(A-1: frozen, -2~0°C; A-2: frozen, 20°C; A-3: thawed, 20°C).

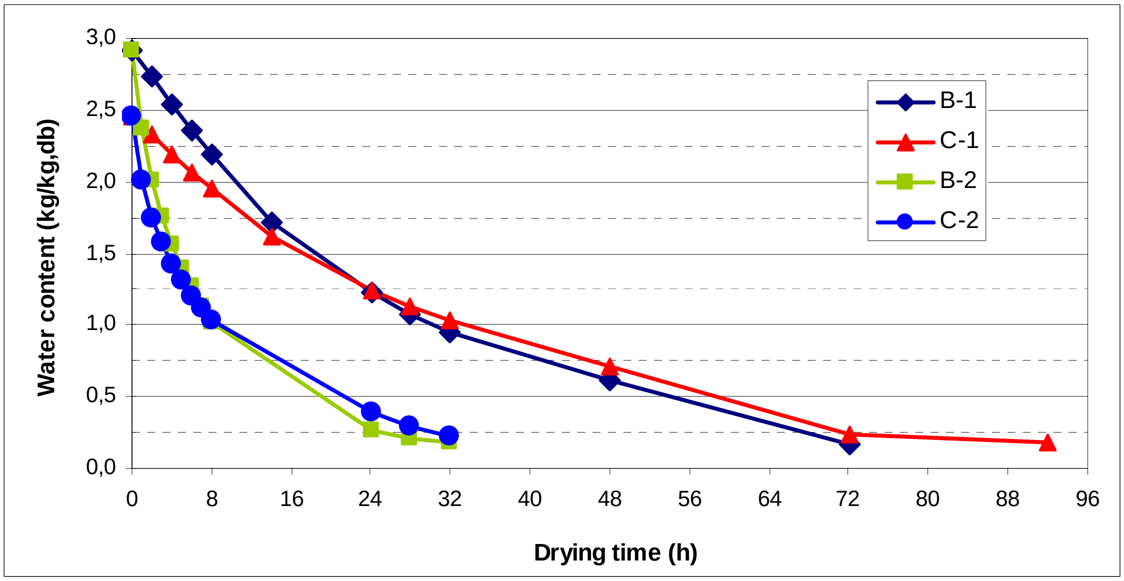

Figure 8: The drying curves of frozen headed shrimp and frozen whole shrimp at different drying temperature.

(B-1: headed shrimp, -2~0°C; B-2: headed shrimp, 20°C; C-1: whole shrimp, -2~0°C; C-2: whole shrimp, 20°C).

A similar pattern is observed for the drying of headed and whole shrimp dried at -2~0°C (Figure 11). There are approximately the same constant drying rate periods (2~14 hours) and the drying rate is kept at a lower level for a long period after 72 hours, whereas the drying at 20°C has no constant drying rate period but has a much high drying rate between 0~2 hours. From Figure 12, we can see that there are constant drying periods from 2~24 and 20~72 hours in the drying of thin fish cake and thick fish cake at -2~0°C respectively, and that there are no constant drying periods at 20°C. We can see from Figure 12, that the drying rate of E-1 (thick fish cake, -2~0°C and 20°C) increased again after 72 hours.

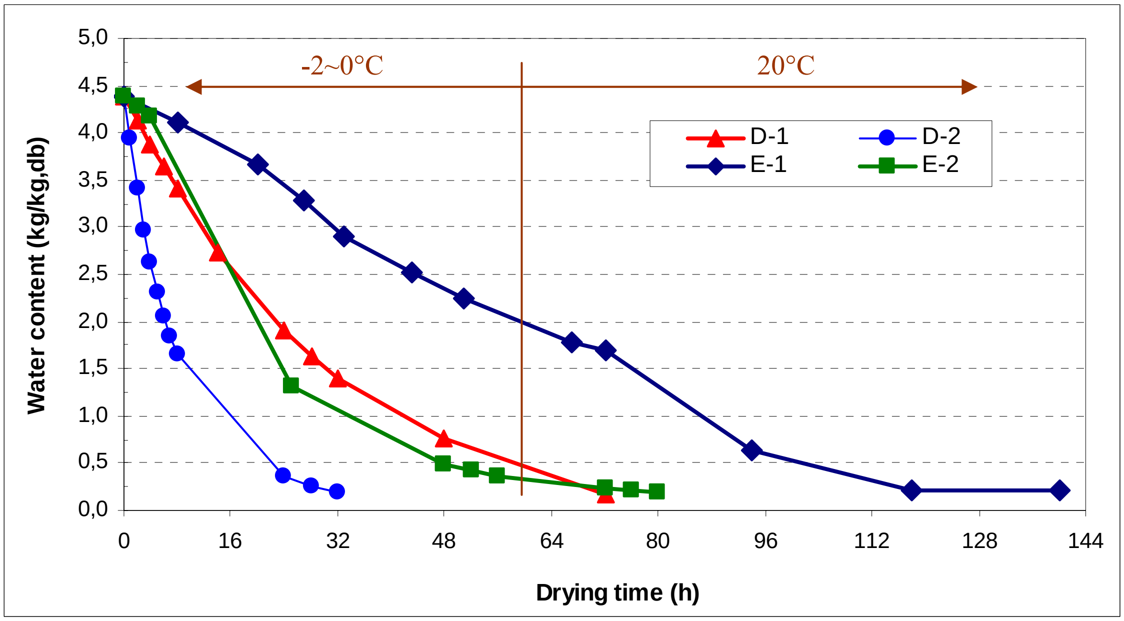

Figure 9: The drying curves of frozen fish cake at different drying temperatures.

(D-1: thin fish cake (7~9 mm), -2~0°C; D-2: thin fish cake (7~9 mm), 20°C; E-1: thick fish cake (14~18 mm), -2~0°C and 20°C; E-2: thick fish cake (14~18 mm), 20°C).

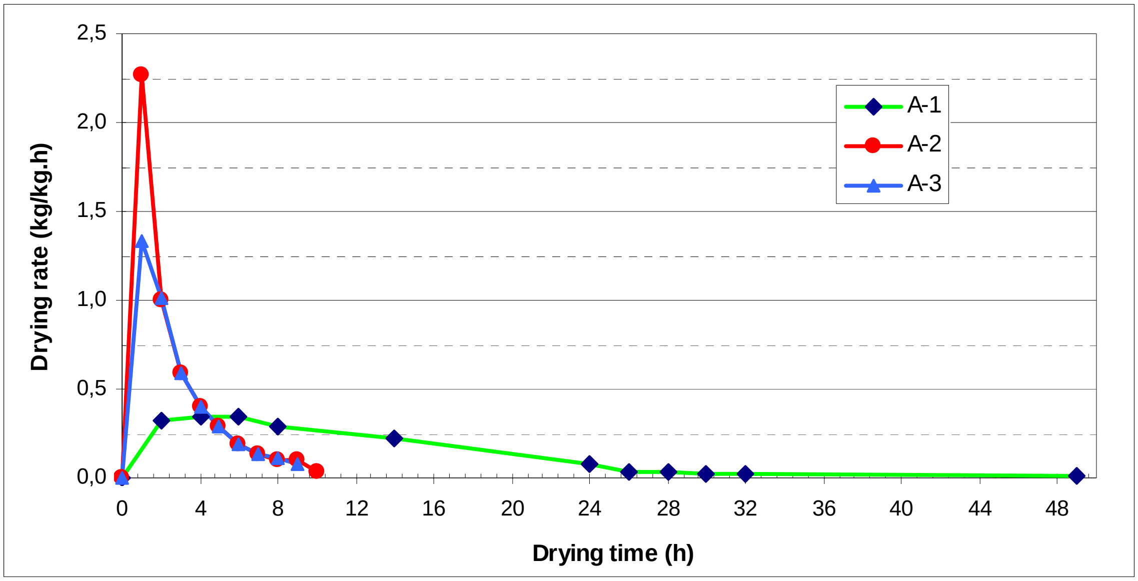

Figure 10: The drying rate curves of peeled shrimp under different treatments.

(A-1: frozen, -2~0°C; A-2: frozen, 20°C; A-3: thawed, 20°C).

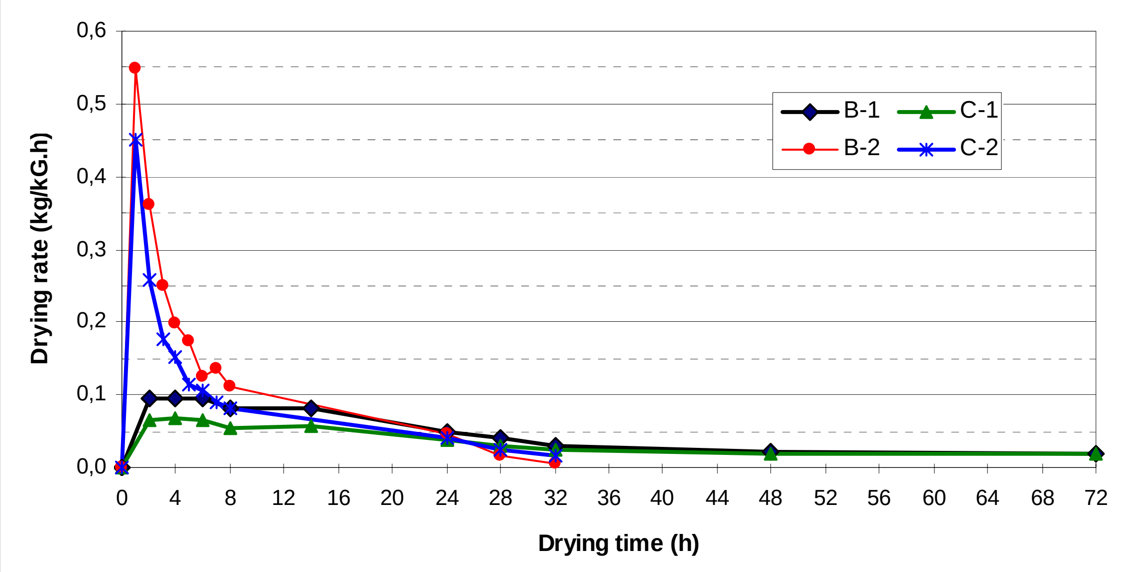

Figure 11: The drying rate curves of frozen headed shrimp and frozen whole shrimp at different drying temperatures.

(B-1: headed shrimp, -2~0°C; B-2: headed shrimp, 20°C; C-1: whole shrimp, -2~0°C; C-2: whole shrimp, 20°C).

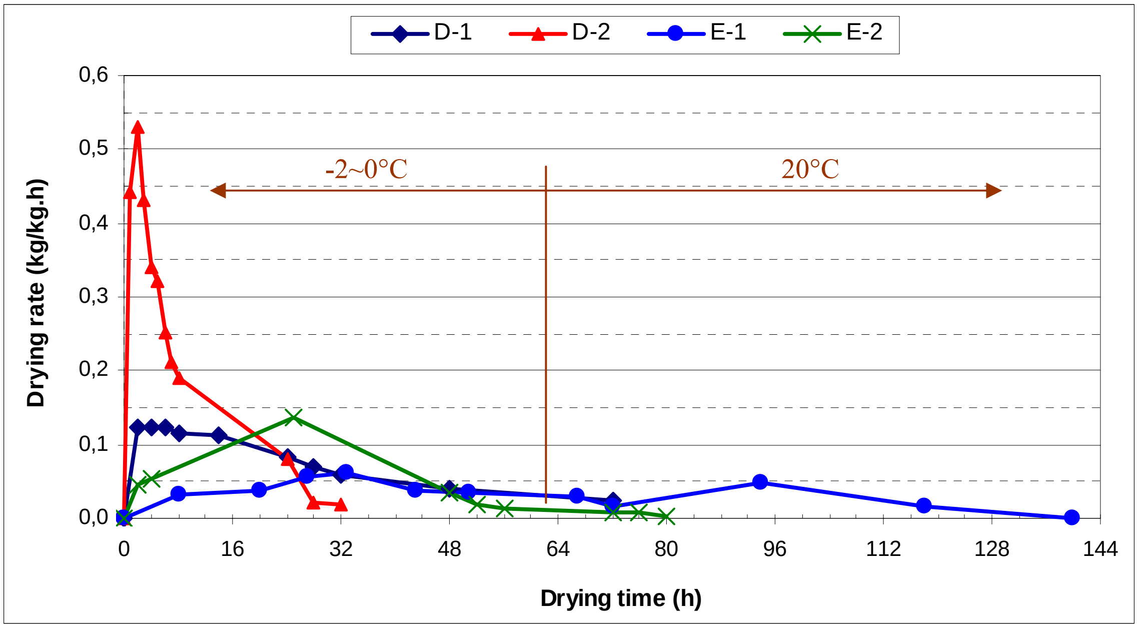

Figure 12: The drying rate curves of frozen fish cake at different drying temperatures.

(D-1: thin fish cake (7~9 mm), -2~0°C; D-2: thin fish cake (7~9 mm), 20°C; E-1: thick fish cake (14~18 mm), -2~0°C and 20°C; E-2: thick fish cake (14~18 mm), 20°C).

4.1.3 Water activity change

The relationship curves between water content and water activity of peeled shrimp (A-1, A-2, A-3), headed shrimp (B-1, B-2) and whole shrimp (C-1, C-2) are shown in Figures 13 and 14.

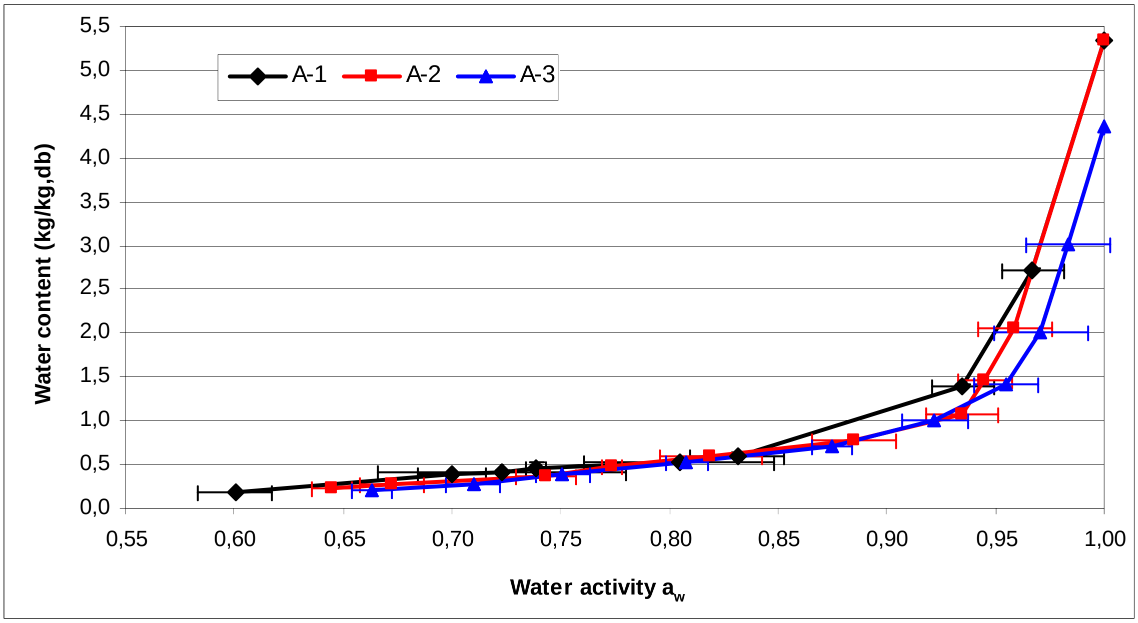

Figure 13: The relationship between water content and water activity of peeled shrimp under different treatments.

(A-1: frozen, -2~0°C; A-2: frozen, 20°C; A-3: thawed, 20°C).

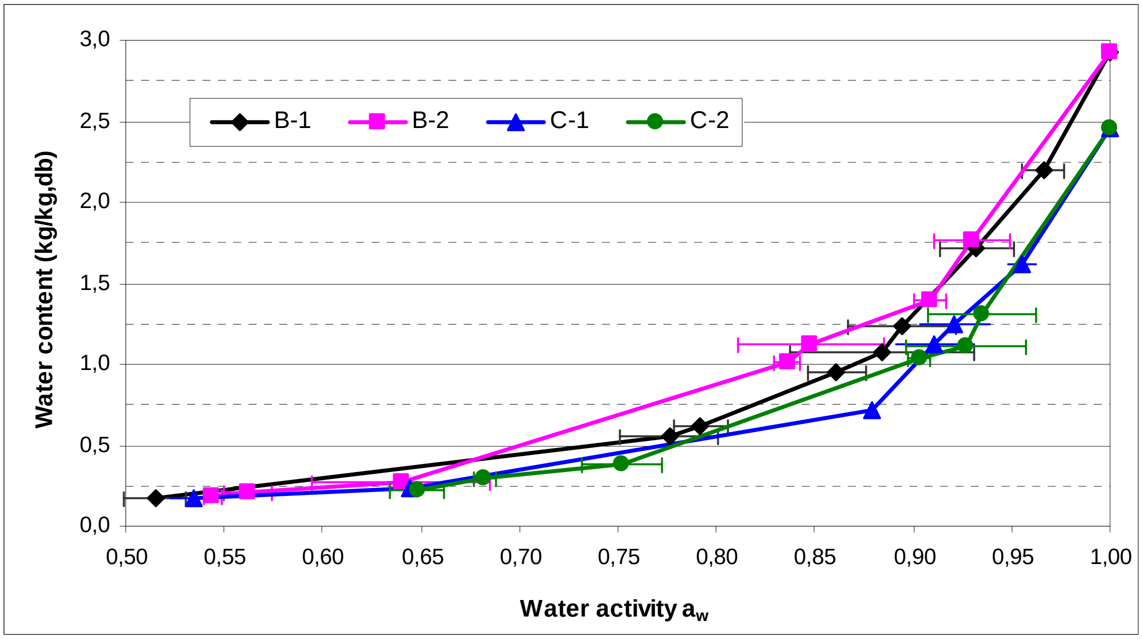

Figure 14: The relationship between water content and water activity of frozen headed shrimp and frozen whole shrimp at different drying temperatures.

(B-1: headed shrimp, -2~0°C; B-2: headed shrimp, 20°C; C-1: whole shrimp, -2~0°C; C-2: whole shrimp, 20°C).

The peeled shrimps under different treatments (frozen or thawed, dried at -2~0°C and 20°C) have nearly the same water content at the corresponding water activity in the range of $a_w < 0.83$ (Figure 13). But when a_w is more than 0.83, the water content is is different at the same water activity. The difference is most pronounced between frozen shrimp dried at -2~0°C and thawed shrimp dried at 20°C (A-1 and A-3, Figure 13). The water content of A-3 is always lower than that of A-1, and the maximum difference of a_w can be more than 0.75 (kg/kg, db) when $a_w >$ 0.96. On the other hand, the desorption isotherms of headed shrimp and whole shrimp dried at different temperatures are quite similar, and only have a tiny difference in the middle range of a_w (from 0.75 to 0.9, see Figure 14). Furthermore, from Figures 13 and 14 we can see that the water activity falls more rapidly when the water content is below 0.5 (kg/kg, db) in all the drying processes of peeled shrimp, headed shrimp and whole shrimp.

4.2 Physical and sensory attributes

4.2.1 Shrinkage

Frozen peeled shrimp dried at -2~0°C has the lowest shrinkage (36.56%) among peeled shrimp samples (Figure 15). The thawed peeled shrimp has shrinkage of 11.88% after thawing and shrinkage of 32.66% during drying, thus the total shrinkage of thawed peeled shrimp dried at 20°C is 44.14% and is the highest among all the samples. The shrinkage of headed shrimp and whole shrimp dried at -2~0°C is lower than that dried at 20°C, respectively. For example, the shrinkage of headed shrimp dried at -2~0°C (18.89%) is lower than headed shrimp dried at 20°C (19.97%) and the shrinkage of whole shrimp dried at 20°C (32.83%) is much higher than whole shrimp dried at -2~0°C (21.48%). In general, the shrinkage of peeled shrimp is higher than headed shrimp and whole shrimp.

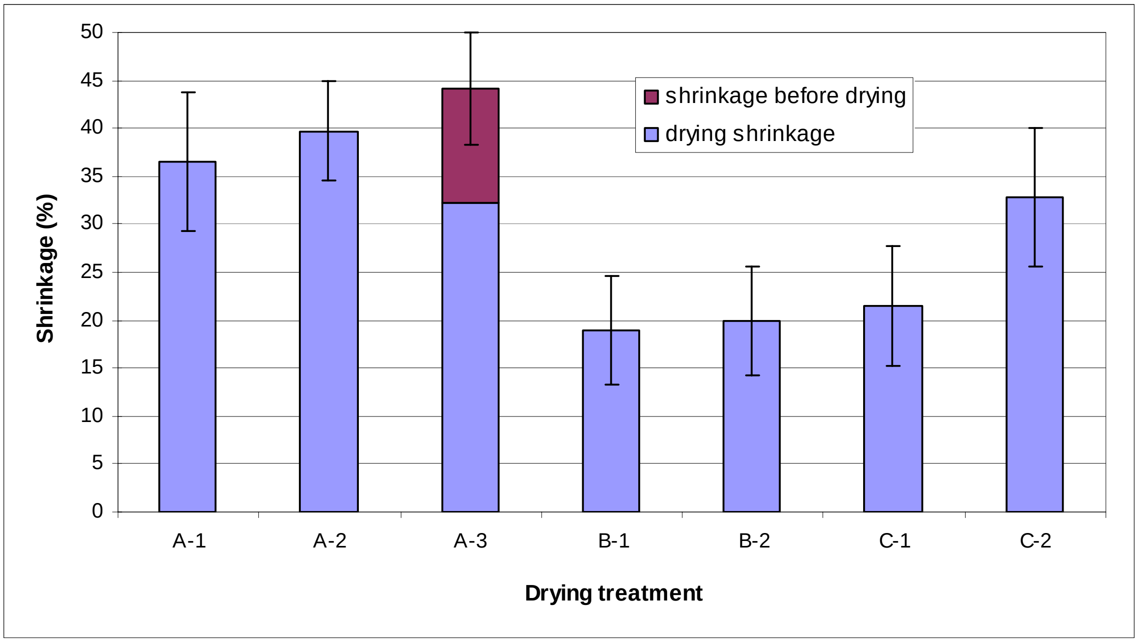

Figure 15: Shrinkage of shrimp under different treatments.

(A-1: frozen peeled shrimp, -2~0°C; A-2: frozen peeled shrimp, 20°C; A-3: thawed peeled shrimp, 20°C; B-1: frozen headed shrimp, -2~0°C; B-2: frozen headed shrimp, 20°C; C-1: frozen whole shrimp, -2~0°C; C-2: frozen whole shrimp, 20°C).

4.2.2 Colour

The colour values of dried and rehydrated samples are shown in Table 2. Among the dried shrimp samples, A-1 (frozen peeled shrimp, -2~0°C) has the highest lightness and yellowness, but slightly lower redness than A-2 (frozen peeled shrimp, 20°C) and A-3 (thawed peeled shrimp, 20°C). The values of lightness and yellowness of A-3 are the lowest but redness is the highest. After rehydration, the rehydrated shrimp samples nearly have the same colour trend of the dried samples except that the redness of A-2 is the hightest. Between the two types of deshelled headed shrimp samples, the redness and yellowness of B-2 (frozen headed shrimp, 20°C) are higher and the lightness is lower than B-1(frozen headed shrimp, -2~0°C), but the differences are small. After rehydration, all the values of B-2 are higher than B-1. Compared with C-1(frozen whole shrimp, -2~0°C), C-2 (frozen whole shrimp, 20°C) has highter values of lightness and yellowness and nearly the same value of redness. The same trends are kept after rehydration. On the other hand, compared between the deshelled headed shrimp and whole shrimp, the redness of the former are higher than the latter before rehydration, and the yellowness of rehydrated whole shrimp are higher than rehydrated headed shrimp. Besides these differences, other colour values of them are similar.

Table 2: Colour values of dried and rehydrated shrimp and fish cake.

Dried sample*	Colour values		
	L	a	b
A-1	57.62 ± 4.05	8.46 ± 1.96	14.3 ± 1.62
A-2	52.04 ± 3.57	9.00 ± 1.72	12.03 ± 1.29
A-3	48.56 ± 3.08	9.90 ± 1.81	11.18 ± 1.36
B-1d	49.72 ± 3.68	12.12 ± 4.40	13.89 ± 3.27
B-2d	49.12 ± 5.91	12.64 ± 3.38	14.60 ± 3.03
C-1d	49.52 ± 5.03	10.69 ± 3.30	14.28 ± 3.17
C-2d	49.97 ± 5.13	10.39 ± 3.50	15.33 ± 3.45
D-1	70.31 ± 4.26	0.42 ± 1.08	9.01 ± 1.14
D-2	59.90 ± 5.19	1.29 ± 1.33	9.98 ± 1.10
E-1	70.31 ± 4.87	0.29 ± 0.96	7.35 ± 1.08
E-2	54.89 ± 5.45	1.65 ± 1.09	7.89 ± 1.90

Rehydrated samples	Colour values		
	L	a	b
A-1	54.58 ± 3.38	6.89 ± 2.01	10.67 ± 1.94
A-2	53.61 ± 3.11	7.39 ± 1.67	7.95 ± 1.47
A-3	52.55 ± 2.83	6.74 ± 1.67	7.28 ± 1.67
B-1d	53.04 ± 4.10	10.66 ± 4.21	12.74 ± 4.08
B-2d	55.01 ± 5.03	11.01 ± 4.68	14.85 ± 3.83
C-1d	53.08 ± 4.77	11.05 ± 4.77	15.00 ± 3.64
C-2d	55.53 ± 4.96	10.97 ± 3.80	17.58 ± 3.32
D-1	62.68 ± 2.29	-1.13 ± 0.71	9.53 ± 1.56
D-2	56.69 ± 3.27	0.02 ± 1.25	9.53 ± 1.56

(A-1: frozen peeled shrimp, 0℃； A-2: frozen peeled shrimp, 20℃； A-3: thawed peeled shrimp, 20℃； B-1d: deshelled B-1(frozen no-head shrimp, 0℃）； B-2d: deshelled B-2(frozen no-head shrimp, 20℃）; C-1d: deshelled C-1(frozen whole shrimp, 0℃）; C-2d: deshelled C-2 (frozen whole shrimp, 20℃）; D-1: frozen thin fish cake (7~9 mm), 0℃; D-2: frozen thin fish cake (7~9 mm), 20℃; E-1: frozen thick fish cake (14~18 mm), 0℃; E-2: frozen thick fish cake (14~18 mm), 20℃）.

From Table 2 we can see that A-1 (peeled shrimp, -2~0°C) has the highest lightness of all the shrimp samples, but the lightness of all the dehydrated shrimp samples are almost the same. In addition, irrespective of whether they are dried samples or rehydrated samples, the redness and yellowness of deshelled shrimp samples are much higher than peeled shrimp samples. Table 2 shows that both the lightnesses of dried and rehydrated D-1 samples (thin fish cake, -2~0°C) are much higher than D-2 samples (thick fish cake, 20°C). Meanwhile, both the rednesses and yellownesses of the former are lower than the latter. The values of dried thick fish cake present the same trends.

4.2.3 Rehydration

Figures 16 and 17 illustrate the rehydration behaviour of all the dried shrimp samples and the dried thin fish cake samples under different treatments.

The trends are similar for all samples in the whole process (Figure 16). The highest rehydration rates were observed at the beginning (0-2 minutes) of the process (Figures 16 and 17), and the rehydration ratio kept increasing from 0-10 minutes. It was found that the sample of A-1 (peeled shrimp, -2~0°C) had a much higher initial rehydration rate (0.575 kg/kg·min) and a much higher final rehydration ratio (1.5 kg/kg). Thawed peeled shrimp (A-3) had the lowest initial rehydration rate (0.324 kg/kg·min) in the peeled shrimp samples, but when rehydration time was longer than 6 minutes, its rehydration rate and rehydration ratio surpassed A-2 (peeled shrimp, 20°C) and it also had a higher final rehydration ratio (1.3 kg/kg) than A-2 (1.09 kg/kg). From Figures 16 and 17 we can also see that the two samples of deshelled headed shrimp have a similar rehydration rate and rehydration ratio in the whole rehydration process. The differences of rehydration rate and rehydration ratio between the two samples of deshelled whole shrimp are small being 0.13 (kg/kg·min) and 0.08 (kg/kg·min), respectively. Compared with the deshelled whole shrimp samples (C-1, C-2), the rehydration rate and the final rehydration ratio of deshelled headed shrimp both dried at -2~0°C and 20°C (B-1 and B-2) are higher. As to the thin fish cake, the samples dried at -2~0°C(D-1) have a faster rehydration rate and a higher final rehydration ratio than those dried at 20°C (D-2).

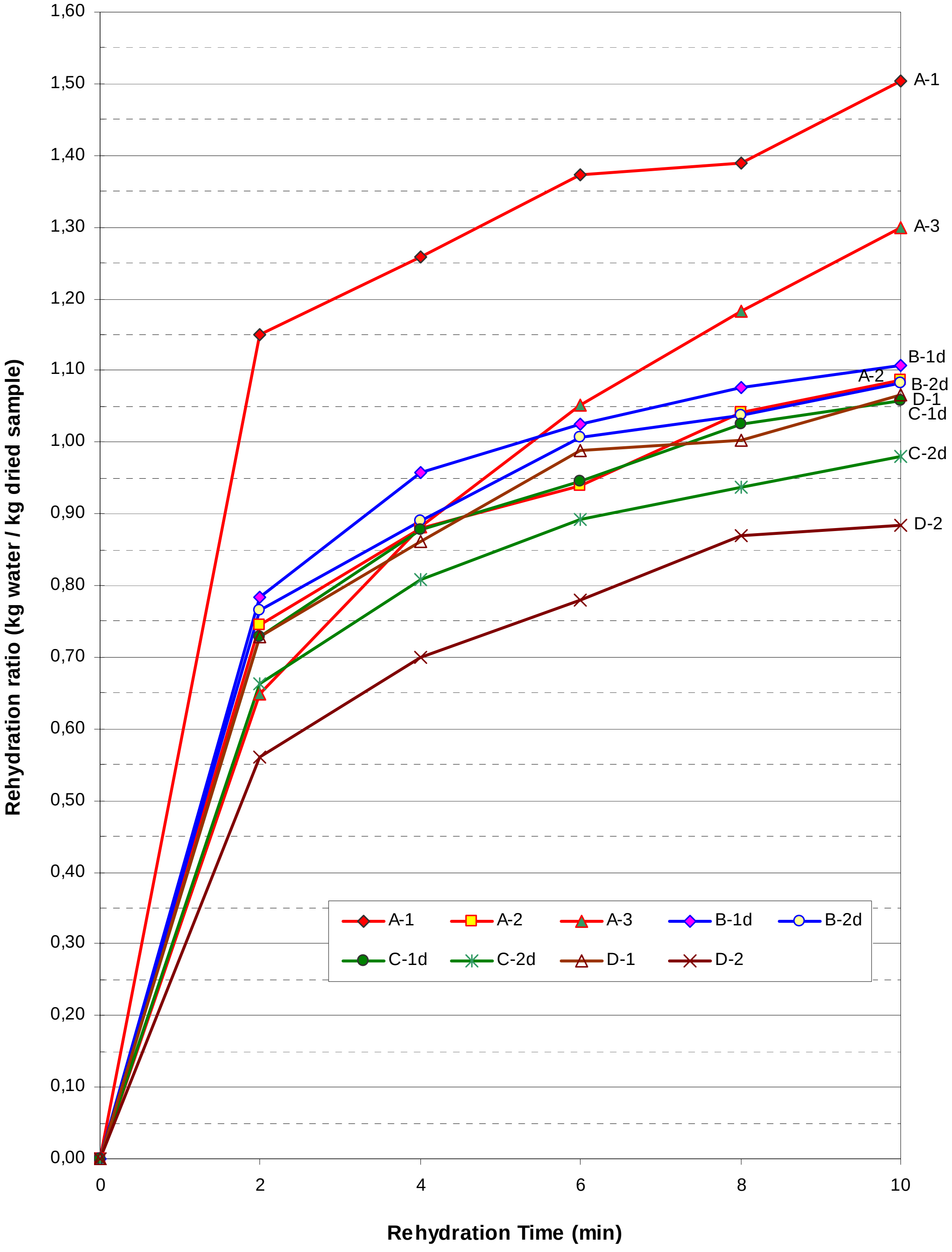

Figure 16: The rehydration curves of dried shrimp and thin fish cake (7~9 mm). (A-1: frozen peeled shrimp, -2~0°C; A-2: frozen peeled shrimp, 20°C; A-3: thawed peeled shrimp, 20°C; B-1d: deshelled B-1(frozen headed shrimp, -2~0°C); B-2d: deshelled B-2(frozen headed shrimp, 20°C); C-1d: deshelled C-1(frozen whole shrimp, -2~0°C); C-2d: deshelled C-2 (frozen whole shrimp, 20°C); D-1: frozen fish cake -2~0°C; D-2: frozen fish cake, 20°C).

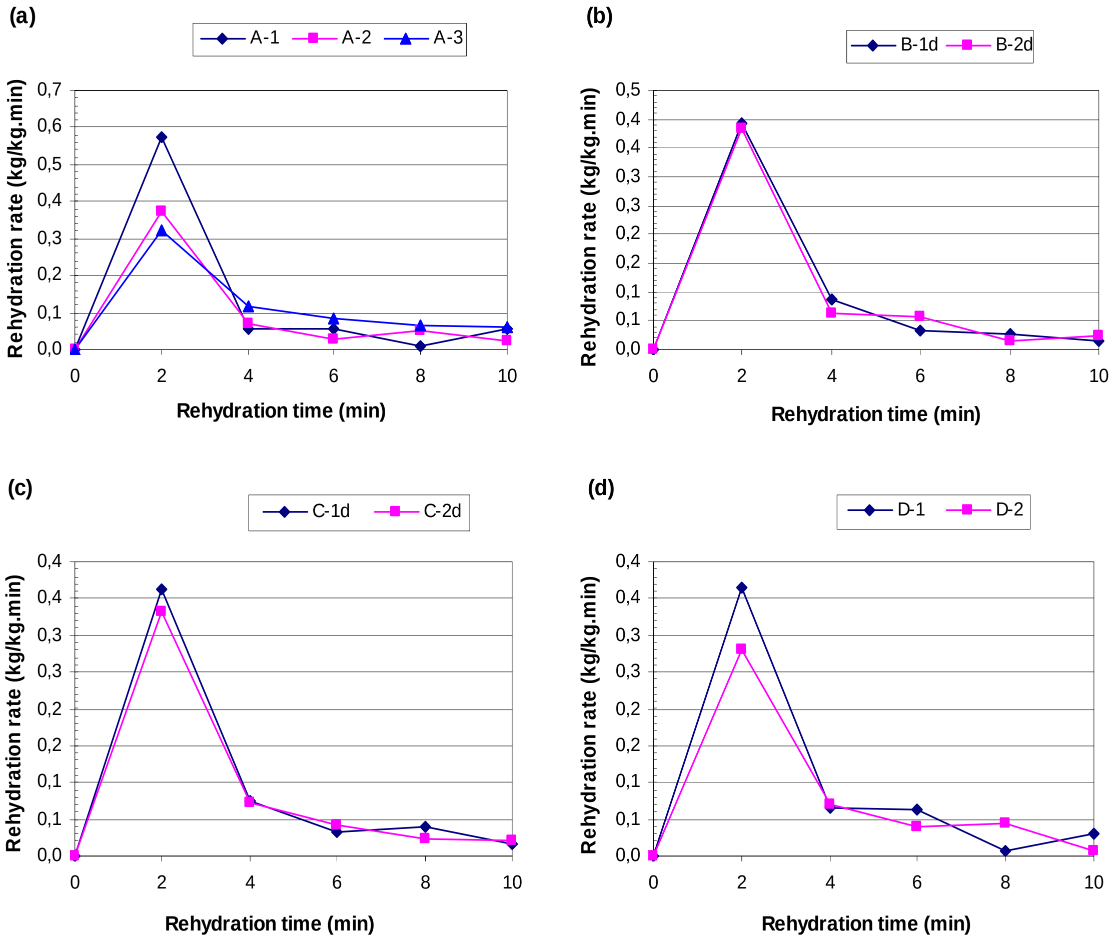

Figure 17: The rehydration rate curves of dried shrimp and thin fish cake (7~9 mm).

(A-1: frozen peeled shrimp, -2~0°C; A-2: frozen peeled shrimp, 20°C; A-3: thawed peeled shrimp, 20°C;B-1d: deshelled B-1(frozen headed shrimp, -2~0°C); B-2d: deshelled B-2(frozen headed shrimp, 20°C); C-1d: deshelled C-1(frozen whole shrimp, -2~0°C); C-2d: deshelled C-2 (frozen whole shrimp, 20°C); D-1: frozen fish cake, -2~0°C; D-2: frozen fish cake, 20°C).

4.2.4 Texture

Dried peeled shrimp have lower shear force than deshelled headed shrimp and whole shrimp (Figure 18). The same trend is evident in the rehydrated shrimp. The differences of shear force between deshelled headed shrimp and deshelled whole shrimp are small either in dried state or in rehydrated state. Among the dried peeled shrimp samples, sample A-1 (frozen, 0°C) has the lowest average shear force (81.2N) and sample A-3 (thawed, 20°C) has the highest shear force (101.7N) but it is similar with the shear force results of A-2 (frozen, 20°C; 96.9N). In general all the samples become much tender after rehydration. Among the deshelled headed shrimp and whole shrimp samples, the average shear force of samples dried at 20°C are always higher than that dried at -2~0°C, but the difference decreases after rehydration. For example, the average shear force difference of rehydrated deshelled headed shrimp (2.2 N) is less than that of dried samples (5.4N) and the samples of rehydrated deshelled whole shrimp nearly has no average shear force difference (0.1N) whereas average shear force difference of dried deshelled whole shrimp is 6.3N.

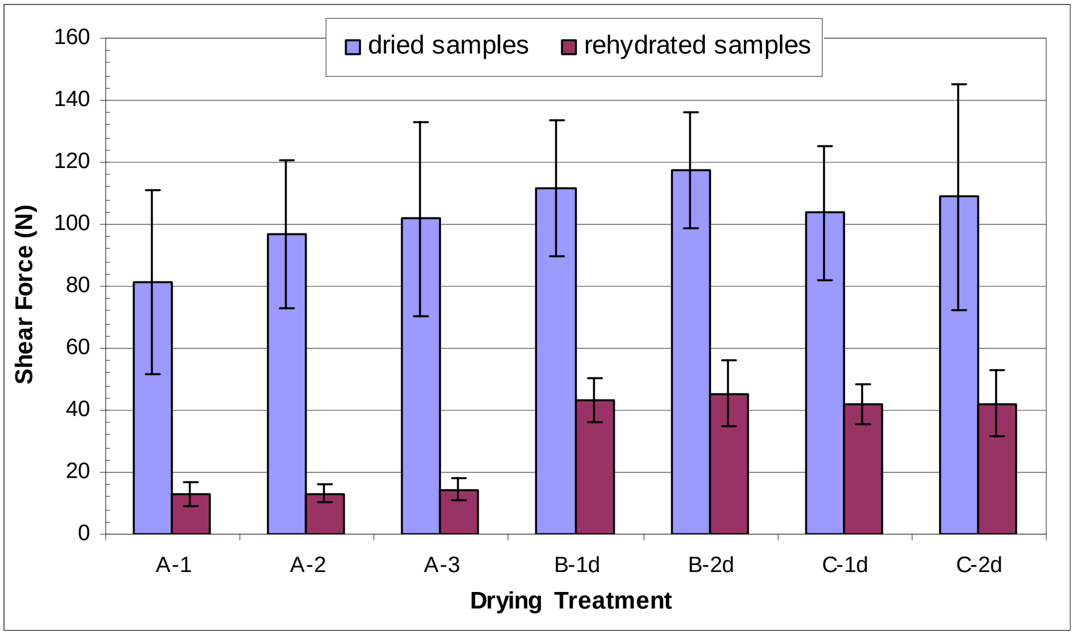

Figure 18: Textural properties of dried and rehydrated shrimp under different treatments.

(A-1: frozen peeled, -2~0°C; A-2: frozen peeled, 20°C; A-3: thawed peeled, 20°C; B-1d: deshelled B-1(frozen headed shrimp, -2~0°C); B-2d: deshelled B-2(frozen headed shrimp, 20°C); C-1d: deshelled C-1(frozen whole shrimp, -2~0°C); C-2d: deshelled C-2 (frozen whole shrimp, 20°C)).

4.2.5 Water Holding Capacity (WHC)

The WHC of all the dried shrimp samples and dried thin fish cake samples under different treatments are shown in Figure 19.

Samples of A-2 (frozen peeled, 0°C), deshelled B-1 (headed shrimp, 0°C), deshelled B-2 (headed shrimp, 20°C), deshelled C-1 (whole shrimp, 0°C), deshelled C-2 (whole shrimp, 20°C) and D-2 (frozen thin fish cake, 20°C) have much higher WHC (WHC >0.967). The WHC of A-1 is the lowest (0.915) among the peeled shrimps, and the samples of D-1 (frozen thin fish cake, 0°C) have the lowest WHC (0.857) in all the samples. But generally speaking, the WHC of all the samples is high.

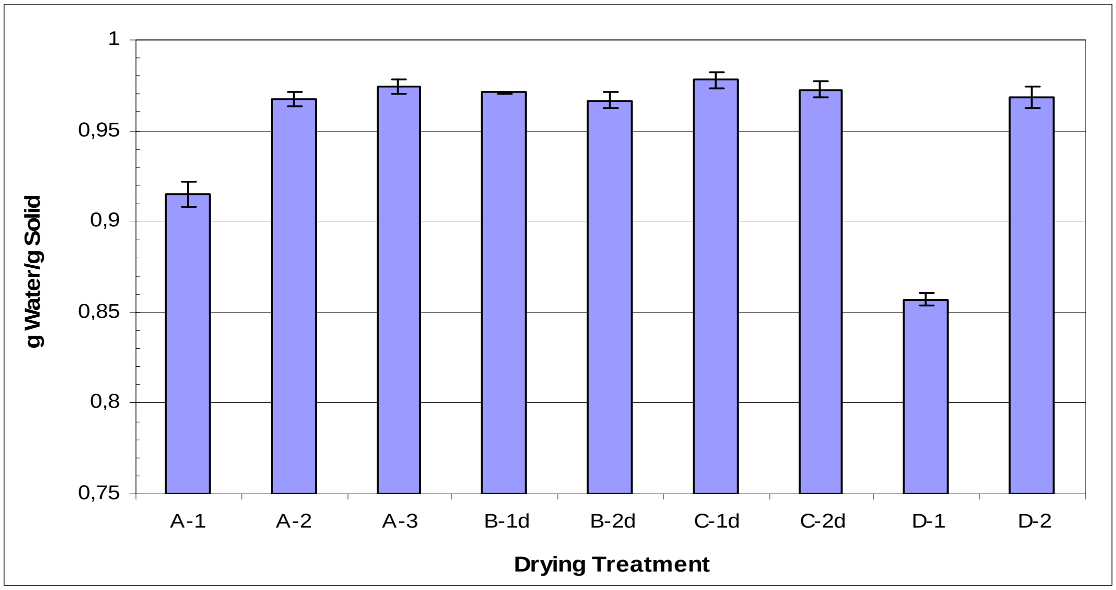

Figure 19: WHC of rehydrated shrimp and thin fish cake (7~9 mm).

(A-1: frozen peeled shrimp, -2~0°C; A-2: frozen peeled shrimp, 20°C; A-3: thawed peeled shrimp, 20°C; B-1d: deshelled B-1(frozen headed shrimp, -2~0°C); B-2d: deshelled B-2(frozen headed shrimp, 20°C); C-1d: deshelled C-1(frozen whole shrimp, -2~0°C); C-2d: deshelled C-2 (frozen whole shrimp, 20°C);D-1: frozen fish cake, -2~0°C; D-2: frozen fish cake, 20°C).

4.3 Chemical and microbiological analysis

4.3.1 Chemical composition

The ratio of protein, fat, salt and water to dry material were calculated (Table 3).

Table 3: The chemical compositions of shrimp and fish cake

Material	Composition content (%, wb)				Composition content (kg/kg, db)			
	protein	fat	salt	water	[1] w_p/w_d	w_f/w_d	w_s/w_d	w_w/w_d
Peeled shrimp (raw material)	12.3±0.4	0.1±0.4	1.7±0.1	84.2±0.1	[2] 0.78	0.006	0.11	5.33
Headed shrimp (raw material)	19.0±0.4	0.7±0.4	1.8±0.1	74.5±0.3	0.75	0.028	0.07	2.92
Whole shrimp (raw material)	18.3±0.4	3.9±0.4	1.7±0.1	71.1±0.3	0.63	0.14	0.06	2.46
Fish cake (dried, 20°C)	79.1±0.4	0.6±0.4	3.1±0.1	15.5±0.4	0.94	0.007	0.04	4.38
Fish cake (raw material)	17.4±0.4	0.13±0.4	0.68±0.1	81.4±0.4				

[1] w_p/w_d, w_f/w_d , w_s/w_d and w_w/w_d are the decimal content of protein, fat, salt and water on dry basis.
[2] Data with colour are calculated values.

Raw peeled shrimp has the highest water (5.33, db IS THIS A MEASUREMENT?) and salt content (0.11, db) and the lowest fat content (0.006, db) of all the samples. Raw whole shrimp has the highest fat content (0.14, db). Raw fish cake has the lowest salt content (0.04, db) as well as the highest protein content (0.94, db). Compared with whole shrimp, headed shrimp has higher protein content, similar salt content and much lower fat content (0.028, db). Moreover, the fat content of raw fish cake (0.007, db) is nearly the same as raw peeled shrimp, and raw headed shrimp has similar protein content (0.75, db) as that of raw peeled shrimp (0.78, db).

4.3.2 Microbiological growth

Initial TVC of the raw material was lower for peeled shrimp and higher for fish cake (Table 4). The TVC values of raw headed shrimp and raw whole shrimp are very similar. The thin fish cake has the highest TVC value for all the raw material samples. The TVC values increased after every drying process. Bacteria content increased significantly during the thin fish cake drying process, especially when dried at 20°C. The peeled shrimp has much lower TVC values even after the drying process, but the bacteria did increase faster (over 7 times) after drying at -2~0°C. Headed shrimp and whole shrimp have similar increases when dried at -2~0°C whereas whole shrimp dried at 20°C has a lower increase.

Table 4: TVC changes of shrimp and thin fish cake during heat pump drying

Material	TVC (no./g)		
	Raw material	dried sample (0°C)	dried sample (20°C)
Peeled shrimp	250	1,800	490
Headed shrimp	8,100	20,000	21,000
Whole shrimp	8,600	23,000	10,000
Thin fish cake	63,000	230,000	350,000

4.4 Stability and water sorption isotherms

4.4.1 The change of water content

Figure 20 illustrates that the frozen peeled shrimp dried at -2~0°C (A-1, initial water content 0.19 kg/kg) absorbs water throughout the whole time period in all the three containers (K_2SO_4, KCl and NaCl). It absorbed the most water at the fastest rate in the K_2SO_4 container, with the highest absorption rate occurring on the first day. Samples of frozen peeled shrimp dried at 20°C (A-2, initial water content 0.30 kg/kg) started absorbing water after two days in the K_2SO_4 container and loses some water in the KCl and NaCl containers. Thawed peeled shrimp (A-3, initial water content 0.25 kg/kg) has similar trends with A-2, in that it starts absorbing water from the fifth day onwards and loses water in the KCl and NaCl solutions.

Samples of deshelled B-1 and B-2 (headed shrimp dried at -2~0°C and 20°C, initial water content 0.19 and 0.21 kg/kg) have the same trends in all three containers. They absorb water much faster in the K_2SO_4 container and absorb water faster in the NaCl container than in the KCl container. The highest absorption rate of all these samples in the three containers occur on the first day (Figure 21). The same trends exist in the absorption process of deshelled C-1 and C-2 (frozen whole shrimp dried at -2~0°C and 20°C, initial water content 0.16 and 0.20 kg/kg), see Figure 22.

Figure 23 shows that the water content of frozen thin fish cake dried at -2~0°C (D-1, initial water content 0.17 kg/kg) increased throughout the time period in these three containers but increased at a lower rate after five days in the KCl and NaCl containers. In the K_2SO_4 container, the largest absorption rate of D-1 is on the first day. Frozen thin fish cake dried at 20°C (D-2, initial water content 0.18 kg/kg) absorbed water in the K_2SO_4 container throughout the whole process but the absorption rate is lower than that of D-1. The total amount of increased water content of D-2 is less than D-1 in all three containers. D-1 and D-2 absorbed water faster in the NaCl container than in the KCl container.

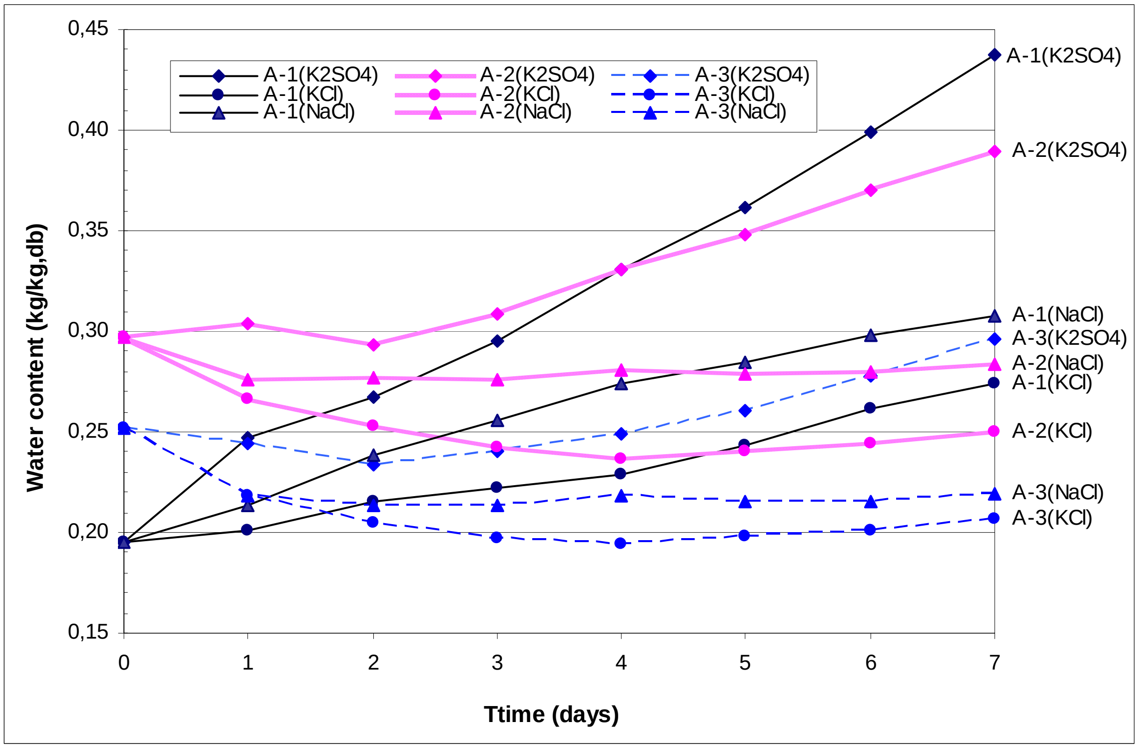

Figure 20: The water content change of peeled shrimp in the first week in containers with K_2SO_4, KCl and NaCl saturated solutions when measured once every day.

(A-1: frozen, -2~0°C; A-2: frozen, 20°C; A-3 thawed, 20°C).

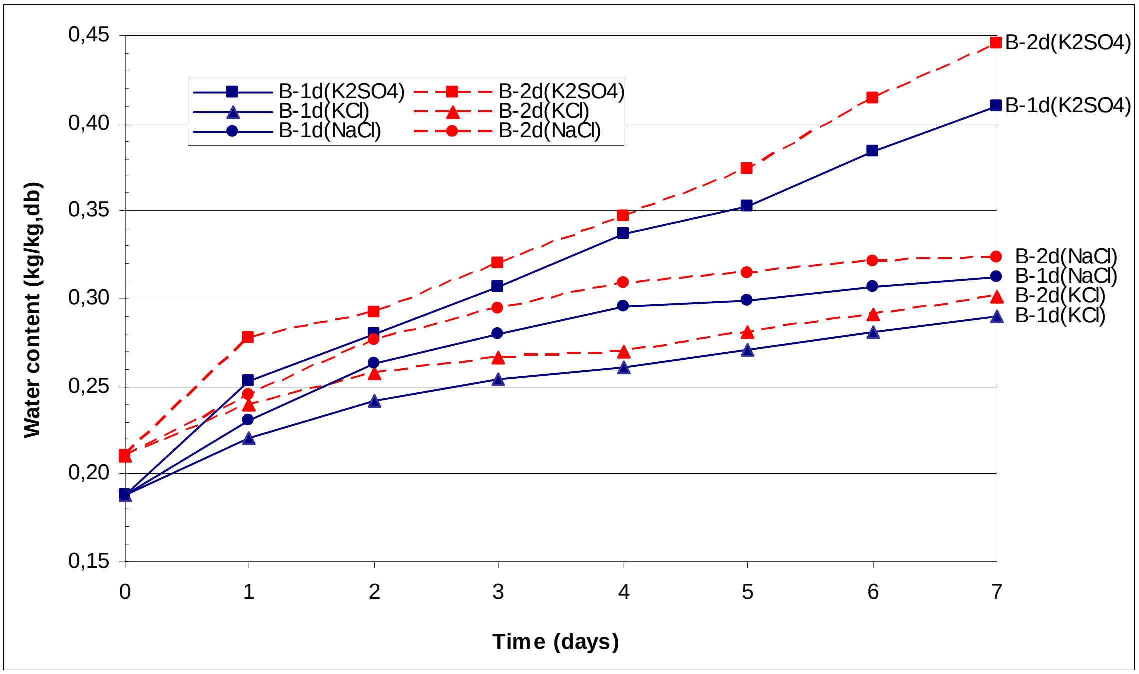

Figure 21: The water content change of deshelled headed shrimp in the first week in the containers of K_2SO_4, KCl and NaCl saturated solutions when measured once every day.

(B-1d: deshelled B-1 (frozen, -2~0°C); B-2d: deshelled B-2 (frozen, 20°C)).

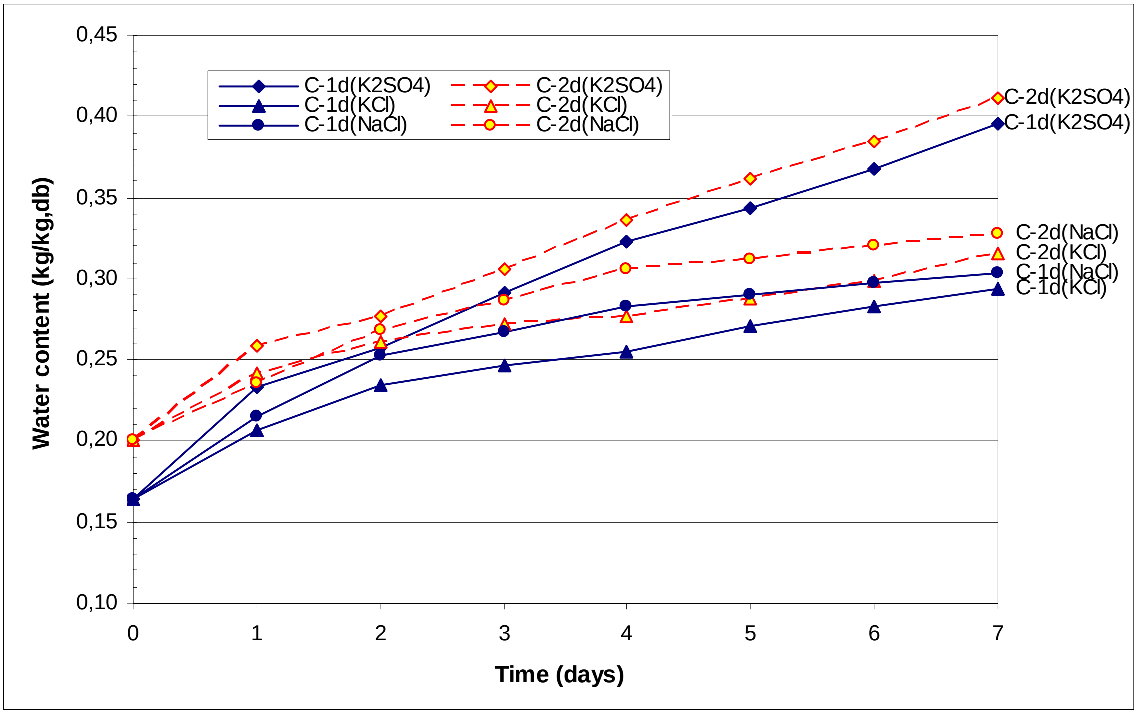

Figure 22: The water content change of deshelled whole shrimp in the first week in the containers of K_2SO_4, KCl and NaCl saturated solutions when measured once every day.

(C-1d: deshelled C-1 (frozen, -2~0°C); C-2d : deshelled C-2 (frozen, 20°C)).

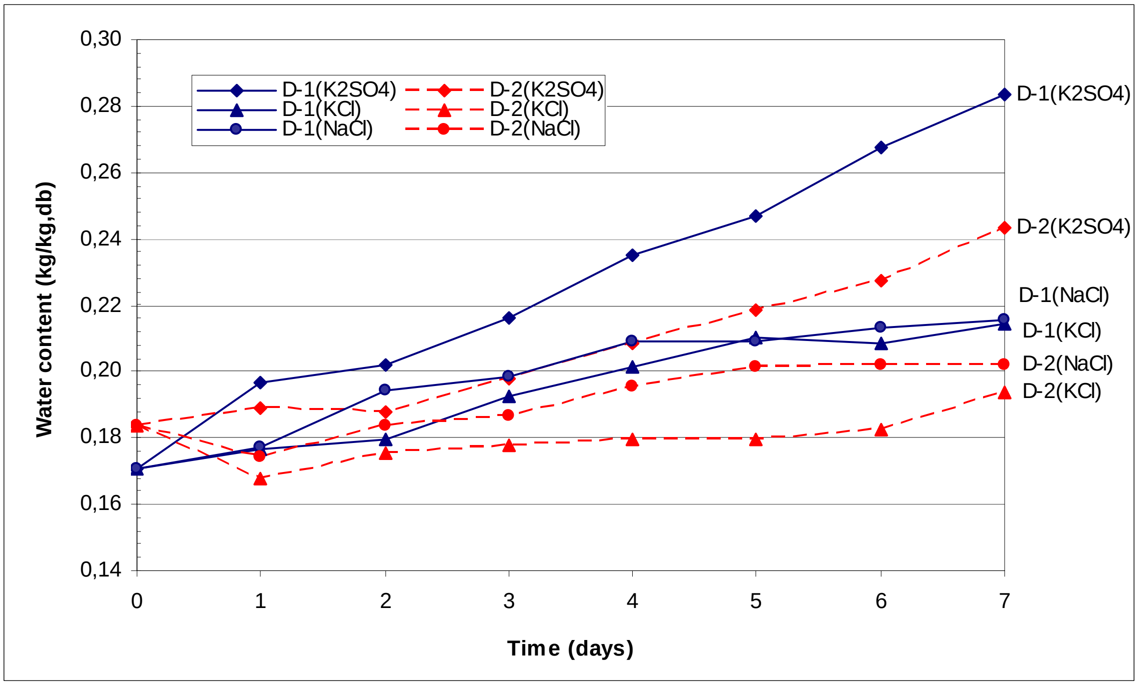

Figure 23: The water content change of thin fish cake (7~9 mm) in the first week in the containers of K_2SO_4, KCl and NaCl saturated solutions when measured once every day.

(D-1: frozen, -2~0°C; D-2: frozen, 20°C).

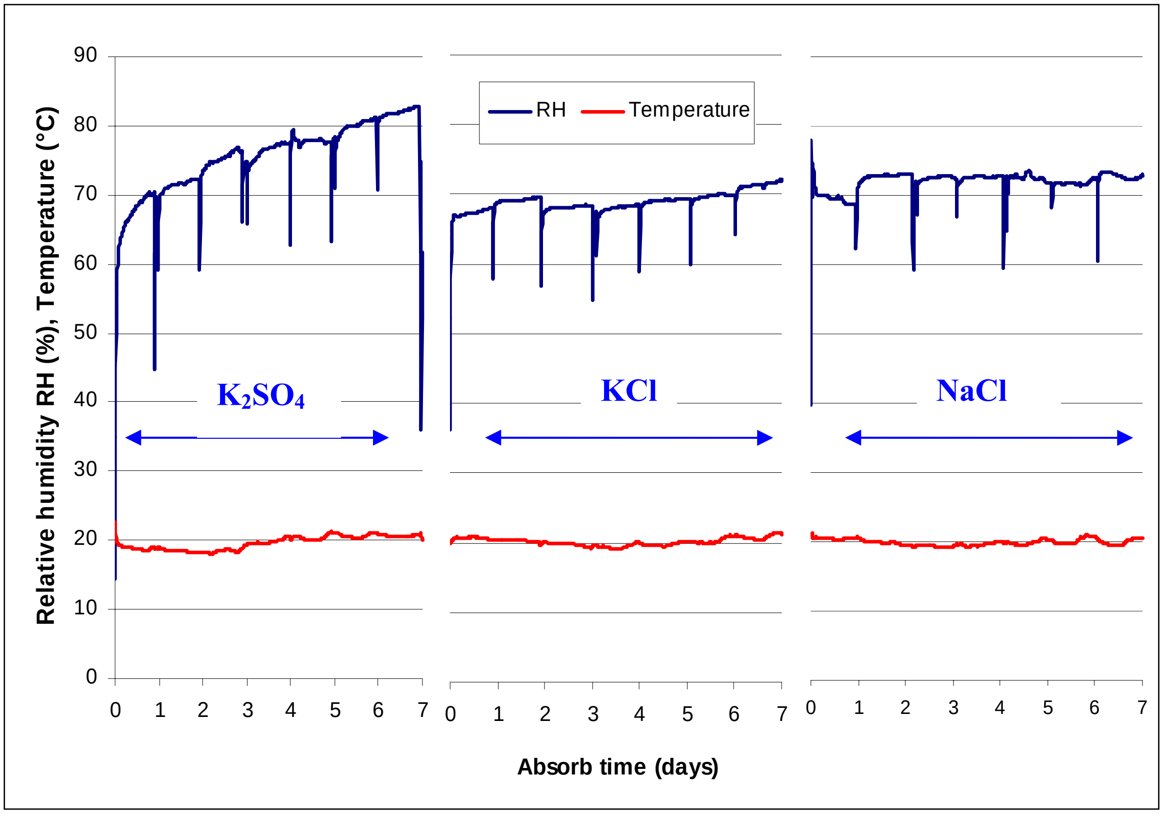

Figure 24: The relative humidity and temperature in the containers of K_2SO_4, KCl and NaCl saturated solutions when measured once every day.

Figure 24 illustrates the relative humidity and temperature changes of the three containers in the first week when measured once every day. Temperatures in the three containers are similar. The RH in the K_2SO_4 container increased in 7 days, increasing the most on the first day. In contrast, the RH in the KCl and NaCl containers was constant in the most part of the 7 days. Moreover, the RH in the NaCl container was higher than in the KCl container.

The water content changes of peeled shrimp, headed shrimp, whole shrimp and thin fish cake under different treatments in one month when measured once every two days are shown in Figures 25 through 28. The changes of relative humidity and temperature in these containers are shown in Figure 29.

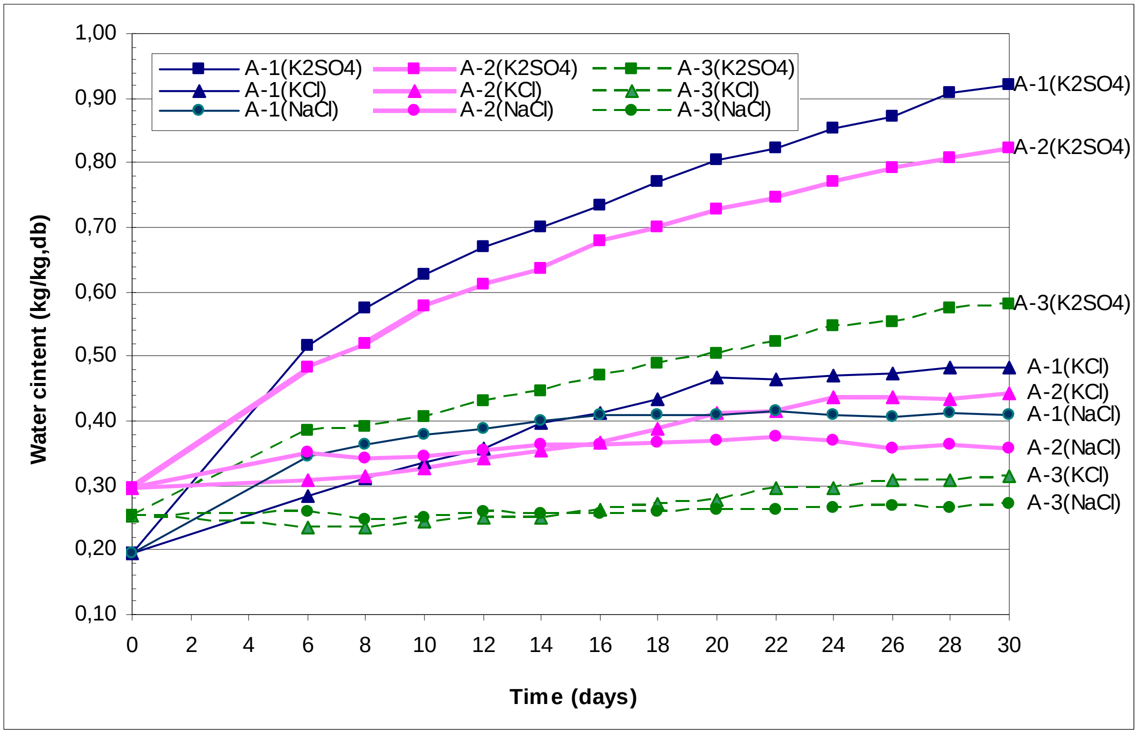

Figure 25: The water content change of peeled shrimp in one month in the containers of K_2SO_4, KCl and NaCl saturated solutions when measured once every two days.

(A-1: frozen, -2~0°C; A-2: frozen, 20°C; A-3 thawed, 20°C).

Figure 25 demonstrates that samples of A-1 (frozen peeled shrimp, -2~0°C) absorb water faster than A-2 (frozen peeled shrimp, 20°C) and A-3 (thawed shrimp, 20°C) in the whole month. The water content of A-2 and A-3 increased faster in the K_2SO_4 container. In all the samples between 0~14 days, the amount of water content increase in the NaCl container is less than in the KCl container, whereas the trends reverse after 14 days. Moreover, All the samples ceased to absorb water after 14~16 days in the NaCl container. A-3 only increased by a tiny amount of water content in the KCl container and nearly has no increase in the NaCl container. It absorbs water slower in the K_2SO_4 container.

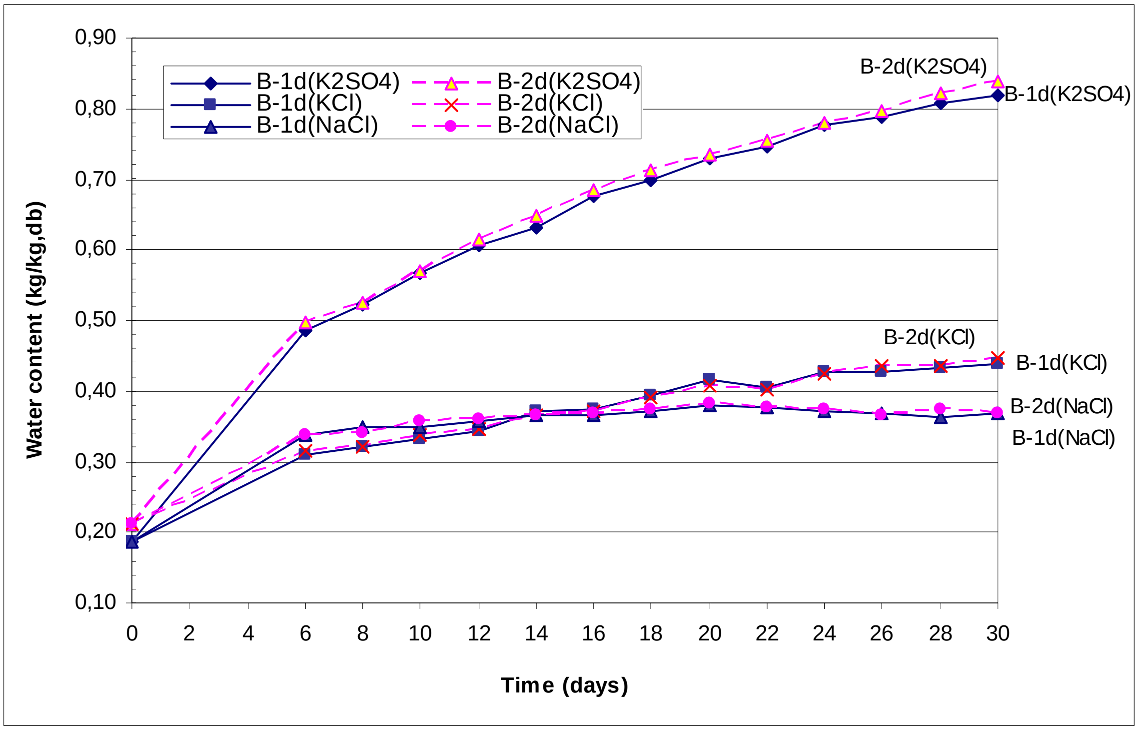

Figure 26: The water content change of deshelled headed shrimp in one month in the containers of K_2SO_4, KCl and NaCl saturated solutions when measured once every two days.

(B-1d: deshelled B-1 (frozen, -2~0°C); B-2d: deshelled B-2 (frozen, 20°C)).

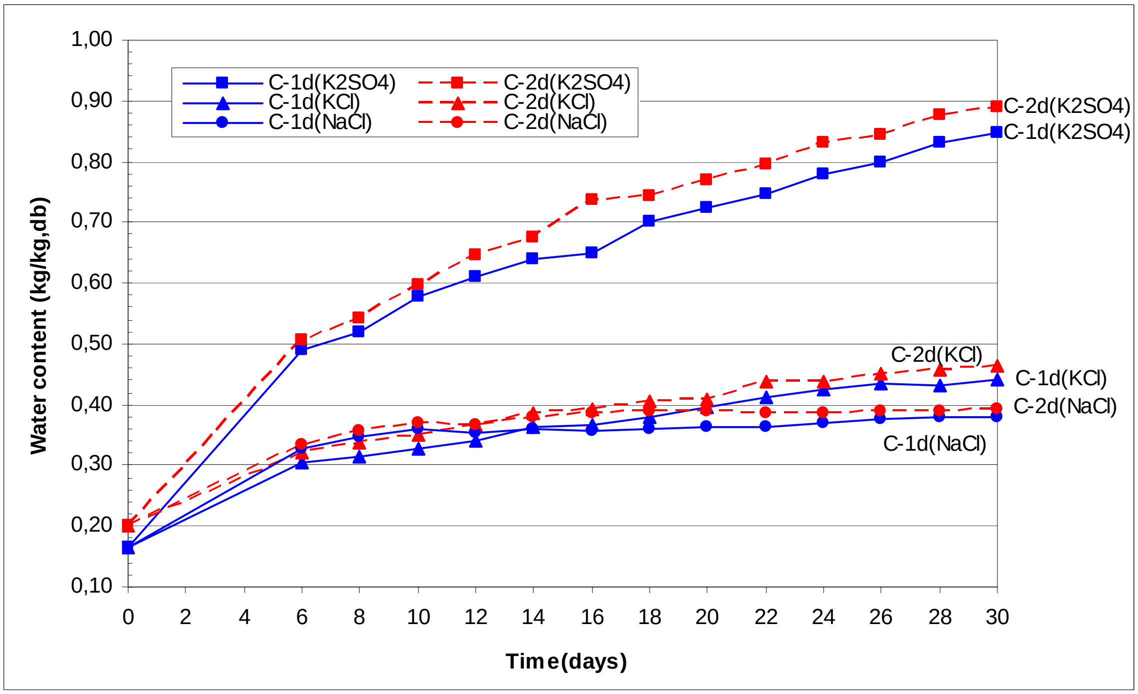

Figure 27: The water content change of deshelled whole shrimp in one month in the containers of K_2SO_4, KCl and NaCl saturated solutions when measured once every two days.

(C-1d: deshelled C-1 (frozen, -2~0°C); C-2d : deshelled C-2 (frozen, 20°C)).

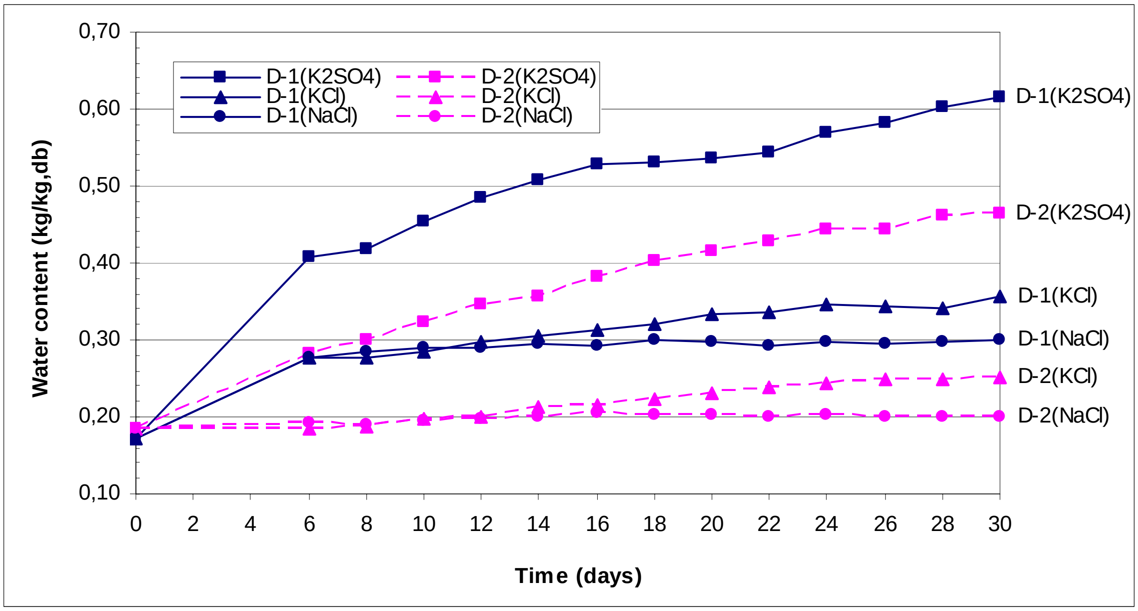

Figure 28: The water content change of thin fish cake (7~9 mm) in one month in the containers of K_2SO_4, KCl and NaCl saturated solutions when measured once every two days.

(D-1: frozen, -2~0°C; D-2: frozen, 20°C).

Deshelled samples of B-1 (headed shrimp, -2~0°C) and B-2 (headed shrimp, 20°C) have the same water content during the whole absorption process (one month) in all three containers (Figure 26). Figure 26 also displays the phenomenon that samples absorb water faster in the NaCl container than in the KCl container and that absorption ceases after 14 days in the NaCl container. From Figure 27 we can see that C-1d (deshelled whole shrimp, -2~0°C) and C-2d (deshelled whole shrimp, 20°C) have the same change trends of water content in the three containers and that the values of water content are similar at the same absorption times. Frozen thin fish cake dried at -2~0°C (D-1) absorb water faster than frozen thin fish cake dried at 20°C (D-2) in all three containers as shown in Figure 28.

The temperature changes in the three containers are very similar (the average values are 20.42°C, 20.58°C, 20.52°C and the SD is 0.62, 0.73, 0.77, respectively.). Compared with the KCl container, the relative humidity in the NaCl container is higher for the first 16 days. After that, the RH in the NaCl container approaches the equilibrium value (75%) and stops increasing. The RH in the KCl container increased slowly in the beginning but kept increasing until the end of the period. The value of RH in the KCl container at the end of one month (79.5%) has a difference of 5% with the equilibrium valve (85%). Obviously, the RH in the K_2SO_4 container is always much higher than the KCl and NaCl container, and its value after 30 days (95%) is similar to the equilibrium value (97%).

The water content changes of all the samples after 30 days absorption are shown in Figure 30. Generally speaking, the water increase in the K_2SO_4 container is much more than in the KCl and NaCl containers. For example, the water content of A-1 (frozen peeled shrimp, -2~0°C), C-2d (deshelled whole shrimp, 20°C) and C-1d (deshelled whole shrimp, -2~0°C) increased by 0.72 kg/kg, 0.69 kg/kg and 0.68 kg/kg in the K_2SO_4 containers respectively. At the same time, the identical samples only raised 0.29 kg/kg, 0.27 kg/kg and 0.28 kg/kg in the KCl container whereas they increased 0.22 kg/kg, 0.19 kg/kg and 0.22 kg/kg in the NaCl container.

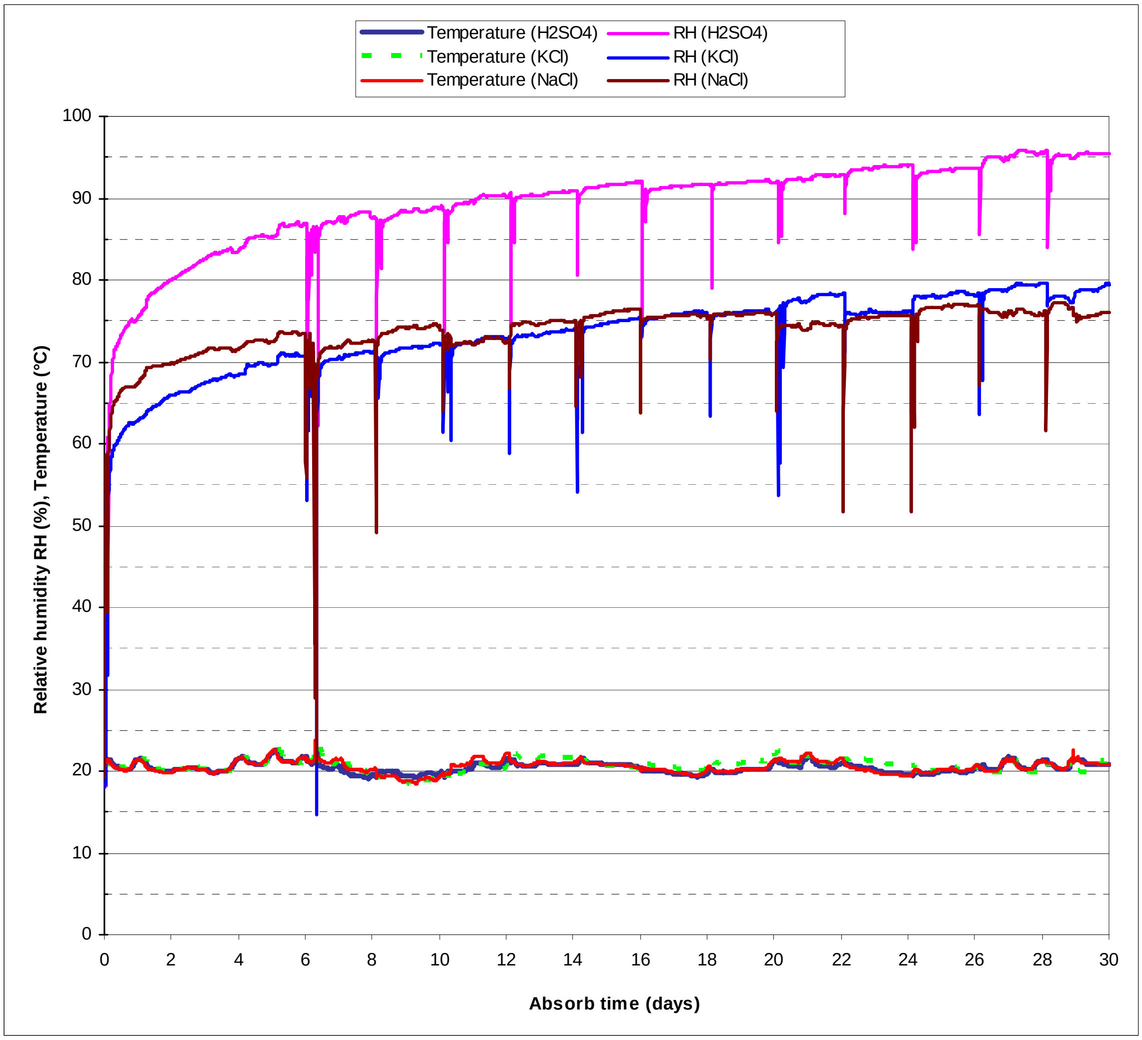

Figure 29: The relative humidity and temperature in the containers of K_2SO_4, KCl and NaCl saturated solutions in one month when measured once every two days.

Comparing Figure 20 with Figure 25, Figure 21 with Figure 26, Figure 22 with Figure 27, and Figure 23 with Figure 28, we can see that the values of water content on the 6th day are different even though the total absorption time is the same. The amounts of water content change after 6 days absorption are shown in Figure 31.

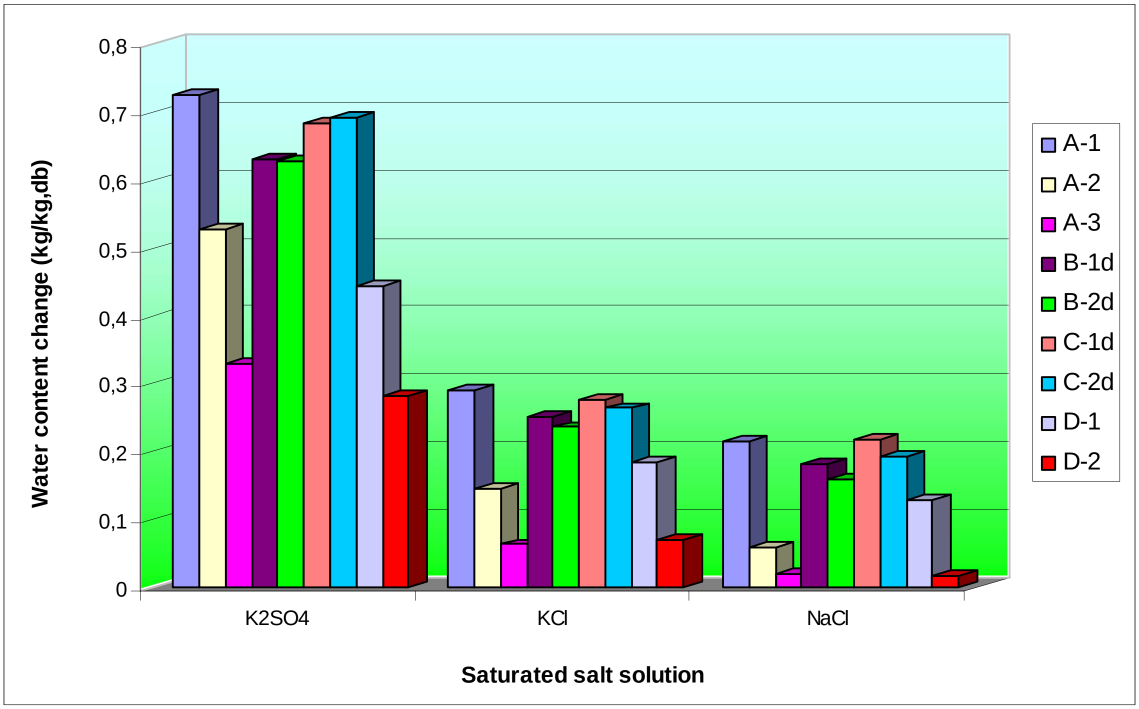

Figure 30: The water content change of shrimp and thin fish cake (7~9 mm) after 30 days absorption.

(A-1: frozen peeled shrimp, -2~0°C; A-2: frozen peeled shrimp, 20°C; A-3: thawed peeled shrimp, 20°C; B-1d: deshelled B-1(frozen headed shrimp, -2~0°C); B-2d: deshelled B-2(frozen headed shrimp, 20°C); C-1d: deshelled C-1(frozen whole shrimp, -2~0°C); C-2d: deshelled C-2 (frozen whole shrimp, 20°C); D-1: frozen fish cake, -2~0°C; D-2: frozen fish cake, 20°C).

Figure 31 illustrates that all the samples absorb water faster under K_2SO_4-6, KCl-6 and NaCl-6 treatments than under K_2SO_4-1, KCl-1 and NaCl-1 treatments. There are large differences in water content increase between K_2SO_4-6 and K_2SO_4-1 treatments. For example, the three types of peeled shrimp samples of A-1 (frozen, -2~0°C), A-2 (frozen, 20°C) and A-3 (thawed, 20°C) have a water content increase of 0.117 (kg/kg), 0.111 kg/kg and 0.107 kg/kg, respectively under K_2SO_4-6 and K_2SO_4-1 treatments (see Figure 31 (a)). The water content increase of B-1d (deshelled frozen headed shrimp, -2~0°C), C-1d (deshelled frozen whole shrimp, -2~0°C) and C-2d (deshelled frozen whole shrimp, 20°C) are 0.102 kg/kg, 0.122 kg/kg and 0.123 kg/kg under the same conditions (see Figure 31 (b) and (c)). The largest difference of water content increase occurs in D-1 (frozen thin fish cake, -2~0°C), which reaches 0.14 kg/kg (see Figure 31 (d)). However, the effect of these two kind absorption manners in the KCl and NaCl containers are not significant for most samples, only sample D-1 has a noticeable water content increase of 0.068 kg/kg and 0.065 kg/kg individually.

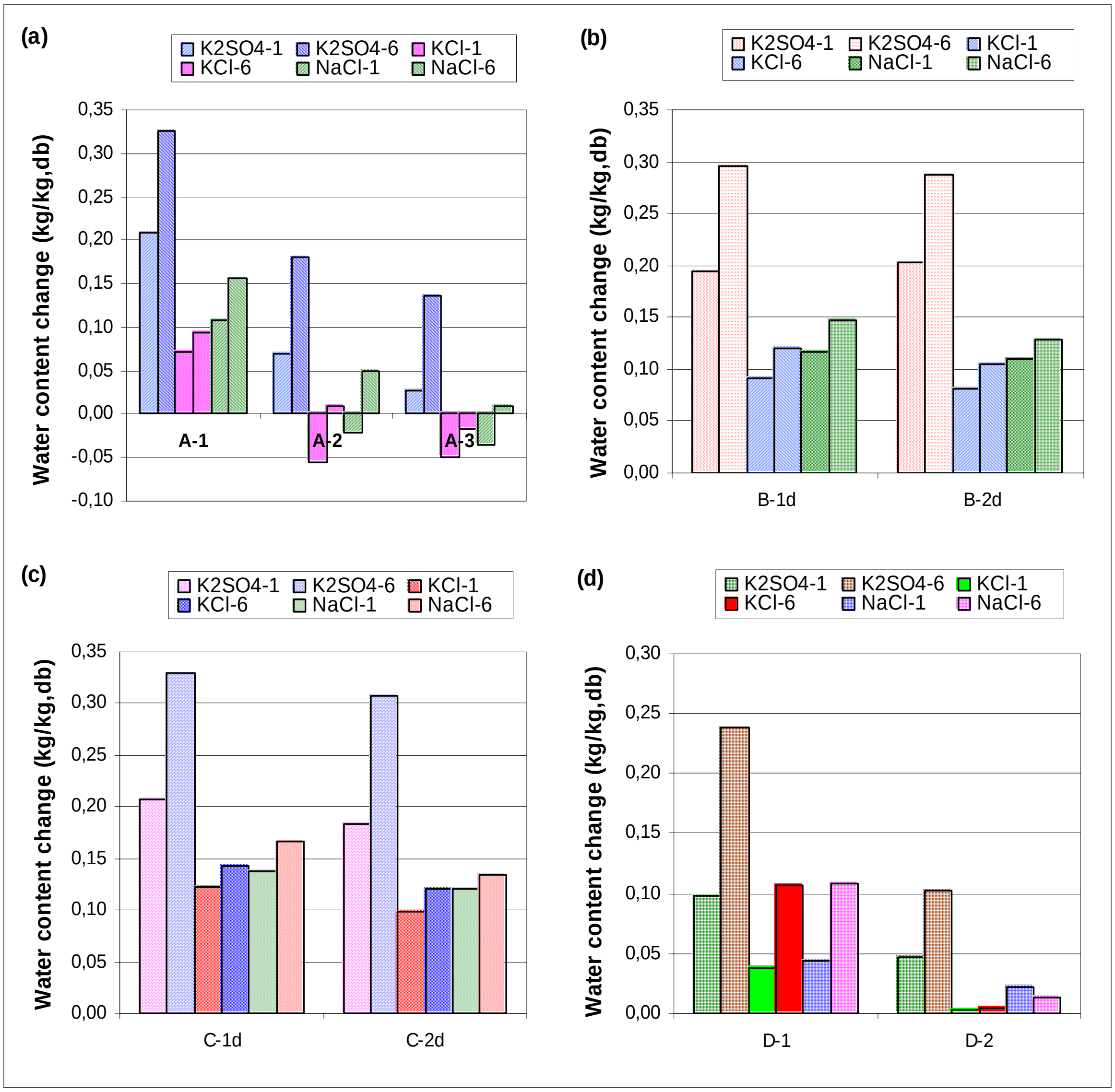

Figure 31: The comparison of water content change of shrimp and thin fish cake (7~9 mm) after 6 days absorption.

(K_2SO_4-1, KCl -1 and NaCl-1: measured once every day; K_2SO_4-6, KCl -6 and NaCl-6: only measured on 6 day. A-1: frozen peeled shrimp, -2~0°C; A-2: frozen peeled shrimp, 20°C; A-3: thawed peeled shrimp, 20°C; B-1d: deshelled B-1(frozen headed shrimp, -2~0°C); B-2d: deshelled B-2(frozen headed shrimp, 20°C); C-1d: deshelled C-1(frozen whole shrimp, -2~0°C); C-2d: deshelled C-2 (frozen whole shrimp, 20°C); D-1: frozen fish cake, -2~0°C; D-2: frozen fish cake, 20°C).

4.4.2 The change of water activity and the sorption isotherms

The relationship between water activity and water content during the absorption process of peeled shrimp, deshelled headed shrimp, deshelled whole shrimp and fish cake is shown in Figure 32(a), (b), (c) and (d). The comparisons of different samples at the same drying temperature of -2~0°C and 20°C are shown in Figure 32 (e) and (f).

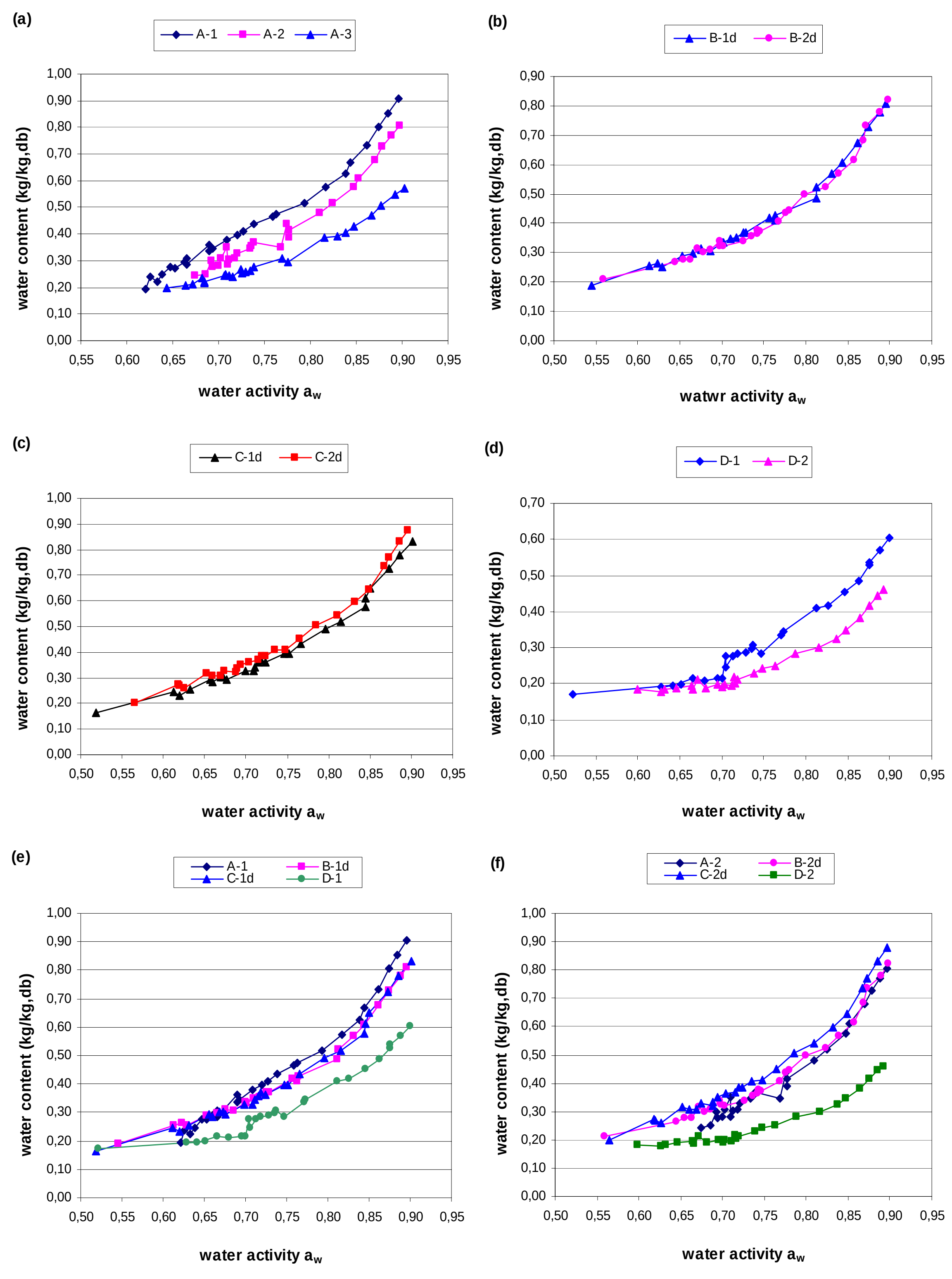

Figure 32: The sorption isotherms of shrimp and thin fish cake (7~9 mm).

(A-1: frozen peeled shrimp, -2~0°C; A-2: frozen peeled shrimp, 20°C; A-3: thawed peeled shrimp, 20°C; B-1d: deshelled B-1(frozen headed shrimp, -2~0°C); B-2d: deshelled B-2(frozen headed shrimp, 20°C); C-1d: deshelled C-1(frozen whole shrimp, -2~0°C); C-2d: deshelled C-2 (frozen whole shrimp, 20°C); D-1: frozen fish cake, -2~0°C; D-2: frozen fish cake, 20°C).

The sorption isotherms are significantly different among the dried peeled shrimps of A-1 (frozen, -2~0°C), A-2 (frozen, 20°C) and A-3 (thawed, 20°C). The water content of A-1 is always higher than A-2 and A-3 at the corresponding water activity. A-3 has the lowest value of water content at the same water activity (Figure 32 (a)). Conversely, the trend of B-1d (deshelled frozen headed shrimp, -2~0°C) is almost the same as with B-2 (deshelled frozen headed shrimp, 20°C), and the same results exist in C-1d (deshelled frozen whole shrimp, -2~0°C) and C-2d (deshelled frozen whole shrimp, -2~0°C) (Figure 32 (b) and (c)). The difference is also shown in figure 32 (d) between D-1 (frozen thin fish cake, -2~0°C) and D-2 (frozen thin fish cake, 20°C). The water content of D-1 is more than D-2 when a_w is more than 0.70. Furthermore, the difference of water content between A-1 and A-3 at the same water activity may reach to 0.3 in the range of $a_w > 0.85$.

Figure 32 (e) demonstrated that the sorption isotherms of dried peeled shrimp, deshelled headed shrimp and deshelled whole shrimp at -2~0°C are similar, but they are different with the sorption isotherm of dried fish cake (D-1). The identical results are presented among dried peeled shrimp, deshelled headed shrimp and deshelled whole shrimp at 20°C (Figure 32(f)).

5 DISCUSSION

5.1 The drying characteristics of shrimp and fish cake

5.1.1 General analysis of drying characteristics

The results of shrimp and fish cake drying showed that drying time decreased greatly as drying temperature increased from -2~0°C to 20°C. Drying time was also considerably affected by the thickness of fish cake. The thin fish cake (7~9 mm) dried faster than thick fish cake (14~19 mm), and this effect is more noticeable at the high temperature (the drying time reduced to 32 hours and 64 hours at -2~0°C and 20°C respectively). For the drying of shrimp, it was found that the shell of the shrimp acted as a barrier to the moisture diffusion out of the shrimp (Bassawh *et al.*2002). The results of this study show that the moisture content was significantly affected by the condition (with shell or no shell, with head or no head) of the shrimp. Among the three different kinds of shrimp (peeled, headed and whole shrimp), the peeled shrimp has the shortest drying time and the headed shrimp dried faster than whole shrimp both at the drying temperature of -2~0°C and 20°C.

The drying rate of shrimp and fish cake was significantly affected by water content and water content-temperature interaction. The drying rate declined as the water content decreased during the drying process. All the samples dried at -2~0°C have both the constant drying rate and the falling drying rate periods. No constant drying rate period was observed when dried at 20°C. This implies that there is an initial period of variable duration in which the drying rate was controlled by the rate of water evaporating at the surface when dried at -2~0°C, whereas the drying rate was controlled by the internal water movement from the begining of the drying process when dried at 20°C. This result is similar with the study of Clement *et al.* (1993) on shark fillets drying. The results also show that the drying rate of peeled shrimp is much higher than headed shrimp and whole shrimp, and this trend is more noticeable at 20°C. At the same time, the thickness of fish cake has a remarkable effect to the drying rate especially at a higher temperature (20°C).

5.1.2 Modelling of drying kinetics

It is generally accepted that the rate of moisture removed from salted fish during the falling rate period is governed by the transfer of water by diffusion (Bellagha *et al.* 2002, Ismail and Wooton 1992, Wheaton and Lawson 1985). The thin layer drying equation according to Fick´s second law of diffusion has been widely used to estimate the drying time during the falling drying rate periods. Thus, drying rate can be expressed by the following equations (Diffusion model):

$$MR = \frac{M_t - M_{eq}}{M_0 - M_{eq}} = A\exp(-kt) \qquad (1)$$

where: MR — water content ratio

M_t — the water content in drying time t, kg/kg (dry basis);

M_0 — the initial water content, kg/kg (dry basis);

M_{eq} — the equilibrium water content, kg/kg (dry basis);

A — constant;

k — drying rate constant (h^{-1}).

In calculating the water content ratio, we can assume M_{eq} to be zero (Prachayawarakorn *et al.* 2002). So the moisture ratio can be expressed by the equation:

$$MR = \frac{M_t}{M_0}$$

Equation (1) can be transformed into the following form:

$$\mathrm{Ln}\,(MR) = \mathrm{Ln}A - kt \qquad (2)$$

There is a strong linear relationship between Ln (MR) with drying time (Figure 33, 34 and 35), showing that equation (1) described well the heat pump drying process of shrimp and fish cake.

Increasing the drying temperature from -2~0°C to 20°C significantly enhanced the drying rate (see Figure 10, 11 and 12) and k-values (see Table 5). Former studies present that an increase of drying air temperature can lead to an increase of the drying rate constant (k) in the drying of many biological materials (Sankat *et al.* 1996, Yusheng and Poulsen 1988, Chiang and Petersen 1985).

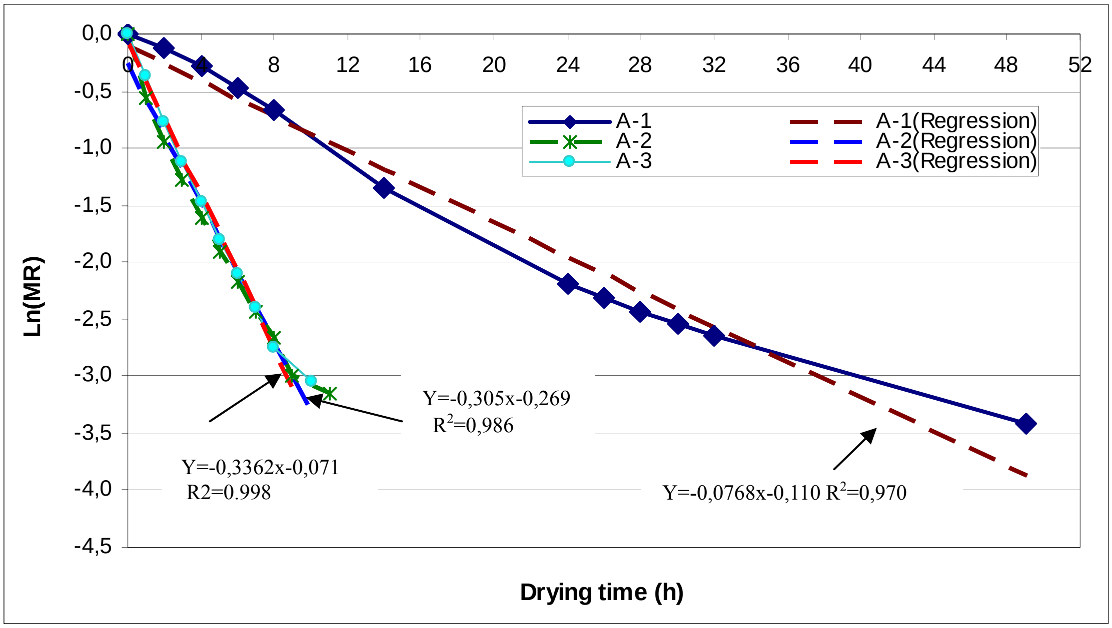

Figure 33: The relation curves of Ln (*MR*) — drying time of peeled shrimp under different treatments.

(A-1: frozen, -2~0°C; A-2: frozen, 20°C; A-3: thawed, 20°C).

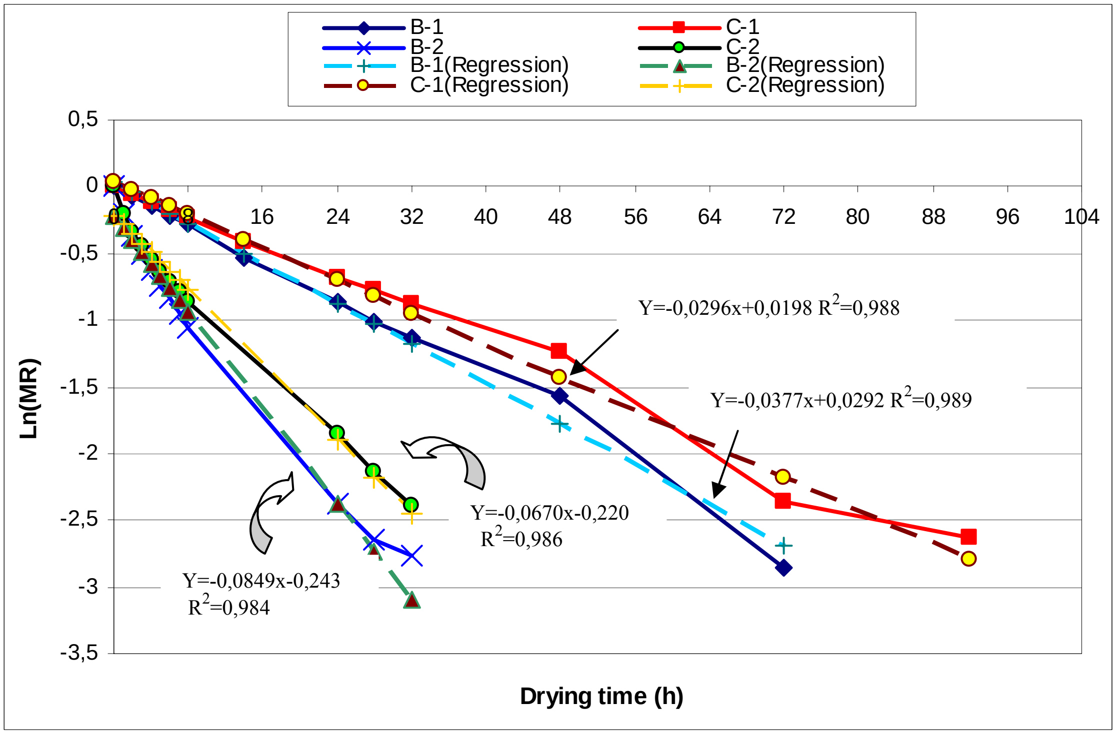

Figure 34: The relation curves of Ln (*MR*) — drying time of frozen headed shrimp and whole shrimp at different drying temperatures.

(B-1: headed shrimp, -2~0°C; B-2: headed shrimp, 20°C; C-1: whole shrimp, -2~0°C; C-2: whole shrimp, 20°C).

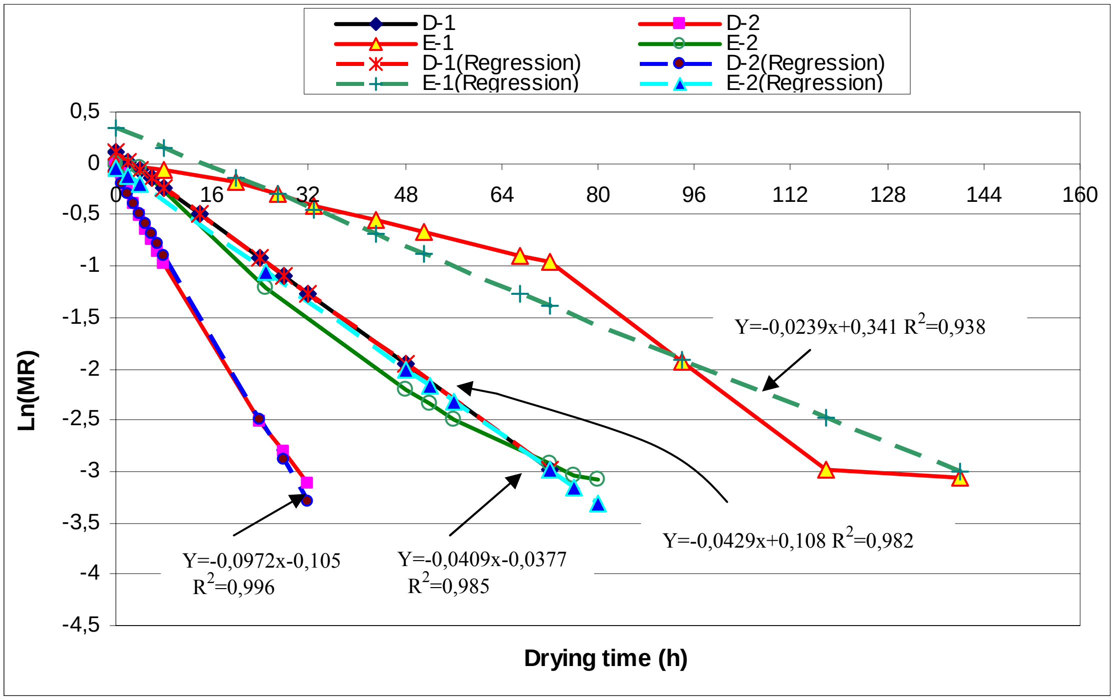

Figure 35: The relation curves of Ln (*MR*) — drying time of frozen fish cake at different drying temperatures.

(D-1: thin fish cake (7~9 mm), -2~0°C; D-2: thin fish cake (7~9 mm), 20°C; E-1: thick fish cake (14~18 mm), -2~0°C; E-2: thick fish cake (14~18 mm), 20°C).

Table 5: The values of constant A, constant k and R^2 of the drying models

Samples*	*A*	*k*	R^2
frozen peeled shrimp, -2~0°C	0.8954	0.07679	0.9703
frozen peeled shrimp, 20°C	0.7643	0.3053	0.9855
thawed peeled shrimp, 20°C	0.9314	0.3362	0.998
frozen headed shrimp, -2~0°C	1.0297	0.03771	0.9887
frozen headed shrimp, 20°C	0.7846	0.08486	0.9836
frozen whole shrimp, -2~0°C	1.0200	0.02964	0.9882
frozen whole shrimp, 20°C	0.8021	0.06898	0.9864
frozen thin fish cake (7~9 mm), -2~0°C	1.1139	0.04294	0.9821
frozen thin fish cake (7~9 mm), 20°C	0.9005	0.09718	0.9955
frozen thick fish cake (14~18 mm), -2~0°C	1.4095	0.0239	0.9376
frozen thick fish cake (14~18 mm), 20°C	0.9630	0.04093	0.0985

5.1.3 Modelling of desorption isotherms of shrimp

Physical, chemical and microbiological stability of dried food product is influenced by water activity. Microbial growth, lipid oxidation, non-enzymatic activity, enzymatic activity and texture of food depend on water activity (Rahman and Labuza 1999). Water sorption isotherms are used in process design and control to predict the end-point of drying (Rahman and Labuza 1999, Yu et al. 1999, Chen and Jayas 1998, Rahman 1995). Numerous theoretical, semi-theoretical and empirical equations have been proposed to represent the sorption isotherms of various products. The five equations commonly used to describe the moisture sorption isotherms of biological materials are the Henderson, Chung-Pfost, Halsey, Oswin and GAB equations (Jayas and Mazza 1993). Among these five equations, the Oswin model has been found to describe well the products with high protein contents (Bellagha *et al.* 2005, Muterjemi 1988).

The Oswin equation is as follows (Bellagha *et al.* 2005):

$$X = a\left(\frac{a_w}{1-a_w}\right)^n \tag{3}$$

where: X — water content (db);
a_w — water activity in decimal;
a, n — constants.

Model (3) could be transformed into the following form:

$$\text{Ln } X = \text{Ln}a + n\text{Ln}[(a_w/(1-a_w)] \tag{4}$$

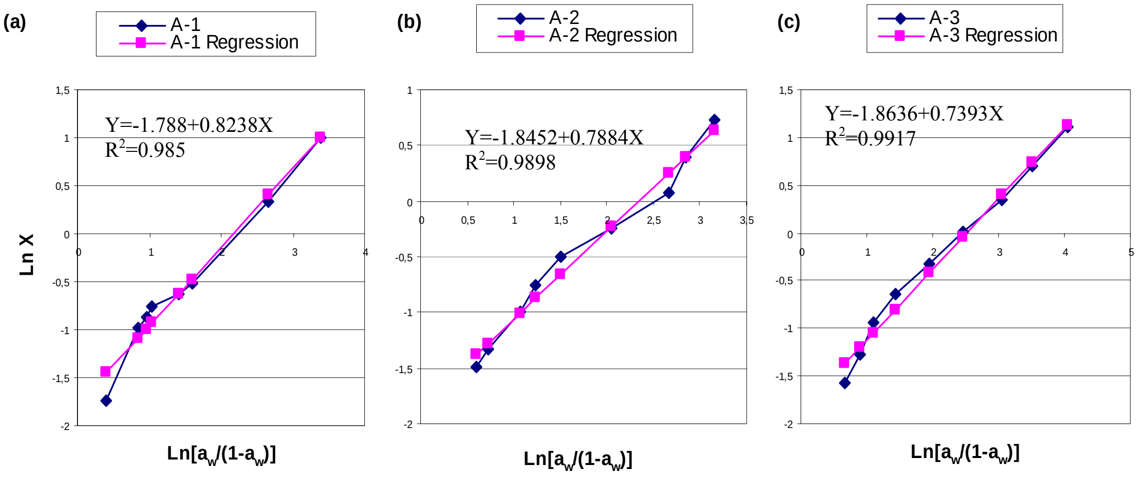

Figure 36: The relation curves of Ln X — Ln[a_w/(1-a_w)] of peeled shrimp under different treatments.

(A-1: frozen, -2~0°C; A-2: frozen, 20°C; A-3: thawed, 20°C).

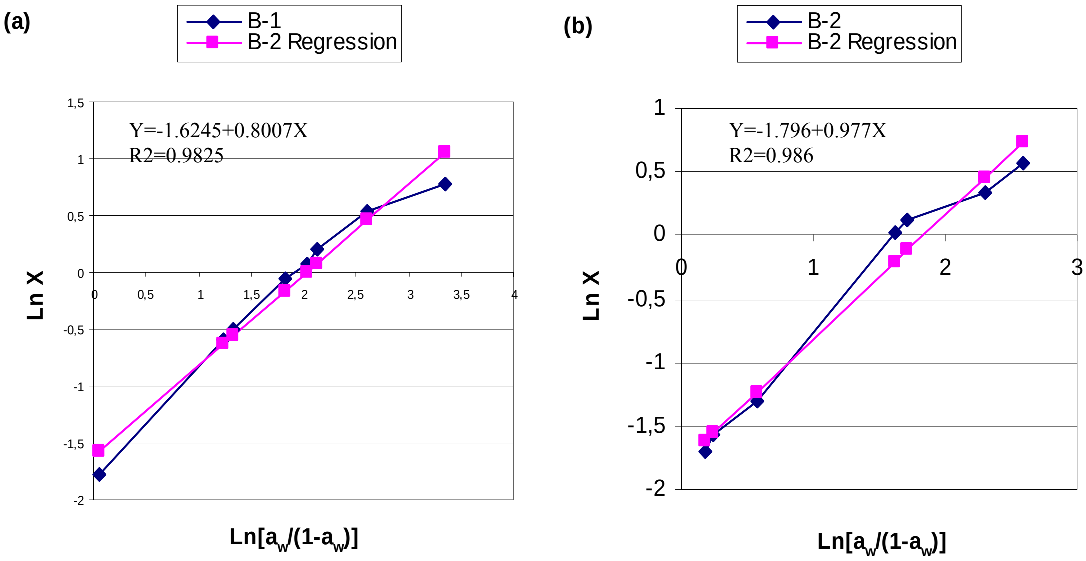

Figure 37: The relation curves of Ln *X* — Ln[a_w/(1-a_w)] of frozen headed shrimp at different drying temperature.

(B-1: -2~0°C; B-2: 20°C).

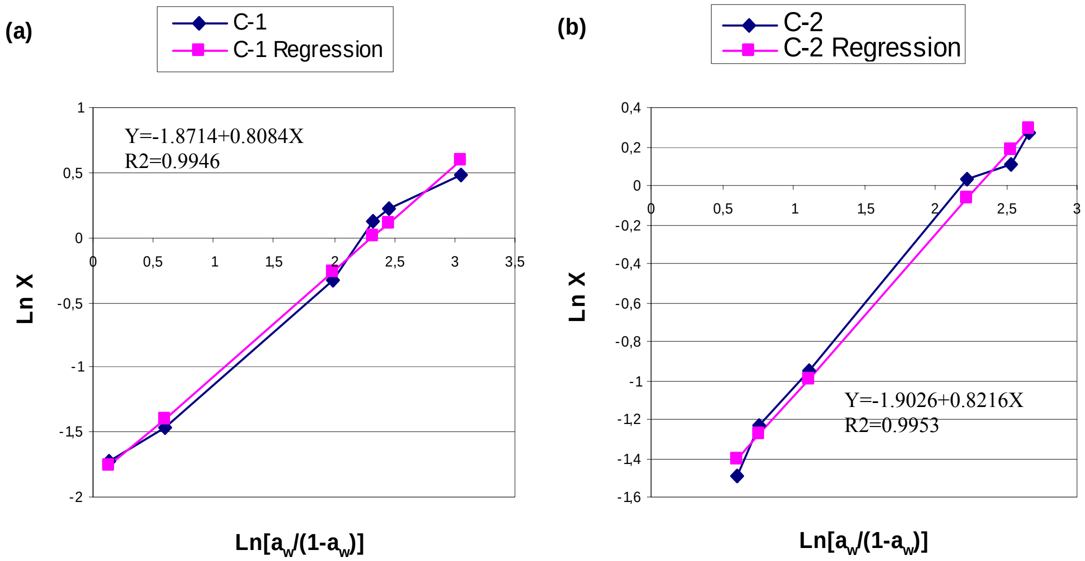

Figure 38: The relation curves of Ln *X* — Ln[a_w/(1-a_w)] of frozen whole shrimp at different drying temperature.

(C-1: -2~0°C; C-2: 20°C).

The Oswin Model gives a good fit to the experimental data (Figure 36, 37 and 38). High correlation coefficients values (R^2=0.9825~0.9953) have been gained from all the samples. On the other hand, from Table 6, we can see that the constants of *a* and *n* only have a small difference in each group (peeled shrimp, headed shrimp, whole shrimp). It indicates that the different treatment for peeled shrimp, the different drying temperature for headed shrimp and whole shrimp have no significant influence on the desorption isotherms. Therefore, the average constants of *a* and *n* can be used to predict the relations of water content and water activity during the drying process of these shrimp samples. From table 6 we can see the correlation coefficient values (R^2=0.9787~0.9948) are high even when use the averaged *a* and *n*. Therefore, we can use one Oswin equation to express the desorption isotherm of each type sample individually. The Oswin Models of peeled shrimp, headed shrimp and whole shrimp are as follows:

Peeled shrimp: $$X = 0.16 \times \left(\frac{a_w}{1-a_w}\right)^{0.7838} \quad (5)$$

Headed shrimp: $$X = 0.1808 \times \left(\frac{a_w}{1-a_w}\right)^{0.8888} \quad (6)$$

Whole shrimp: $$X = 0.1539 \times \left(\frac{a_w}{1-a_w}\right)^{0.8150} \quad (7)$$

Table 6: The values of constant *a, n* and R^2 of the Oswin models for the desorption isotherms of shrimp

Samples*	*a*	*n*	R^2
frozen peeled shrimp, -2~0°C	0.1673	0.8238	0.9850
frozen peeled shrimp, 20°C	0.1580	0.7884	0.9898
thawed peeled shrimp, 20°C	0.1551	0.7393	0.9917
frozen headed shrimp, -2~0°C	0.1970	0.8007	0.9825
frozen headed shrimp, 20°C	0.1660	0.9770	0.9860
frozen whole shrimp, -2~0°C	1.1539	0.8084	0.9946
frozen whole shrimp, 20°C	0.1492	0.8216	0.9953
peeled shrimp -average	0.1600	0.7838	0.9850
headed shrimp -average	0.1808	0.8888	0.9787
whole shrimp -average	0.1539	0.8150	0.9948

A comparison of the predicted curves of equations (5), (6) and (7) and the experimental data at a_w>0.5 shows an excellent agreement for peeled shrimp and whole shrimp and a good fitness for headed shrimp (Figure 39). The desorption isotherms of peeled shrimp and whole shrimp are similar, but differ significantly from those for headed shrimp. The water activity of headed shrimp is always lower than that of peeled shrimp and whole shrimp at the corresponding values of water content. That is to say that headed shrimp has better stability than either peeled shrimp or whole shrimp.

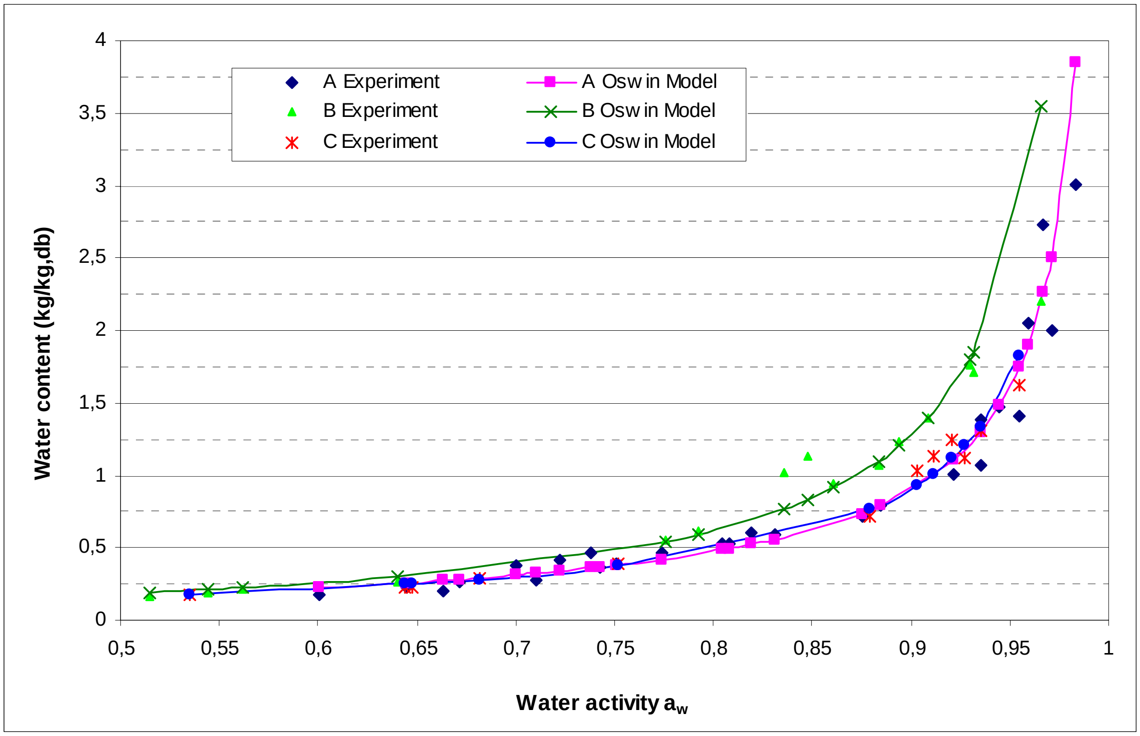

Figure 39: The comparison of predicted curves with experimental data of peeled shrimp.

(A Oswin Model with A Experiment), headed shrimp (B Oswin Model with B Experiment) and whole shrimp (C Oswin Model with C Experiment).

5.2 Physical and sensory evaluation of heat pump dried shrimp and fish cake

5.2.1 Shrinkage and colour

During drying, foods undergo volume changes due to shrinkage or expansion depending on the drying materials and the drying methods. Normally, the muscle fibres shrink during drying. Different drying techniques can cause different degrees of shrinkage (Rahman 2001). A considerable amount of research has been reported about the shrinkage of food during drying. Some studies have been carried out on the drying behaviour of shrimp in recent years (Namsanguan *et al.* 2004, Prachayawarakorn *et al.* 2002, Lin *et al.* 1999).

The results of heat pump drying of shrimp revealed that the degree of shrinkage increased with temperature. The degree of shrinkage of the shrimp with shell (headed and whole shrimp) is much lower than that of peeled shrimp. So, the shell of the shrimp has a potential to reduce the degree of shrinkage. It was also noticed that the degree of shrinkage of headed shrimp is lower than for whole shrimp. A possible reason for this is that the drying time of headed shrimp is shorter than whole shrimp at the same temperature.

Tein (1999) studied the shrinkage of shrimp under different drying methods. The shrinkage of shrimp (*Penaeus indicus*) at 70°C hot air drying was 35%, which is higher than the shrinkage of whole shrimp dried by heat pump at -2~0°C (21.48%) but it is near to that for whole shrimp dried at 20°C (32.83%).

Nearly all the colour values of dried and rehydrated thawed peeled shrimp are the lowest for all shrimp samples (except the redness of dried peeled shrimp is a litter higher than A-1 and A-2) which indicates that the thawing process has an adverse effect on preserving the colour of dried shrimp. The results do not show a remarkable difference in the colour values of shrimp samples dried at -2~0°C or 20°C, but that temperature has a considerable effect on the colour of dried fish cake. The low drying temperature (-2~0°C) helps preserve the colour of fish cake. Since the intense red and orange colour indicates the good quality of dried shrimp, it can be said that the sample of B-2d (deshelled headed shrimp, 20°C) has the best colour appearance among all the shrimp samples.

Compared with studies on shrimp drying, heat pump dried *Pandalus borealis* has much higher lightness than hot air dried *Penaeus indicus* (Lin *et al.* 1999) and superheated steam dried *Penaeidae* (Prachayawarakorn *et al.* 2002). Meanwhile, they have the similar redness and yellowness.

5.2.2 Rehydration, texture and water holding capacity (WHC)

The degree of rehydration depends on the degree of cellular and structural disruption as well as the nature of internal porous structure and the mechanical properties of dried materials (Krokida and Morinos-Kouris 2003). The space in dried materials is indispensable during rehydration for it will provide necessary avenues for conveying water into the muscle fibers. Commonly, with lower shrinkage the rehydration potential is higher and rehydration is faster. The results of this study show the same pattern, except for peeled and shelled shrimp where the peeled shrimp has more shrinkage and higher rehydration.

Shear stress is used as an indicator for toughness of shrimp when consumed in both dried state and rehydrated state (Lin *et al.* 1999, Namsanguan *et al.* 2004). Higher shear force was required to cut the dried shrimp samples when the drying temperature was increased, whereas the drying temperature had little influence on rehydrated shrimp samples. Peeled shrimp was less tough than shelled shrimp both in dried or rehydrated conditions.

Water holding capacity has frequently been used as an indicator for protein denaturation (Bhattacharya, 1989, Hsieh and Regenstein, 1989). The results show that the drying temperature has a notable effect on the water holding ability of dried fish cake, the samples dried at -2~0°C displayed a diminished ability to hold water. Meanwhile, among shrimp samples, only the WHC of peeled shrimp dried at -2~0°C is considerably low, other samples almost have the same water holding ability.

5.3 Chemical and microbiological analysis

There are only a limited number of reports on the effect of headed shrimp on microbial quality. In this project, the heads of shrimp (*Pandalus borealis*) were removed manually. The size of whole shrimp (with head on) was 98-104 counts/kg and the size of headed shrimp was 196-200 counts/kg. The head accounts for 46.9-51.0% of the total weight of shrimp. The TVC values of the raw materials of headed shrimp and whole shrimp was 8,100 and 8,600, respectively. Thus, the head contains 50.0-53.8% of the bacteria load. This concurs with the results observed by Koburger *et al.* (1973), who reported that the *Penaeus* shrimp contained essentially the same total counts whether the shrimp tails were stored with or without heads.

The bacteria grew during the drying process. The results show that bacteria increase was inversely correlated with temperature in the shrimp samples. This is probably because the total drying time of shrimp samples dried at -2~0°C is much longer than for those dried at 20°C. However, in the drying of thin fish cake, the bacteria grew faster when dried at 20°C than dried at 0°C. In any case the TVC of all the shrimp samples after heat pump drying is much lower than the spoiling level of 10^6 cfu (colony forming units) per gram (Ozogul *et al.* 2004). The TVC value of dried thin fish cake is with an acceptable level.

Though the protein content of headed shrimp and whole shrimp are exactly the same, the fat content of whole shrimp is notably higher than of headed shrimp. It implies that most of the fat exists in the head of shrimp. Usually, high fat content means longer drying time and may cause bad smell during the drying process. In the experiments of this project, such trend was obtained.

5.4 Evaluation and prediction of stability

5.4.1 General analysis of adsorption characteristics

Safety and spoilage of processed foods are major concerns of both manufactures and consumers. High quality dried products could be developed by knowing their complete isotherms. Adsorption isotherms of dried products can also be used in packaging design for the products. Sadly, there is a little information on the isotherms of fish, shrimp and other seafood. The isotherms of squid, fish flour and sardine have been developed by Rahman *et al.* (1995), Labuza *et al.* (1985), Sablani *et al.* (2001) and Bellagha et al. (2004).

This study showed that dried shrimp and fish cake adsorb moisture when their water activity is lower than the external relative humidity and loose moisture if their water activity is higher than the relative humidity of the surroundings. The relative humidity of the surroundings decides the final water content of the products. The difference between the relative humidity of the surroundings and the water activity affects the rate of absorption water (see Figure 31). The absorbing rate is faster with higher difference.

5.4.2 Modelling of moisture adsorption

The most widely used empirical equations to describe thin layer drying and re-wetting of biological food material are the Diffusion model and Page model (Basunia and Abe 2003, Dadgar *et al.* 2004). It has been indicated that the diffusion model (equation (1)) can be used as the drying model of shrimp and fish cake. The Page model is as follows:

$$MR = \frac{M - M_e}{M_i - M_e} = e^{-kt^n} \tag{8}$$

where: MR —moisture ratio;
M — moisture content of samples;
Mi — initial moisture content of samples;
Me — EMC of samples;
k, n — constant.

Model (8) could be transformed as:

$$\mathrm{Ln}[-\mathrm{Ln}(MR)] = \mathrm{Ln}k - n\mathrm{Ln}\ t \tag{9}$$

By regressing each experiment with equation (2) and (9) respectively, we can gain all the correlation coefficient values of the Diffusion model and Page model (Table 7).

Table 7: The values of correlation coefficient (R^2) of the Diffusion and Page models

Solution	Model	Sample								
		A-1	A-2	A-3	B-1d	B-2d	C-1d	C-2d	D-1	D-2
K_2SO_4	Diffusion	0.9942	0.9979	0.9912	0.9976	0.9976	0.9922	0.9965	0.9840	0.9966
	Page	0.9936	0.9985	0.9969	0.9943	0.9948	0.9883	0.9946	0.9842	0.9969
KCl	Diffusion	0.9864	0.9670	0.9157	0.9885	0.9918	0.9733	0.9890	0.9791	0.9712
	Page	0.9910	0.9910	0.9702	0.9841	0.9838	0.9647	0.9841	0.9753	0.9758
NaCl	Diffusion	0.8923	0.6814	0.8393	0.7541	0.7714	0.9070	0.9236	0.8050	0.6954
	Page	0.9367	0.6505	0.9316	0.7989	0.8141	0.9185	0.9503	0.8963	0.7382

(A-1: frozen peeled shrimp, -2~0°C; A-2: frozen peeled shrimp, 20°C; A-3: thawed peeled shrimp, 20°C; B-1d: deshelled B-1(frozen headed shrimp, -2~0°C); B-2d: deshelled B-2(frozen headed shrimp, 20°C); C-1d: deshelled C-1(frozen whole shrimp, -2~0°C); C-2d: deshelled C-2 (frozen whole shrimp, 20°C); D-1: frozen thin fish cake (7~9 mm), -2~0°C; D-2: frozen thin fish cake (7~9 mm), 20°C.)

From table 7, we can see that both the Diffusion and Page models fit with the adsorption of the samples in K_2SO_4 container. The Page model gives a better fit with the adsorption in the KCl container than the Diffusion model. Analysing the adsorption process, these results were probably caused by the different differences between the initial water content of the samples and relative humidity of the surroundings. The higher the difference the better the fit is. Generally, we can use the Page model to predict the adsorption process of dried shrimp and fish cake when the relative humidity is more than 85%.

5.4.3 Adsorption isotherm

In the study of desorption isotherms of shrimp, we have discussed that the Oswin model can better describe the sorption isotherms of high protein level products. Also the studied results of desorption isotherms of shrimp show that the Oswin model can be used to predict the relationship of water content and water activity during the drying process. So, we should try to use this model to describe the adsorption isotherm of shrimp and fish cake.

A regression has been carried out using the transformed equation (4). Table 8 shows the values of constants a, n and correlation coefficient (R^2) of all the samples.

Table 8: The values of constants a, n and correlation coefficient (R^2) of the Oswin models for the adsorption isotherms of shrimp and fish cake

Samples*	*a*	*n*	R^2
frozen peeled shrimp, -2~0°C	0.1655	0.8312	0.9810
frozen peeled shrimp, 20°C	0.1487	0.7995	0.9868
thawed peeled shrimp, 20°C	0.1338	0.6714	0.9966
deshelled B-1(frozen headed shrimp, -2~0°C)	0.1802	0.7164	0.9972
deshelled B-2(frozen headed shrimp, 20°C)	0.1765	0.7147	0.9967
deshelled C-1(frozen whole shrimp, -2~0°C)	1.1731	0.7434	0.9949
deshelled C-2 (frozen whole shrimp, 20°C)	0.1867	0.7344	0.9956
frozen thin fish cake (7~9 mm), -2~0°C	0.1394	0.6868	0.9816
frozen thin fish cake (7~9 mm), 20°C	0.1265	0.5919	0.9843
headed shrimp-average	0.1786	0.7140	0.9969
whole shrimp -average	0.1798	0.7388	0.9953

Table 8 displays that the correlation coefficients (R^2) are all above 0.98. This indicates that the Oswin model can also be used to express the adsorption isotherms of dried shrimp and fish cake. From Table 8, it is clear that constants *a* and *n* for B-1 and B-2, C-1 and C-2 are similar. Therefore, we can use the averaged values of *a* and *n* to predict the relationship of water content and water activity during the drying process of deshelled headed shrimp and whole shrimp. The values of the constants *a*, *n* and the correlation coefficient (R^2) of B-average and C-average are also shown in Table 8.

The desorption isotherm and sorption isotherm of frozen peeled shrimp dried at -2~0°C are almost the same in the range of $a_w < 0.85$ (Figure 40). The hysteresis is observed when water activity is higher than 0.85 (Figure 40). That is to say, the water content of sorption samples is less than that of desorption at the same water acticity. This difference increased with the increasing of a_w. Figure 41 displays that there is hysteresis in the middle range ($a_w = 0.75$~0.88) of frozen peeled shrimp dried at 20°C. The maximum difference of water content between the desorption isotherm and sorption isotherm occurred in the stage of $a_w = 0.80$~0.85.

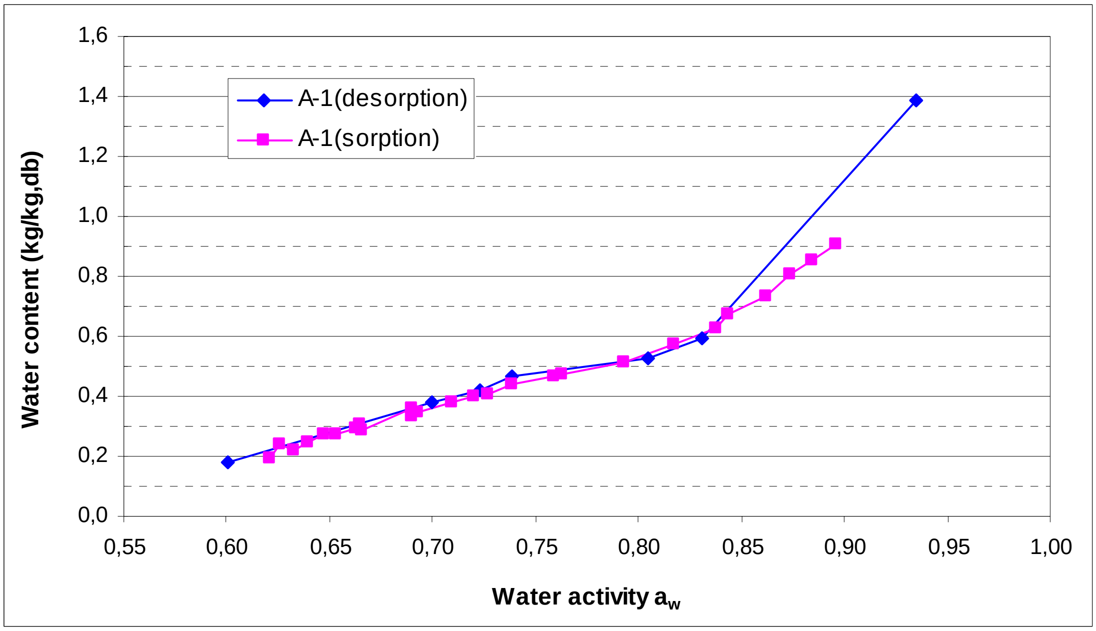

Figure 40: The comparison of the desorption isotherm and sorption isotherm of frozen peeled shrimp dried at -2~0°C.

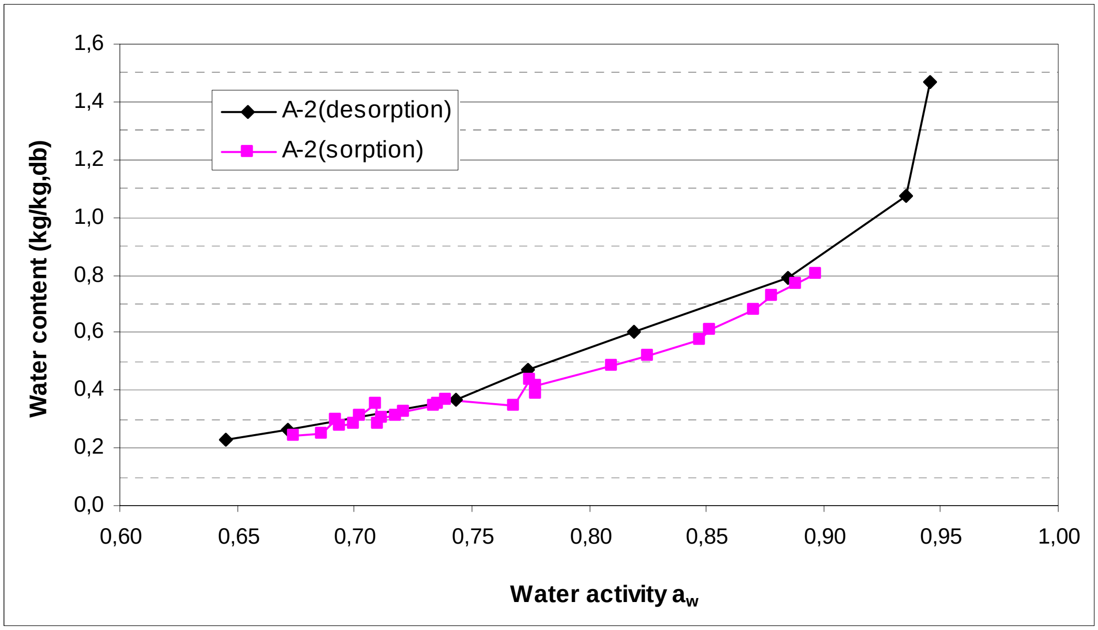

Figure 41: The comparison of the desorption isotherm and sorption isotherm of frozen peeled shrimp dried at 20°C.

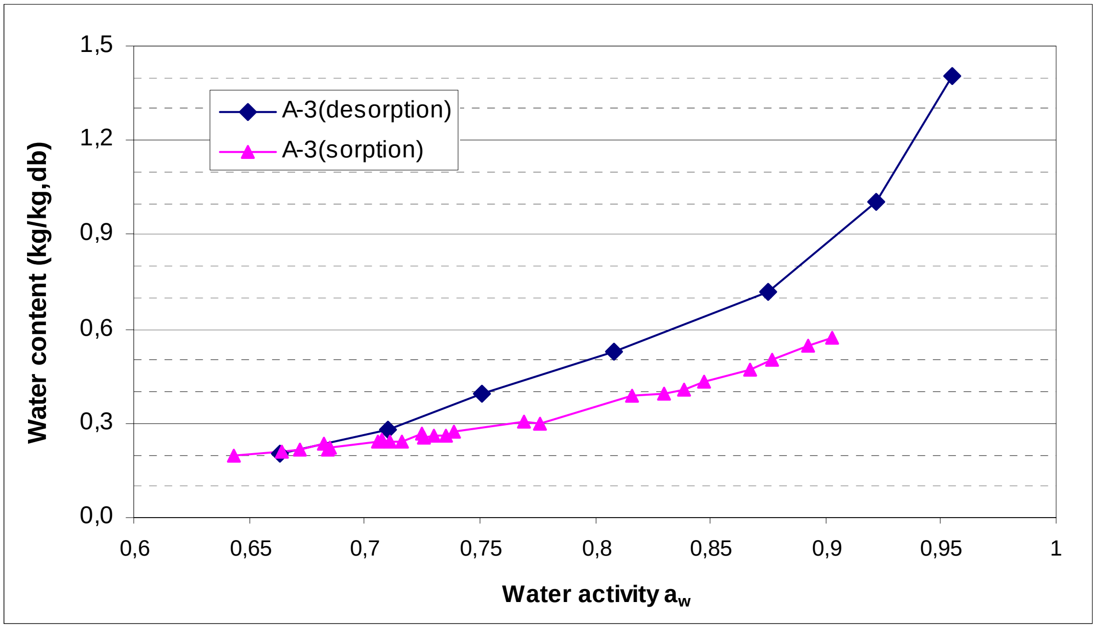

Figure 42: The comparison of the desorption isotherm and sorption isotherm of thawed peeled shrimp dried at 20°C.

A strong hysteresis existed between the desorption isotherm and sorption isotherm of thawed peeled shrimp dried at 20°C(see Figure 42). The difference of water content between the two curves increased greatly with increasing water activity. The maximum value of this difference is over 0.3 at a_w >0.91.

6 CONCLUSIONS

The temperature of the drying air in the heat pump (-2~0°C and 20°C) had a significant effect on the drying of shrimp and fish cake. The results show that the drying time decreased greatly and the degree of shrinkage increased as drying temperature increased from -2~0°C to 20°C. Higher shear force was required to cut the dried shrimp samples when the drying temperature was increased. The bacteria in fish cake grow faster when dried at 20°C than when dried at -2~0°C. The results also present that the temperature has a considerable effect on the colour of dried fish cake, the low drying temperature (-2~0°C) helps preserve the colour of fish cake. Nevertheless, the results indicated that the temperature does not affect the colour values of shrimp samples remarkably and the increase of bacteria was inversely correlated with the raising of temperature in the shrimp samples. Drying at -2~0°C or 20°C has no effect on the sorption isotherms of headed shrimp and whole shrimp and has little influence on peeled shrimp, but remarkably affects the adsorption characteristic of fish cake.

The drying of shrimp and fish cake at -2~0°C or 20°C in the heat pump dryer shows that the drying characteristics could be well described by the Diffusion model. A series of empirical regression equations have been established and they were found to be applicable for the prediction of drying rate of shrimp and fish cake. These models also indicated that increasing the drying temperature from -2~0°C to 20°C significantly enhanced the drying rate and k-values.

It can be concluded from this study that the Oswin model is suitable for predicting the desorption isotherms of shrimp, and the adsorption isotherms of shrimp and fish cake. Drying temperature (-2~0°C or 20°C) has no influence on the constants of *a* and *n* of the headed shrimp and whole shrimp and little influence on peeled shrimp, but affects the adsorption characteristic of fish cake considerably. The hysteresis phenomenon between desorption isotherms and adsorption isotherms of frozen peeled shrimp was observed in the range of $a_w>0.85$ and $a_w = 0.75\text{-}0.88$ when dried at -2~0°C and 20°C, respectively. A strong hysteresis existed in thawed peeled shrimp, nearly from the point of $a_w = 0.65$, and the difference of water content between desorption isotherm and adsorption isotherm increased fast with the increased water activity.

The type of shrimp (peeled, headed and whole) as well as the thickness of fish cake has a noticeable influence on the drying characteristic and the quality of products. Since the frozen headed shrimp dried at 20°C (B-2) has nearly the lowest shrinkage (19.97%), the best colour appearance and best stability of all the shrimp samples as well as requiring the shortest drying time in all the with shell shrimp samples (headed and whole shrimp), it can be said that the frozen headed shrimp dried at 20°C has the best overall performance of all the shrimp samples. The frozen headed shrimp dried at 20°C could be an excellent product. Of the dried fish cake samples, the thin fish cake dried at -2~0°C (D-1) is the best. Using a heat pump to dry shrimp and fish cake is a good alternative method, which can yield high quality products. More drying experiments on seafood using heat pump should be done in the future, in order to provide sufficient data and experiments for this method to be more widely used in seafood drying production.

ACKNOWLEDGEMENTS

I would like to thank my supervisors Sveinn Víkingur Árnason and Sigurjón Arason for their elaborate guidance and help to me. A lot of thanks to Kristín Anna Þórarinsdóttir, Soffía Vala Tryggvadóttir, Ingibjörg R. Þorvaldsdóttir, Heiða Pálmadóttir and Páll Steinþórsson for their enthusiastic assistance. Thanks to the Icelandic Fisheries Laboratories and Gullfiskur Company for offering facilities and assistance.

Special thanks to Dr. Tumi Tomasson, the director of the Fisheries Training Programme of United Nations University and the deputy director Thor Heidar Asgeirsson for valued guidance to my study and much care to my life here. Also thanks to Sigridur Kr. Ingvarsdóttir for her careful care to me. Thanks to all the people of the Marine Research Institute and IFL for their support.

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APPENDIX I:

PARTIAL INSTRUMENTS USED IN THIS PROJECT. (a): Novasina AW-Center; (b): Minolta Chroma Meter; (c): TA-XT2I Texture Analyzer; (d): Absorb container and data logger; (e): Sorvall Centrifuge (RC-5B); (F): Sample glasses and sample glass holder for WHC measurement.

(a) (b)

(c) (d)

(e) (f)

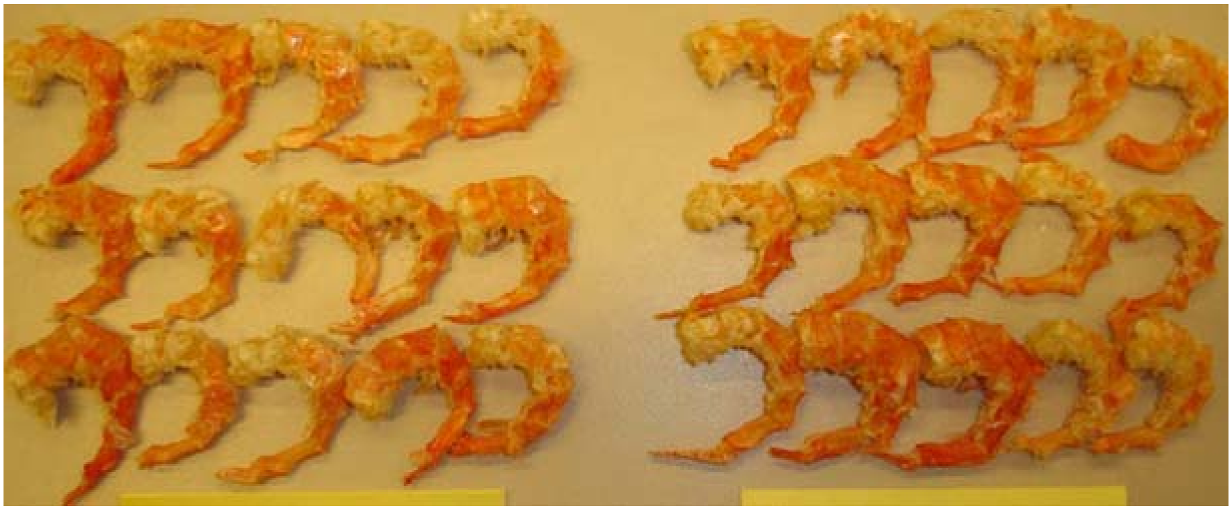
APPENDIX II:

PICTURES OF DRIED SAMPLES. A-1: frozen peeled shrimp, -2~0°C; A-2: frozen peeled shrimp, 20°C; A-3: thawed peeled shrimp, 20°C; B-1d: deshelled B-1(frozen headed shrimp, -2~0°C); B-2d: deshelled B-2(frozen headed shrimp, 20°C); C-1d: deshelled C-1(frozen whole shrimp, -2~0°C); C-2d: deshelled C-2 (frozen whole shrimp, 20°C); D-1: frozen thin fish cake (7~9 mm), -2~0°C; D-2: frozen thin fish cake (7~9 mm), 20°C

A-1 A-2 A-3

B-1 B-2

C-1 C-2



B-1d B-2d

C-1d C-2d

D-1 D-2 E-1 E-2

APPENDIX III:

PICTURES OF REHYDRATED SAMPLES. A-1: frozen peeled shrimp, -2~0°C; A-2: frozen peeled shrimp, 20°C; A-3: thawed peeled shrimp, 20°C; B-1d: deshelled B-1(frozen headed shrimp, -2~0°C); B-2d: deshelled B-2(frozen headed shrimp, 20°C); C-1d: deshelled C-1(frozen whole shrimp, -2~0°C); C-2d: deshelled C-2 (frozen whole shrimp, 20°C).

A-1 A-2 A-3

B-1 d B-2 d

C-1 d C-2 d