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FRYING OF POTATO CRISPS – AN INVESTIGATION AIMING AT REDUCTION OIL CONTENT AND ACRYLAMIDE FORMATION

A thesis submitted for the fulfillment of the requirements of the degree of

Doctor of Philosophy

in Department of Chemical and Materials Engineering

THE UNIVERSITY OF AUCKLAND
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Abstract

Reducing oil content, minimizing any carcinogenic acrylamide in the high temperature frying process for potato crisps, and producing good products with considerable crispiness and acceptable color were the objectives of this research. Vacuum frying with pre-treatment of potato crisps was investigated as an effective process for oil content reduction. Pre-drying and subsequent dipping (PSSD) in a sugar solution ('sugar dipping') were considered as an advantageous procedure for the treatment of potato crisps before frying in order to reduce oil uptake during frying. Vacuum frying was observed as an excellent process to decrease significantly the acrylamide formation at low temperature frying of potato crisps. In this study, potato crisps were respectively blanched, pre-dried, and dipped in a solution of sugar (23.07 wt %) for two seconds, before vacuum frying at 120^{o}C, 110^{o}C under different vacuum pressures (170mbars, 150mbars, 100mbars and 50mbars in separate experiments). Conventional frying at 180^{o}C was also used as the control to benchmark the reductions in the oil contents and acrylamide formation among various techniques. There was a significant reduction in oil content of the potato crisps observed when the new techniques were applied. The crisps that had been pre-treated and fried with conventional frying have given the result of 30 wt % reduction. The crisps that were fried under vacuum frying achieved greater oil reduction with varying percentages when applying different pretreatments. The lowest oil content was achieved when the potato crisps were fried at 110^{o}C and 150 mbars giving 58 % reduction on the dry basis compared with control samples. There are various advantages of the technique with PSSD as we have discovered: it is simple and can be applied in potato crisp industries in continuous mode in both vacuum and conventional frying systems. The crisps that had been treated with pre-drying and subsequent sugar solution dipping and then fried were crunchier and possibly had better perceived taste to the consumer, due to the small sugar addition.

Pre-drying and vacuum frying have all turned out to be excellent techniques to reduce acrylamide formation in potato crisps as we have found in this study. Vacuum frying at 120^{o}C and 150 mbars reduced acrylamide formation by 80 to 85%. The 95% reduction was obtained when the crisps had been pre-dried. Acrylamide was undetectable when crisps were pre-dried and vacuum fried at 110^{o}C, 150 mbars. The crisps with pre-drying subsequent sugar dipping and vacuum fried at low temperature had improved color compared with the control samples, which were produced by conventional frying at high temperatures.

I Thank God and Master Suma Ching Hai, who have blessed me to complete the work …

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Abbreviations

CF	Conventional frying
NPNS	No pre-drying no sugar solution dipping (No pre-treatment)
NS	Not significant
PNSD	Pre-dried but with no sugar dipping
PSSD	Pre-dried and subsequently dipped in sugar solution
SN	Significant
VF	Vacuum frying

LIST OF SYMBOLS

db	Dry basis
k_{oil}	Rate constant for oil uptake kinetics (min^{-1})
k_w	Rate constant for moisture loss kinetics (min^{-1})
X_{oil}	Oil content on dry basis (kg. kg^{-1})
$X_{oil,\ e}$	Final values of the oil content on dry basis (kg. kg^{-1})
t	Time (min)
S	Sum of the squares
X_w	Moisture content on dry basis (kg. kg^{-1})
wb	Wet basis
wt	Weight (on wet basis)
$X_{w,e}$	Final values of water content on dry basis (kg. kg^{-1})
$X_{w,o}$	Initial moisture content before frying on dry basis (kg. kg^{-1})

1. GENERAL INTRODUCTION

Potato chips (thick or thin) are consumed in huge quantities in various countries around the world. In America, potato chips have been a popular salty snacks for over 150 years and its retail sales in the US are about $6 billion per year (Garayo and Moreira, 2002; Clark, 2003). Potato crisps are also one of the most popular consumer snack products throughout the world (Kulkarni, Govinden and Kulkarni, 1994).

However, oil fried potato chips contain up to 39 wt% oil, which acounts for 60% of their calories (Gladwell, 2001). Fat and calorie content of these chips are of serious concern to health conscious consumers (Lefort, Durance and Upadhyay, 2003). In many countries, medical authorities have implicated a high fat diet as being one of the major factors causing increased incidence of cardiovascular disease (Glew, 1988). In particular, during the past 10 years, the American Heart Association and other health organizations have encouraged reduction of fats in foods to less than 30% of calories for most people (USDA, 1990; USDA and USDHHS, 1990).

Reducing the oil content of the potato crisps is becoming an important requirement for manufacturing fried chips. Potato materials are usually fried in the form of crisps (thin circular slices) or French fries (sticks). Due to the difference of the shape related with the surface and the thickness of the samples, the special treatments are applied for each type of fried potato product. In this research, the samples are thin circular potato slices (crisps).

This project was started at the time when the Swedish National Food Administration had just published the data and commented on disturbingly high concentrations of acrylamide, which was considered as a potential carcinogen in the animals study (Tareke et al., 2000) in some foods with high consumption by the population (SNFA, 2002). In particular, potato chips, French fries, roast potatoes, breakfast cereals, and crispy breads. Acrylamide is a compound classified in Group 2A, which means ‘probably carcinogenic to humans’ by the International Agency for Research on Cancer (IARC, 1994). Therefore, the serious problem has raised much concern in the international food organizations. An urgent expert consultation meeting organized by The World Health Organization (WHO) jointly with The Food and Agriculture Organization of the United Nations (FAO) was held in June, 2002. The FAO and The WHO also established an international network on acrylamide in foods on the 18^{th} October 2002 as the central information point for on going work on acrylamide (WHO website, 2002). The research on the acrylamide formation in foods is becoming necessary. The scientists and experts in food science and engineering have been encouraged to investigate methods to reduce the acrylamide concentration in food products. The related issue also attracted the attention of the food specialists in the other countries having high consumption of potato chip products. New Zealand is one of them. “We should do what we can to minimise food-related risk, but not lose sight of an important reason for eating… enjoyment!” (Shaw and Thomson, 2002).

As to the requirement of reducing acrylamide in the potato fried products, the use of vacuum frying at low temperatures is one way to minimize the formation of acrylamide, which is created when potatoes are fried at higher temperature (Tareke et al., 2002, Mottram et al., 2002; Stadler et al., 2002; Gertz and Klostermann, 2002). In our study, the pre-drying and subsequent sugar-solution dipping (PSSD) has been suggested as a pre-treatement technique to reduce the oil content of potato crisps under conventional frying conditions (at $180^{o}C$ and 1atm) among the pretreated and vacuum fried crisps has been the second method. The reduction of oil was particularly focused upon due to the lack of any study on this technique. The qualities of potato crisps affected by the pre-treatment (PSSD) and fried under vacuum and conventional frying were also investigated in this study.

In this work in the main content, the first chapter (**Chapter 2**) presents the effect of pre-treatment technique PSSD on the reduction of the oil contents of potato crisps under conventional frying condition. The next chapter (**Chapter 3**) discusses the effect of this technique on the reduction of oil contents of potato chips fried under vacuum at different low temperatures $110^{0}C$ and $120^{0}C$ under various vacuum pressures of 170 mbars, 150 mbars, 100 mbars and 50 mbars respectively. The following chapters (**Chapter 4** and

Chapter 5) illustrate the colour and crispness of the fried potato crisps as influenced by pre-treatments, vacuum and conventional frying operation at different temperatures and pressures. **Chapter 6** investigates the effect of vacuum frying on acrylamide formation in the fried potato crisps, which are produced using different pretreatment techniques, compared with the control. It is hoped that this work will make a small contribution to the field of human health.

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2. REDUCING OIL CONTENT OF FRIED POTATO CRISPS CONSIDERABLY USING A 'SWEET' PRE-TREATMENT TECHNIQUES

2.1 Introduction

High oil content is a major factor affecting consumer acceptance of oil-fried products today and the low fat food products are becoming more popular (Bunger, Moyano & Rioseco, 2003). Fats (lipids) are implicated in cardiovascular disease due to the fats being a major source of energy supplying about 9 kcal/g, whereas proteins and carbohydrates each supply about 4 kcal/g; eating a high-fat diet is conducive to obesity (Baur, 1995). Saturated fat and trans-fat are the undesirable fats (Allan, 2004). Reducing oil content in potato chips is motivated by the other reasons also; oil is a costly raw material and is an important determinant of the cost of a product. A high oil content often make the chips greasy or oily. On the other hand, it is possible to make chips so low in fat content that they lack flavor and seem harsh in texture (Prosise, 1990).

There have been various techniques applied to minimize the fat content of frying products. The coating techniques were discussed in United Stated Patents (3,424,591 and 4,511,583; 4,917,909, respectively). Numerous coating materials could be used. Gold (1969, patent number of 3,424,591) disclosed the treatment with an aqueous hydrocolloid solution, which is methylcellulose, hydroxypropylcellulose, carboxymethyl ethyl cellulose. The surface of potato pieces were treated with an aqueous solution prior to deep fat frying. However, those thermal gel-coated French fried potato chips contained over 10% by weight water compared to only 4% or less in uncoated chips. This high water content causes thermal gel-coated chips to exhibit a soggy texture which is unacceptable to the consumer (Prosise, 1990). Olson and Zoss (1985, U. S. patent number of 4,511,583) described the process for preparing battered and breaded coated comestibles. The comestibles, e.g., fish and fried food products prepared therefrom which exhibit reduction in cooking fat absorbed during frying. The coating agent is gelatin or certain starches, which created a film to the batter to prevent oil absorption by the finished breading product upon frying. However, potato chip products with starch or gelatin film were not mentioned in this invention. Prosise (1990, U.S. patent number of 4,917,909) disclosed coating the potato slices with polyvinylpyrrolidone, which is a synthetic product considered as a soluble fiber suggested by Morley and Sharma (1986, U.S. patent number of 4,565702) for the purpose of coating an insoluble fiber with a soluble fiber to made a fiber composition. Later, Williams & Mittal (1999) discussed about the use of a gellan gum coating (a polysaccharide) to form edible films to reduce fat absorption in fried foods. As the same result with Gold (1969), the gum coated samples had fat reduction compared with the control but they retained much larger water contents in potato chips.

Besides the coating techniques Nonaka, Hautala, and Weaver (1974) invented a method for reducing the oil content of fried potatoes by immersing in oil-free difluorodichloromethane to remove the excess oil from fried products. Difluorodichloromethane is considered harmful to the ozone layer and, for this reason, is not a readily available chemical product (Prosise, 1990). Lee, Bretch, Bath and Merritt (1988) designed a process for preparing low oil potato crisps. The products transferred to the zone in which the potatoes are protected against oxidation after conventional frying to the moisture of 10 – 20% by blasting with saturated steam, to remove the oil from the partially fried potatoes and then drying in an atmosphere of superheated steam to a moisture content of 1.5 – 3.0%. However, a substantial investment in capital plant and equipment is required to convert a conventional potato crisp manufacturing facility to the Lee process (Prosise, 1990). El-Nokali and Hiler (1992) used 0.5-2 wt % silica as an additive in the frying oil to decrease fat adsorption of potato trips. This method might incur some grittiness of the products. The pre-fry drying techniques reduced fat content of French fries (Krokida, Oreopoulou, Maroulis, Marinos-Kouris, 2001 b.; Gupta , Shivhare

& Bawa, 2000). Soaking in NaCl can also decrease fat content and improve the quality of French-fries (Bunger , Moyano and Rioseco, 2003) though rather a salty taste is expected. Krokida , Oreopoulou , Maroulis and Marinos-Kouris (2001a) used osmotic dehydration as a pre-treatment to produce low-fat French fries where potato strips were immersed into different solutions, which are sugar (40% w/w), NaCl, maltodextrine 12 and maltodextrine 21, for 3 hours before frying.

Although there have been numerous inventions with the purpose of reducing the oil content of potato crisps, the particular method, which is pre-drying and subsequently dipping in the sugar solution and frying has not been investigated so far.

This Chapter investigates the effect of a pretreatment technique, which is pre-drying and sugar dipping (PSSD) on the potato crisps during frying at conventional conditions; atmospheric pressure and 180^{o}C of frying oil temperature. The comparison on the oil content of pre-drying potato slices with sugar dipping, non-sugar dipping, and control samples, which are none pre-drying and non-sugar dipping are performed in this study. The water contents of potato chips during frying with different pretreatment techniques are identified and evaluated. This chapter also discusses the mechanism of oil reduction on potato crisps with pre-drying and sugar solution dipping.

2.2 Materials and methods

2.2.1 Materials

The variety AGRIA potato used in this reseach is of a yellow colour (golden potato). This potato is planted by the growers in New Zealand. Potato tubers with diameter larger than 50mm and weights approximately between 200-300g were obtained from a local supermarket and the potatoes with a the narrow density range of 1.0848 ± 0.0057g.cm^{-3} were selected for testing of oil and water content analysis. Analytical grade solvent n-Hexane (85% purity), ethanol (96% v/v), analytical grade sucrose were purchased from Ajax Finechem, BDH Laboratory Supplies, England and BDH Chemical, Ltd, respectively. White sugar, which was produced by Chelsea (New Zealand) Sugar

Company and Canola oil (the frying oil used in this study) were obtained from the local supermakets.

2.2.2 Methods

2.2.2.1 Potato crisp preparation

Potato tubers were stored in a darkroom at about 10°C and a relative humidity of 60%. Potatoes were taken out of the storage room and they were left at the normal room conditions at least 12 h in order to make sure they reach room temperature. The potatoes were washed, peeled and sliced with the flat ridge cutter (a modified bench cutter from a commercial piece from Goodman Fielder, Auckland, NZ). A 40 mm cylinder with a thickness of 2mm was cut from the centre region of the potato slices. To minimize enzymatic browning, the slices were blanched for 5 min in a thermostatically- controlled stirred water bath at 80°C and then were cooled down to 25°C. A single layer of blanched potato slices was placed on stainless steel trays, which were covered loosely with an aluminum foil, and then dried in a convection oven at a temperature of 60^{o}C to approximately 60% of their initial weight (a flow diagram of the these procedures is shown in **Figure 2.1**.

2.2.2.2 Dipping and frying process

Also refer to **Figure 2.1**, after air drying; the potato slices were left to cool to ambient conditions for 1 hour. Slices were individually dipped in 23.1 wt% sugar solution for 2 s. The sugar solution was prepared with boiling water that had been cooled down to an ambient temperature for 1 hour before it was made into a sugar solution (to prevent microorganism contamination). After dipping, about 100g of slices were submerged in 3L of canola oil in an immersion fryer (Kambrook 6L Deep Fryer, Kmart, Auckland, New Zealand) at 180 °C. To optimize the heat diffusion, a Citence Type KQPS /29 Mixer (Griffen & George Limited, Great Britain) was placed in the fryer and set at 250 rpm. During frying, ten slices were removed every minute for 6 minutes. After frying, samples were wrapped on absorbing tissue paper for 5 minutes prior to testing (Southern, 2000). This was done to minimize the absorption of oil due to the cooling down period, when most of oil content of potatoes is affected by this process (Aguilera and Stanley, 1999). In relation to this issue, Gamble and Rice (1987) also declared that oil uptake was a post-frying phenomenon, where surface oil was absorbed during the cooling of the crisp; with little or no oil absorbed during frying. The frying oil was replaced after each frying section and no longer used after 6 heating hours.

2.2.2.3 Analysis

During the frying process, the samples were taken out and the oil, moisture, sucrose contents, SEM and sensory analysis of the potato chips were measured.

Oil content analysis

The oil content of potato crisps means the quantity of oil in the potato crisps. Oil content was measured by Soxhlet extraction using n-hexane (Gamble & Rice, 1987; Southern, 2000). Potato samples after frying were ground by coffee grinder and 3 g of ground sample was placed in a thimble, which was then placed in the soxhlet extraction apparatus (**Figure 2.2**). The volume of 150 ml n-hexane (85% purity) was added to the soxhlet extraction apparatus, which was placed in the round flask of 250ml and connected with the condenser column where the evaporate hexane was condensed during the extraction process. The condenser column was cooled with cold tap water. The water was turned on when the extraction was started.

Due to the use of the hexane solvent all work was performed in a fume cupboard approved under existing NZ law. The full soxhlet extraction apparatus (composed of the round flask, soxhlet extraction apparatus & thimble, and condenser) was placed in a temperature controlled water bath at 80^{o}C (± 1^{o}C) with the flask semi submerged (**Figure 2.2)**. The extraction time was 3 hours (Southern, 2000). When the extraction process was finished, the cooling water was turned off and the soxhlet extraction apparatus was removed from the condenser. The thimble was removed from the soxhlet and placed in a

Storage at 10^{o}C

Selected

Peeling

Potatoes from food shops

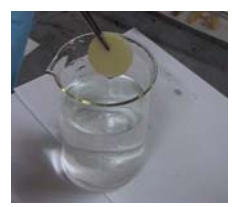
Washing

Slicing

Blanching at 80^o C in 5 minutes

Drying at 60^o C until fresh potato weigh ≈ 60wt % initial weight

Dipping in sugar solution (23.07wt %) for two seconds



Frying at 180^o C

Figure 2.1 Potatoes with pre-treatments and fried under conventional conditions.

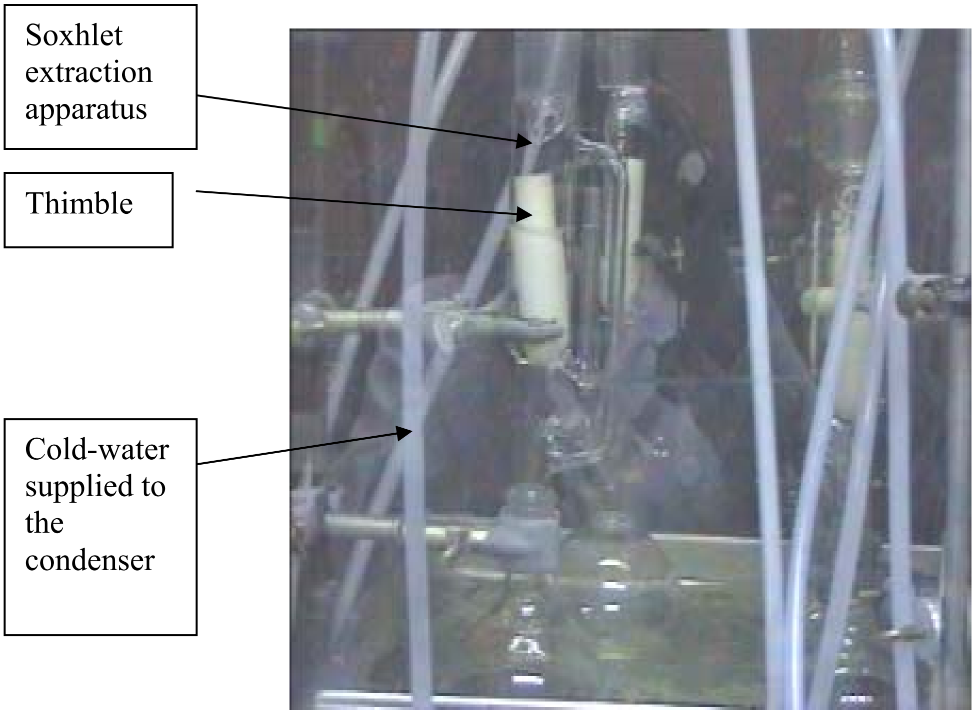


Figure 2.2 Soxhlet extraction system placed in the fume cupboard, as used in the current study.

50ml beaker, which was pre-weighed and labeled. The samples were left in the fume cupboard for 1 hour to allow the n-hexane to evaporate.

The extraction solvent (and oil) was poured out into an evaporating dish (200 ml), which was also pre-weighed & labeled. The sample was then placed in a forced air oven, which was connected with a closed air drain system and the temperature was set at 80^{o}C for hexane to be evaporated. When the hexane was completely evaporated, the evaporating dish (with oil) was removed from the oven and immediately put in a glass desiccator to cool down. The evaporating dish was weighed and any difference from its original weight was taken as the oil weight, which was extracted from the potato samples. The test was performed in duplicate and average values taken. The solid contents in the thimble were poured into a beaker and placed in an oven for drying for 48 hours. After 48 hours, the beaker was removed and placed in a desiccator to cool down and re-weighed. This drying process was repeated until the solid weight reached a constant weight (±0.01). This was considered as the dry weight (solid content) of the fried crisp.

Oil content calculation: The oil content of potato crisps was calculated based on wet weight basis (wet basis) or dry weight basis (dry basis).

$$\text{\% Oil content (on wet basis)} = \frac{\text{Weight of oil in sample}}{\text{Weight of wet sample}} \text{ X } 100 \qquad \textbf{(2.1)}$$

$$\text{\% Oil content (on dry basis)} = \frac{\text{Weight of oil in sample}}{\text{Dry weight of solid content in sample}} \text{ X } 100 \qquad \textbf{(2.2)}$$

Moisture content analysis

The moisture content of the potato is considered as an amount of water existing in the potato.

Moisture content of raw potatoes: The initial moisture content was determined by drying approximately 5 g of raw potato slices to a constant mass over 72 hours at 105^{o}C (AACC, 1986; Garayo & Moreira, 2002). The tests were done in triplicates.

Moisture content of potato crisps: Potato crisps were grounded in a coffee grinder after frying. Moisture content of potato crisps were determined by weight loss after drying 5 g of samples of the ground crisps in a forced air oven at 105^{o}C for 24 hours (AACC, 1986; Garayo & Moreira, 2002). The test was performed in duplicates.

Moisture content calculation: The moisture content of potato crisps was calculated based on wet weight basis (wet basis) or dry weight basis (dry basis).

$$\text{\% Moisture content (on wet basis)} = \frac{\text{Weight of water in sample}}{\text{Weight of wet sample}} \text{ X } 100 \qquad \textbf{(2.3)}$$

$$\text{Weight of water in sample} = \text{Weight of wet sample} - \text{Weight of dry sample} \qquad \textbf{(2.4)}$$

$$\text{\% Moisture content (on dry basis)} = \frac{\text{Weight of water in sample}}{\text{Weight of dry sample}} \text{ X } 100 \qquad \textbf{(2.5)}$$

In this study, the simple of “wt %” was used to indicate the percentage of oil (or moisture) content of potato crisps on wet basis.

Sugar content analysis

Sucrose in potato slices during frying process was analyzed by HPLC using the methodologies previously described by the authors (Montreuil et al., 1996 and Zhou, 2004). A Shimadzu HPLC system equipped with two pumps, a UV refractive index (RI) detector (Shimadzu, RID-10A) and an automatic sample injector (20µm). Using carbohydrate chromatography column is a calcium-based cation-exchange column (Alltech, Deerfield, IL). The temperature of the column was maintained at 90 ± 0.1^{o}C by a temperature controller. The operating pressure of the carbohydrate column was under 1500 psi. Milli-Q water was degassed, filtered with a 0.2µm filter and was the mobile phase (0.4 ml/min) for the HPLC.

Sample preparation: Solid potato after oil extraction and dehydrated at 80^{o}C as described in **Section 2.2.2.3** was used to extract the sugar content of fried potato slices. The recorded weight of 2 g potato solid was added in the thimble; 40ml of ethanol (96%) was diluted with Milli-Q water to have the volume of ethanol (80%); which was used as the solvent to extract the sugar in fried potato slices. Soxhlet extraction system as described in **Section 2.2.2.3** was also used for sugar extraction in this study. After extraction, the sample with ethanol solvent was placed in the same forced air oven as described in **Section 2.2.2.3** for ethanol evaporated at 40^{o}C; or placed in the vacuum oven at room temperature and the pressure of 10mbars. After that, the solution of sample was diluted with Milli-Q water to the measure volume (10ml) and then the filtered sample was injected to the HPLC.

Shrinkage analysis

The shrinkage of potato crisps was calculated as below:

$$S_v = \frac{Vo - V(t)}{Vo} \times 100 \qquad \textbf{(2.6)}$$

Where V_0 is the original volume of the sample (m^3) and $V(t)$ is the sample volume (m^3) at frying time t. The volume of the samples of an elliptical shape was calculated as $V = (\pi Dd/4)L$ where D, d, L are the larger, smaller diameter and thickness (m) of the sample respectively (Garayo and Moreira, 2002). Measurements were performed in duplicates for each condition.

Scanning Electron Microscopy

Preparation for Cryo SEM was carried out as follows. Small pieces of pre-dried potato slices both before and after dipping into sugar solution were cut and attached to the Cryo SEM sample holder with agar gel. Care was taken not to compress the samples. The samples were cooled to -196^{o}C; evacuated and encapsulated at this temperature. Then, they were inserted into the Cryo preparation instrument at less than -140^{o}C and fractured at this temperature. The instrument temperature was raised to -95^{o}C and the samples were etched for 2 hours. The samples were coated with gold at -120^{o}C for 240 seconds. After that, the samples were inserted into SEM instrument (Philips SEM, model of XL30S Field Emission Gun, Netherland) at less than -140^{o}C for examination. The electron micrographs were taken at the voltage of 5.00 kV, spot size of 4.0 with detector style of secondary electron detector (SE). The magnification, working distance and scale bar were indicated on the electron micrographs when taken.

2.3 Results and discussion

2.3.1 Oil uptake

There was a significant difference ($P<0.05$) between the final oil contents of pre-dried and sugar dipped and the control samples (**Table 2.1** and **Figure 2.3**). The oil content was dependent on the frying time. The pre-dried and dipped samples had lower oil contents compared with the untreated samples (the control) and pre-dried samples. On average, 0.05 g of sugar was added to each potato slice after dipping. To calculate the amount of sugar attached into each potato slice, the weights of potato slice before and after dipping were determined. The difference in weight of the potato slice before and after dipping was the weight of sugar solution added into each slice. With the concentration of sugar solution being 23.07 wt %, the amount of sugar added in each slice of potato was calculated. On average, after dipping the percentage of sugar increasing is about 3% on wet basis with pre-dried potatoes; compare with fresh potatoes without pre-drying the increase is only about 2% on wet basis. The sugar addition may induce a higher specific gravity or high solids thus leaving less space for oil uptake (Lulai, 1986 and Smith, 1987). In order to establish whether the sugar-dipping affects much of the oil content, separate experiments which are pre-dried non-dipping and pre-dried with sugar dipping were carried out on the crisps. The results show that there was a significant reduction of oil content of pre-dried and dipping compared with pre-dried and non-dipping (as well as with the control samples). There was 30% oil reduction obtained in this research study. This is a considerable reduction compared with previous techniques. For example, the NaCl soaking method only had 22.2% reduction in oil content. This indicates the effect of sugar solution on the pre-treated samples is not a simple additive effect on to the solids density which effects the oil uptake.

Table 2.1 The oil content (wt %) of the fried potato crisps with different pre-treatment techniques.

Frying time (min)	Control samples		Pre-drying and non-sugar solution dipping		Pre-drying and sugar dipping (23.07 wt%)	
	Oil content	Stdev	Oil content	Stdev	Oil content	Stdev
0	0.00	0.000	0.00	0.000	0.00	0.000
1	9.92	0.031	15.81	1.131	15.16	0.722
2	24.31	1.121	31.09	0.132	27.02	0.553
3	32.12	1.627	35.10	0.573	25.00	3.147
4	39.39	0.529	38.33	1.837	24.04	0.781
5	40.72	0.207	41.38	2.092	28.93	0.706

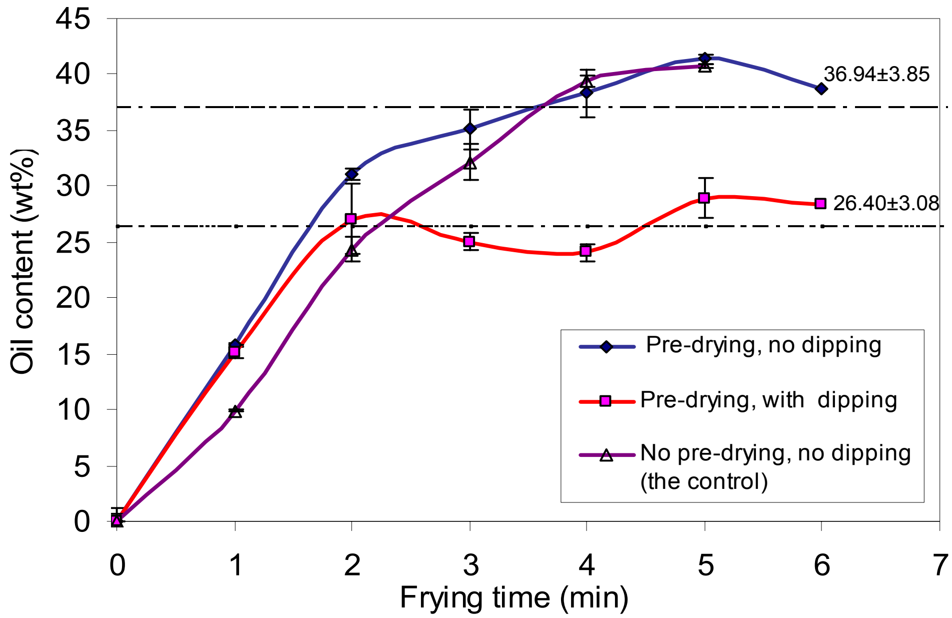


Figure 2.3 Effect of pre-drying followed by sugar dipping on the oil content of potato crisps during the frying process.

2.3.2 Sugar content in potato crisps- the mechanism of oil reduction with pre-drying and sugar solution dipping technique

HPLC was the chosen method for analyzing the sucrose content in fried potato slices in this study. The retention time of sucrose was detected at 9.5 minutes with a flow rate of 0.4ml/min of mobile phase. **Figure 2.4** shows the standard curve of peak area vs sucrose concentration (mg/ml). **Table 2.2** presents the sucrose contents of pre-drying potato slices with sugar dipping and non-sugar dipping. The results indicate that the sugar content concentration of pre-drying potato slices with sugar dipping was much increased compared with non-sugar dipped pre-dried potato slices. As shown in **Table 2.2** the first concentration of sugar of potato slice with sugar dipping was 44.69 mg/g solid. This amount is quite close to the amount of sugar determined by calculated (50mg/ per slice).

On average, 0.05 g of sugar was added to each potato slice after dipping. To calculate the amount of sugar absorbed into each potato slice, the weights of potato slice before and

Table 2.2 The sucrose contents of the pre-dried potato crisps with sugar solution dipping and non-sugar solution dipping frying at conventional conditions (180^{o}C).

Frying time (min)	Sucrose contents of pre-dried & non-sugar dipped potato crisps (mg/g solid)	Sucrose contents of pre-dried & sugar dipped potato crisps (mg/g solid)
0	0.96	44.69
1	0.18	ND
2	0.04	0.76
3	0.34	0.49
4	0.04	0.49
5	0.10	0.36

ND : not determined

after dipping were determined. The difference in weight of the potato slice before and after dipping was the weight of sugar solution absorbed into each slice. With the concentration of sugar solution being 23.07 wt % the amount of sugar absorbed in each slice of potato was calculated. On average, after dipping the percentage of sugar increase is about 3 % on wet basis of the pre-dried potatoes.

The phenomena of oil reduction with pre-drying and sugar solution dipping of potato crisp samples based on the phenomena of increased solid content of potato slices. Lulai (1986) and Smith (1987) found that the solid content of fresh potato affected the oil

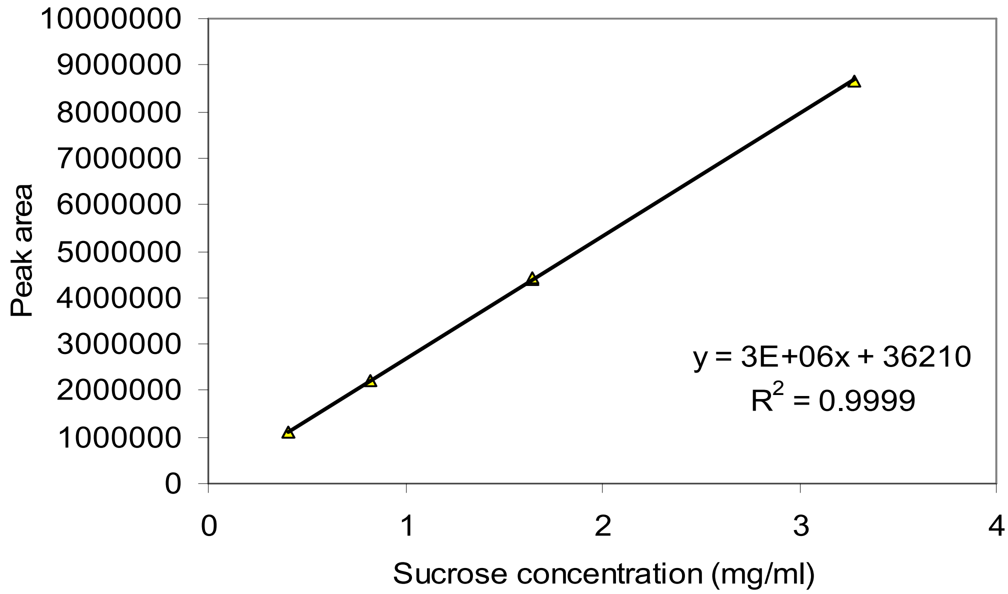


Figure 2.4 The standard curve of peak area versus sucrose concentration (mg/ml).

content of the fried potato chips. The pre-dried and sugar solution dipped potato crisps had a higher solid content than other original potato crisps. The lower solid contents of fresh potato crisps allowed for greater oil absorption during frying. When pre-dried potato slices were dipped into the sugar solution, they would have been rehydrated by the sugar solution.

Figures 2.5, 2.6 and **2.7** show the scanning electron micrographs of the surface of pre-dried potato slices before and after the dipping process. The micrographs appear to suggest that the surface of potato slices after dipping in sugar solution had a more 'wet looking' surface. This might indicate the high concentration of sugar solution present around the cells of potato crisp. During the frying process, the water in potato cells evaporates leaving behind the sugar, which occupies the spaces in between potato cells or seals parts of the cell walls so the oil uptake becomes less. As a result, the oil content of treated samples was lower compared with the untreated samples.

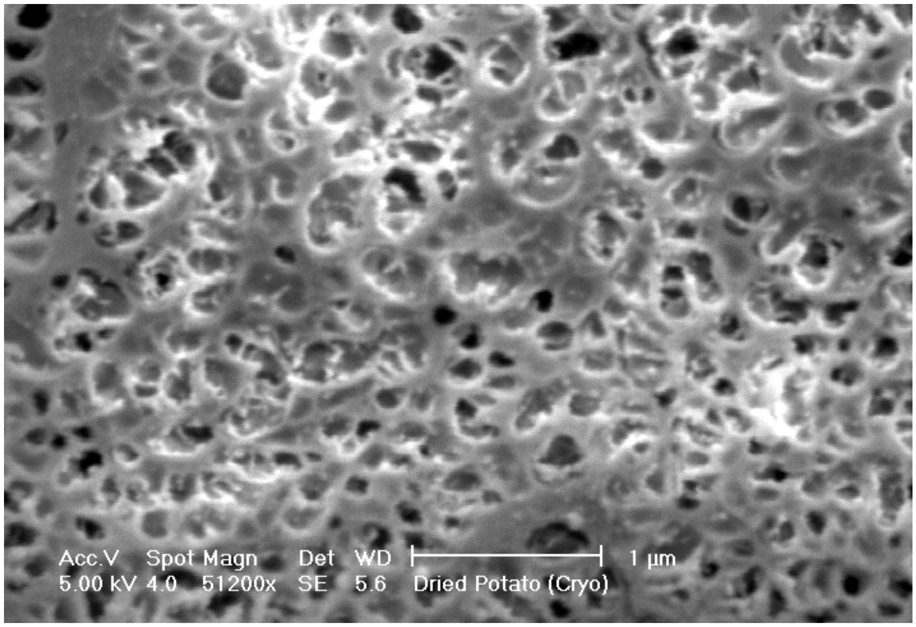


Figure 2.5 Fresh potato after pre-drying (to 60% of the initial weight) and no sugar solution dipping (Cryo SEM photo of the potato surface).

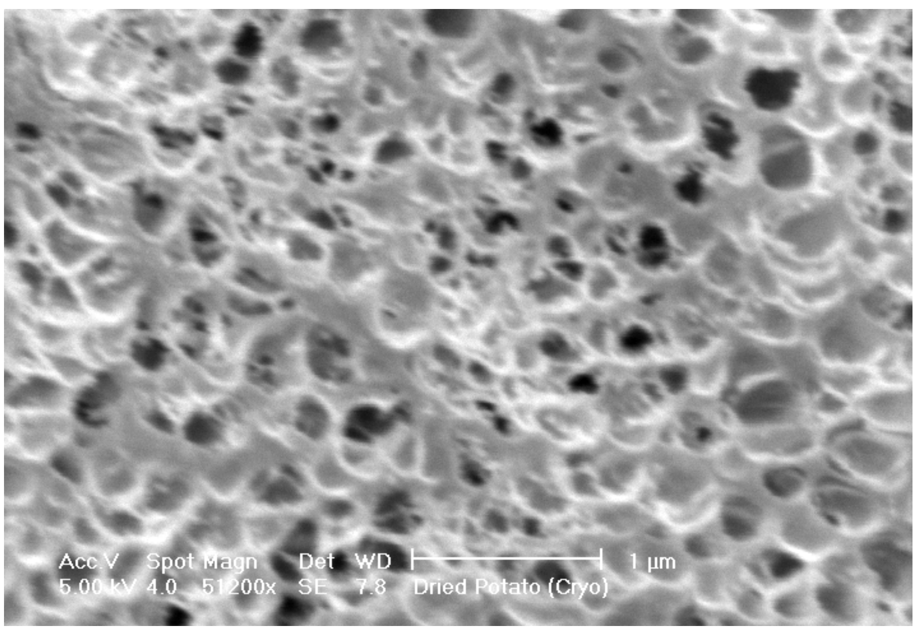


Figure 2.6 Fresh potato after pre-drying (to 60% of the initial weight) and after sugar solution dipping (Cryo SEM photo of the potato surface).

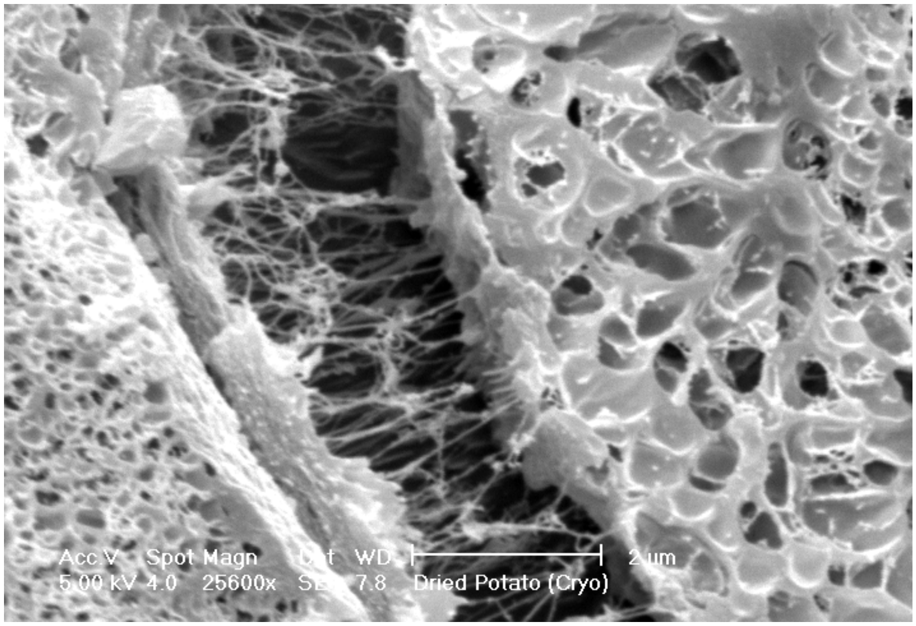


Figure 2.7 Fresh potato after drying (to 60% of the initial weigh) and after sugar solution dipping (Cryo SEM photo of the potato surface, scale= 2µm).

2.3.3 Moisture loss during frying

Moisture content is an important parameter of the quality control of fried potato crisps. The good quality of the potato crisps usually requires the moisture content to be lower 1.5 ± 0.1 wt % (Gould, 1985). The mechanism of water loss during potato frying has been studied by Costa, Oliveira and Gekas (1996). These authors have concluded that the water loss during frying of thin potato slices may be divided into three different stages. The first stage corresponds to the heating of the potato, involving mainly the loss of water at the cut surfaces. This period takes 6-12 seconds at 180^{o}C, being dependent on the potato thickness tested (e.g. 0.5- 8.5 mm). During the second stage, there is an intense formation of water bubbles (boiling) and an exponential decrease of water content with time is evident. The third stage occurs after the formation of the crust. Because this crust greatly hinders the movement of the vapor bubbles, the build up of internal vapour pressure occurs. The gas phase at high pressure may cause bursting of the crust, which may cause small crackles.

In this study, the initial moisture content of potato after blanching was 85 wt %, after pre-drying the moisture content loss 40%. Therefore, the amount of water content residual in potato flesh is on average 45 on the total of 60 or 75% water content in the potato after pre-drying. In the **Figure 2.8 and Table 2.3**, the data of the moisture content of potato after drying is 74 ± 0.2 %, after sugar dipping the moisture content of the sample was a little higher, which is in average of 75.5 ± 0.21% at t = 0 **(Figure 2.8).** Pre-dried samples had lower contents than the original due to the pre-drying step. The moisture loss of the sugar dipped slices decrease more quickly than that of non-sugar dipping slices during the frying process. However, the percentage of the final moisture content of the two treatments were similar (2.7 ± 0.2) for the pre-dried and dipped; 2 ± 0.3 (for pre-dried and non-dipped) at 3 minutes and they were reached to 1.8 to 1.5 % when the frying time were 4 to 6 minutes. This amount of moisture content is not different compare with the control samples, which had the percentage of the moisture content of 2.2 ± 0.1 (at 5 minutes tine frying) on wet basis. The results of moisture content of pre-treatment samples are different from those observed for the coating methods.

Table 2.3 Water content (wt%) of the potato crisps under conventional frying at 180^{o}C.

Frying time (min)	Control samples		Pre-drying and non-sugar solution dipping		Pre-drying and sugar dipping (23.07 wt%)	
	Water content (wt%)	Stdev	Water content (wt%)	Stdev	Water content (wt%)	Stdev
0	85.13	1.118	74.01	0.233	75.50	0.214
1	60.28	8.820	38.55	0.677	23.95	2.136
2	33.66	0.412	17.96	1.181	10.37	0.028
3	27.55	2.507	4.27	2.397	2.42	0.600
4	4.29	0.249	1.15	0.253	1.84	0.035
5	2.55	0.058	1.05	0.084	1.61	0.085

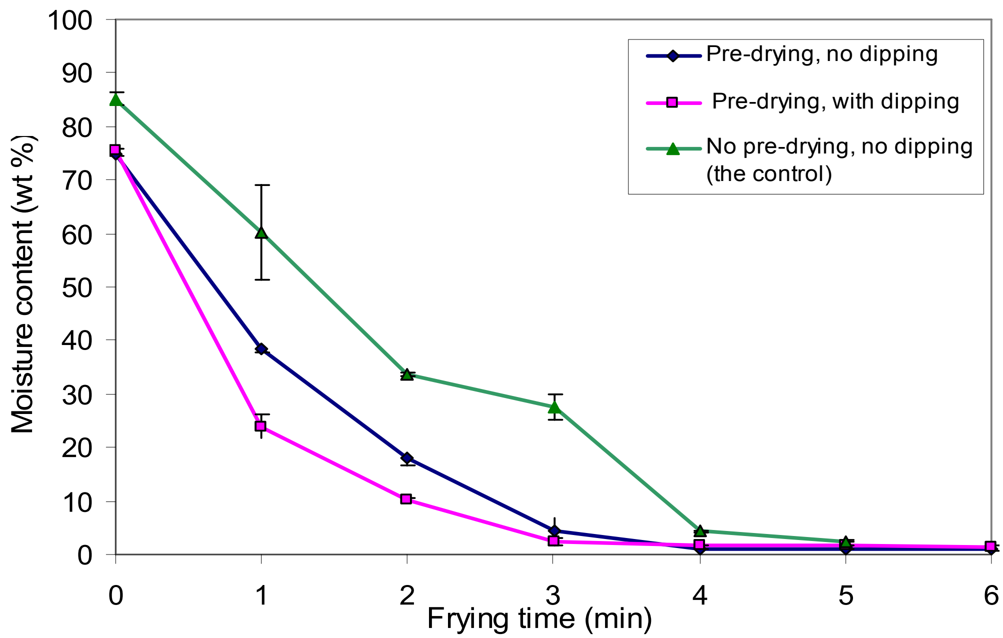


Figure 2.8 Effect of pre-drying followed by sugar solution dipping and frying time on the moisture content of the fried potato crisps.

For example, with PVP coating (Prosise, 1990) the moisture content of sliced potato chips was 4% by wt; with film-forming hydrocolloids the moisture content of French fried potato chips were 10% (Gold, 1969); with dietary fiber coating the moisture content of the final products should not be less than 6% by weight (Morley and Sharma, 1986). Similarly, gellan gum coated samples (by dipping in the gum solution for 10 s and air dried, Williams and Mittal, 1999). The gum coated samples had fat reduction compared with the control but they retained much larger water contents (Williams and Mittal, 1999)

2.3.4 The relationship of oil uptake and moisture loss

The moisture content of raw potato slices varies between 75% to 85% (Farkas, Singh and McCarthy, 2000), depending on the environmental growing conditions and varieties. When potato slices are fried in oil at a high temperature, the moisture would boil explosively. This may result in cell wall bursting and damages, and consequently, the formation of capillary holes and voids. Oil adheres to the surfaces of the chips and is also absorbed into the pores or the voids in the porous slices. This is particularly pronounced if the chips which just leave the frying oil are exposed to the atmosphere, and cooled creating a vacuum within. For these reasons, regular potato chips can have high oil contents, ranging from 35% to 39%, and even as high as 42% (Lee et al., 1988). This mass transfer process has been characterized by the movement of oil into the product and water, in the form of vapor, from the product (Farkas et al., 2000).

The relationship of oil uptake and moisture loss of the thin crisps during immersion frying has been studied previously by Southern, Chen, Farid, Howard and Eyres (2000). A linear moisture-oil relationship reported for crisps (Gamble, Rice and Selman, 1987) has been obtained in this study (see **Figure 2.9**). The data has also demonstrated that the initial moisture content (85.5 ± 1 wt % on wet basis) and the final content of control samples (37 ± 4 wt %) are in the range shown by Lee et al (1988).

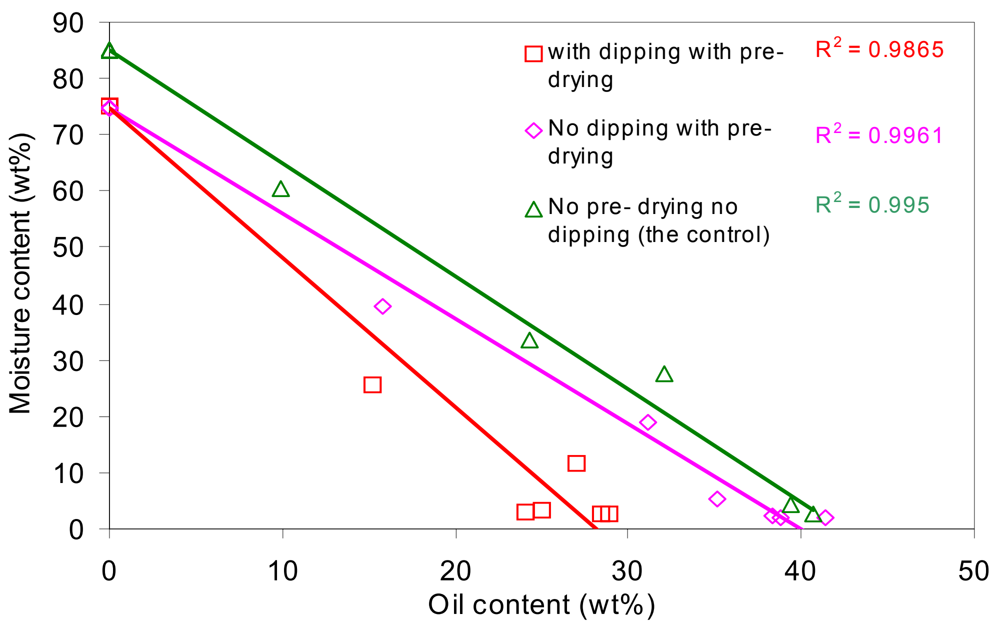


Figure 2.9 Effect of the pre-treatment on the relationship of the oil uptake and the moisture loss of the same sample.

The pre-dried and then sugar-dipped crisps had much lower oil content than the control samples. It was found that the pre-drying and sugar dipping were the crucial steps in reducing the oil content. Each of the two processes alone cannot yield such a good result. That means the oil reduction did not happened when dipping without pre-drying (data not show) or pre-drying without dipping.

2.3.5 Effect of pre-treatment on shrinkage

Figure 2.10 presents the effect of different techniques on the degree of volume shrinkage of the potato crisps under conventional frying of 180^{o} C as a function of frying time. Volume shrinkages during the early stages of frying very were largely due to the net loss of water. However, in the final stages of frying the volume shrinkage became smaller (Johnson, 1999). The degree of shrinkage is related to the water loss and oil uptake of potato crisps. The potato crisps with pre-dried and dipping underwent shrinkage more considerably than that of the pre-dried non-dipping (and that of the control) during the frying process due to the less oil uptake and more water loss in these samples in comparison with the other samples (**Figures 2.3** and **2.8**). The extent of shrinkage was much more pronounced in the early stage of frying (the first 60s). The degree of shrinkage had gone over a maximum then dropped back. The shrinkage was then settled at a moderate level, when the moisture content and oil content of potato crisps reached the 'final' level (**Figures 2.3** and **2.8**).

2.3.6 Sensory analysis

A un-trained panel sensory analysis was carried within a group of 15 persons. The tests of the samples with treatment and without treatment were evaluated. There was a clear agreement that the potato crisps with pre-dried and sugar dipping had increased the sweetness compare with the untreated samples.

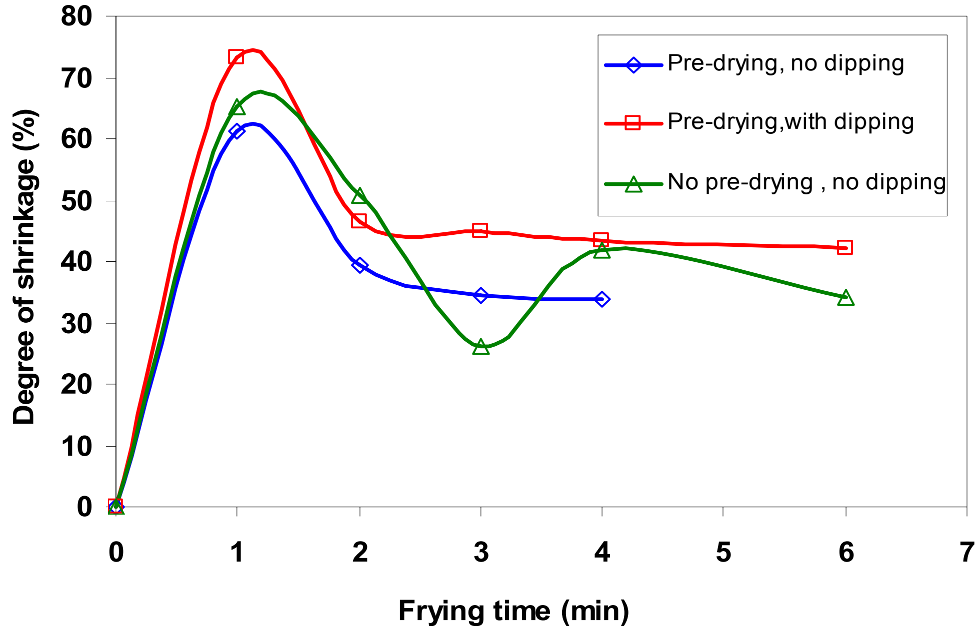


Figure 2.10 Effect of pre-drying followed by sugar dipping on shrinkage in potato crisps during frying.

2.4 Conclusions

Pre-drying followed by dipping potato crisps in a sugar solution can reduce the oil content of the fried crisps with an increased sweetness. This procedure has been shown to be capable of significantly reducing the oil uptake (fat content) in the crisps during frying. There was a significant 30% oil reduction compared with the control samples. The moisture contents were not different compared with the control. The crisps that had gone through the pretreatment procedure had some changes in color and seemed to shrink more.

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3. REDUCING OIL CONTENT OF FRIED POTATO CRISPS USING SOME PRE-TREATMENTS FOLLOWED BY VACUUM FRYING

3.1 Introduction

Vacuum frying is an advantageous technique, which not only preserves the natural color of the original material and maintains the hardness of the product, but also reduces the final oil contents of potato crisps (Garayo and Moreira, 2002). Kato and Sato (1991) showed that a good flavored and crispy tempe (a traditional Indonesia food) can be obtained using vacuum frying technique and the peroxide value (POV) of these vacuum fried tempes were stable for 60 days of storage at 40^{o}C. The stability of oil during the vacuum frying process was maintained. Fatty acid and composition of oils and fats were not changed by recycling frying oil for 26 to 30 times during vacuum frying (Hidaka, Fuduka and Sakamoto, 1991). The storage stability and the quality of the carrot chip products after vacuum frying was better compared with the other commercial products (Shyu and Hwang, 1999). Garayo and Moreira (2002) studied vacuum frying of potato chips.

In this study, the effects of vacuum frying and pretreatment techniques (pre-drying non-sugar dipping (PNSD) and pre-drying & subsequently sugar dipping (PSSD) Tran and Chen (2004); Tran, Chen and Southern (2006) on the reduction of oil contents, water loss and the shrinkage of the potato crisps were investigated. The kinetics of oil uptake and moisture loss of the treated potato crisps have also been established in this study.

3.2 Materials and methods

3.2.1 Materials

As described in **Section 2.2.1,** variety AGRIA potato with the same selected process, n-Hexane (85% purity), white sugar and canola oil were used in this research study.

3.2.2. Methods

3.2.2.1 Potato crisp preparation (before frying)

Before frying, potato slices were also prepared as described in **Chapter 2, Section 2.2.2.1** and as early part of **Section 2.2.2.2**. However, after dipping, about 20-30g of the slices were fried under the vacuum or the conventional protocol, which will be described in the following **Section 3.2.2.3** and **3.2.2.4** respectively. The potato frying process is illustrated in **Figure 3.1**

3.2.2.2 Vacuum frying setup

A stainless steel pressure-vessel with an inner diameter of 400 mm, a height of 540 mm and a wall thickness of 6 mm was modified to serve as the vacuum chamber. An electrical deep fryer (Kambrook, 6L Deep Fryer) with an inserted stirrer was placed in the vacuum chamber. The stirrer was driven by a motor. A stainless steel mesh basket of the deep fryer could be held or moved back & forth with a rod. The rod could be fixed in a certain position during the frying time so that the basket could be immersed in the Canola frying oil inside the deep fryer. The stirrer was set up at a speed of 250 rpm during the frying process. A rotary vacuum pump (model S150, No 070133 F, Shimadzu Seisakusho Ltd., Kyoto, Japan) that can generate a vacuum down to 1.333 kPa (13.33 mbars) was used to produce and maintain the low pressure in the vessel. An electricity system was created for the vacuum frying chamber. A heater controller was used to control the temperatures of oil during frying process. A Picolog software was installed to record the temperatures of frying oil, center and surface potato chip during frying.

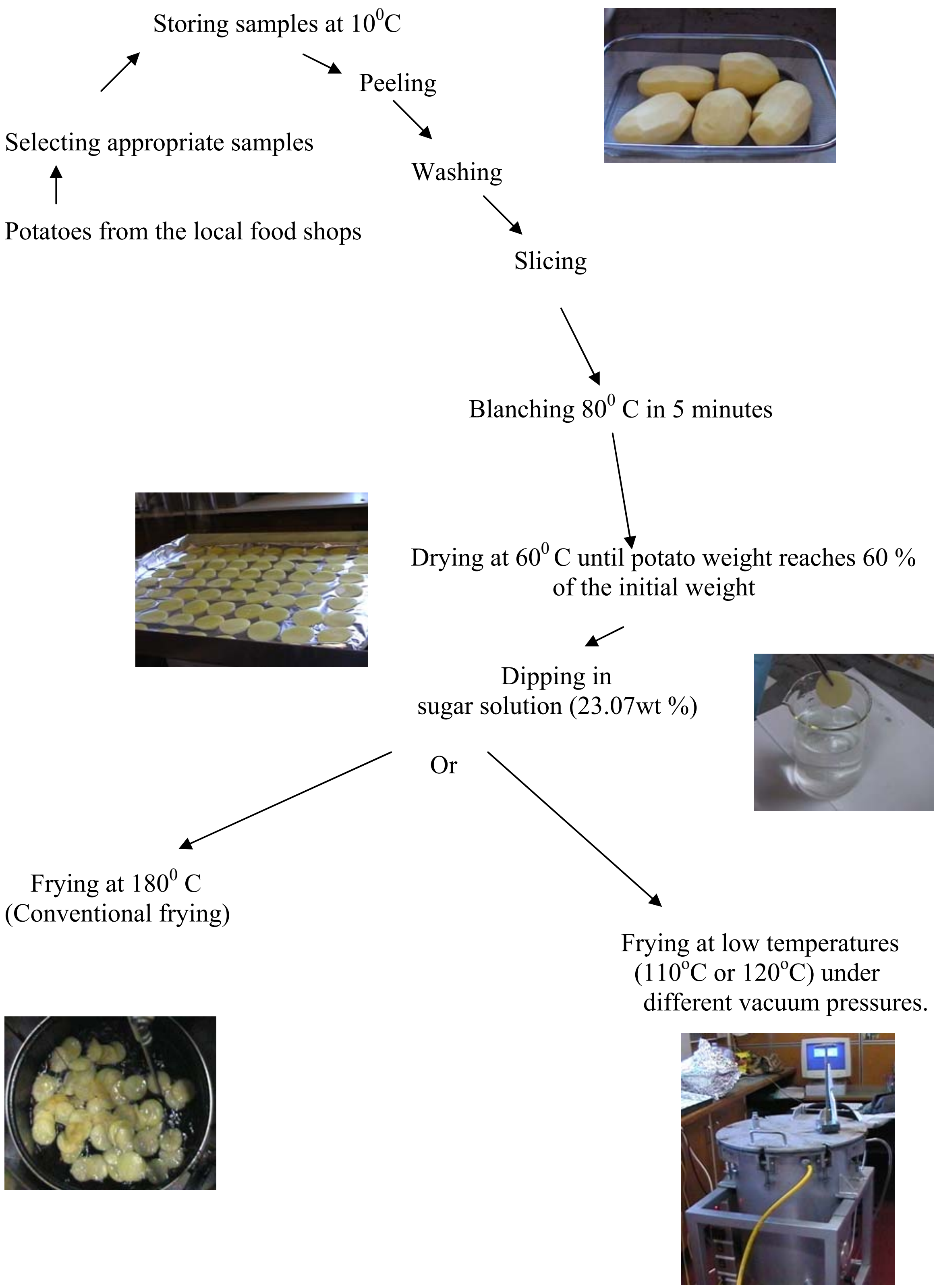

Figure 3.1 Potato crisps after the pre-treatment and the frying processes.

The pressure gauge and the vacuum pressure transducer system (Thyracom comp.) were set up to measure the pressures of vacuum chamber. All software measurements were installed in the PC, which was connected with the vacuum frying chamber. An ice-trap was used to capture the oil droplets that came with the water vapor, to avoid possible damage to the vacuum pump. The vacuum frying system is illustrated in **Figure 3.2** and **Figure 3.3.**

3.2.2.3 Experimental conditions for the vacuum frying process

Four levels of vacuum pressures (170, 150, 100 and 50mbars, respectively) and two oil temperatures (110^0C and 120^0C) were considered in this study. The oil volume in the deep fryer was 2.5 L. When the oil bath reached at the required temperature, the potato slices (20-30 g) were placed in the steel mesh basket. The lid of the vacuum chamber was closed and the nuts were tightened. The vacuum pump was started. After reaching the required pressure, the basket was pushed down into the oil bath. A stopwatch was used to determine the frying time. During the frying process, the pressure of the chamber was adjusted by closed valve of the vacuum chamber in order to achieve the required pressure. When each frying process was completed, the basket was lifted up, and the pressure of the vacuum was released back to the atmospheric condition. The lid was then opened and the basket was taken out of the vacuum chamber. The potato crisps were immediately poured out and wrapped with the kitchen tissues. They were later placed in the plastic bags, and stored in the desiccators under slight vacuum for further analyses.

3.2.2.4 Conventional deep frying experiments

For the conventional frying experiments, the same electrical deep fryer and stirrer were used where the lid of vacuum chamber was left open during the experiment. The frying temperature was 180^oC. About 20-30 g of potato slices were fried in each oil bath containing 2.5 L of Canola oil.

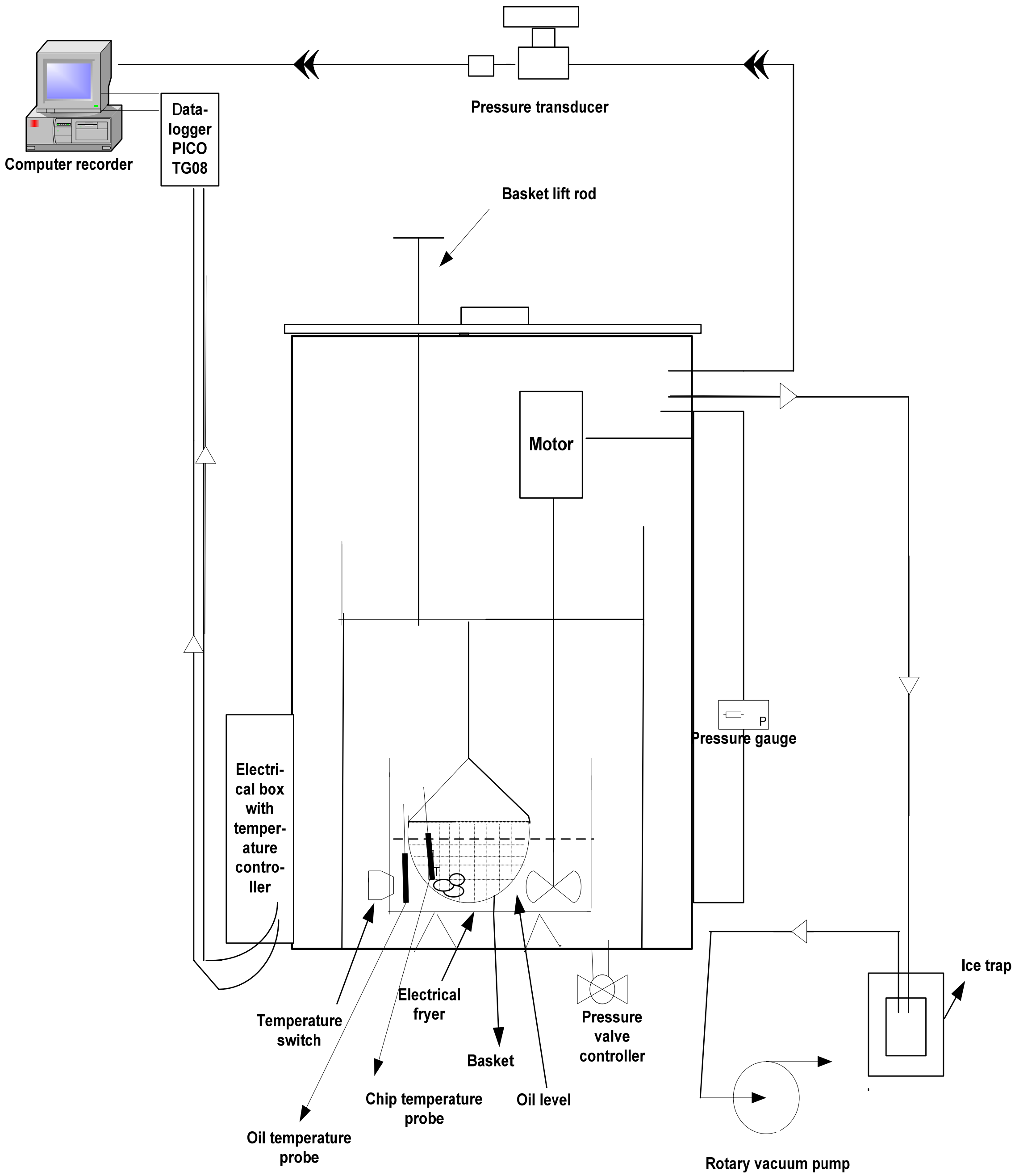

Figure 3.2 Schematic illustration of the vacuum frying system used in this study.

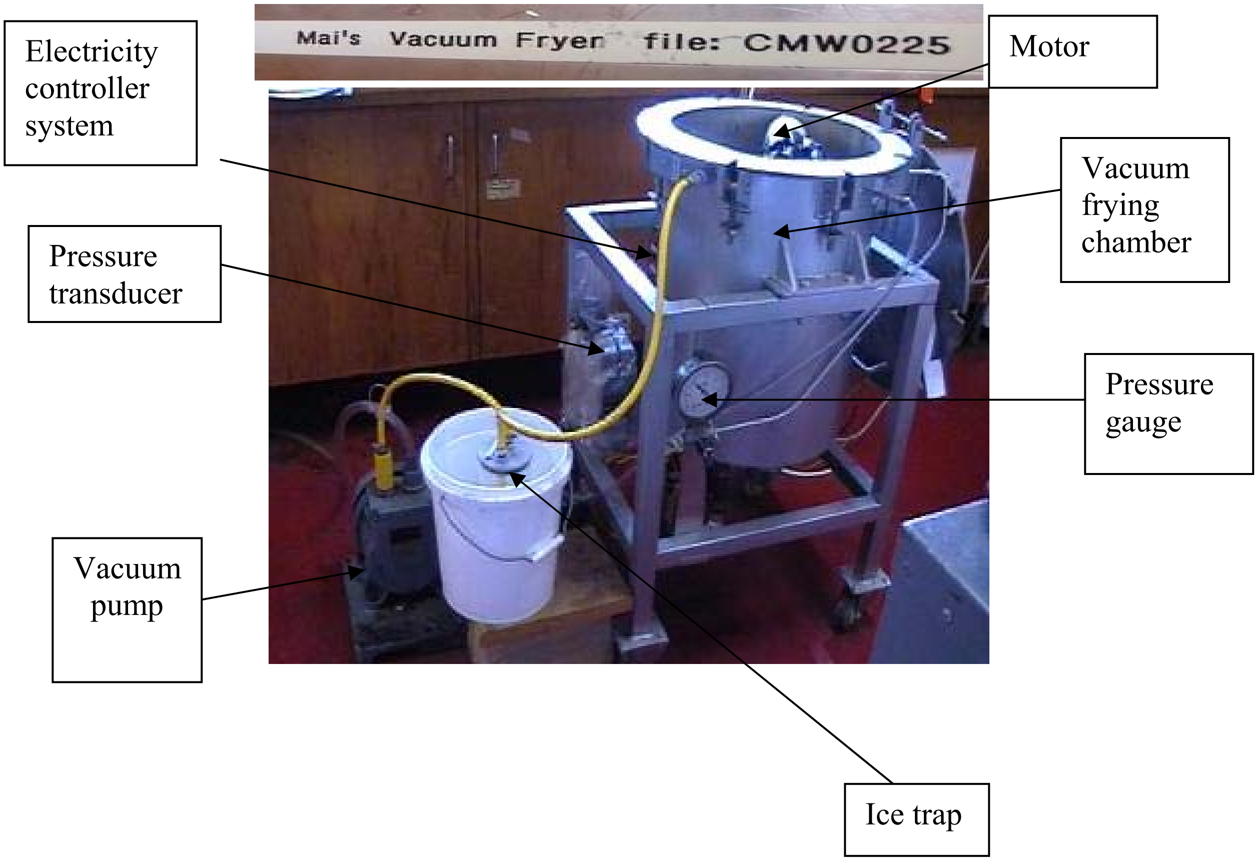

Figure 3.3 Vacuum frying chamber and their components

3.2.2.5 Analysis

Oil, moisture contents and the shrinkage of the potato slices (crisps) were similar measured as described **in Section 2.2.2.2** of **Chapter 2.**

3.2.2.6 Statistical analysis

The data were analyzed using regression analysis and two-way ANOVA analysis for the oil content with significant $P<0.05$ using the MINITAB statistical software for Windows®95 NT™ (Release 12, Language Systems Corp., 1999).

3.2.3 Kinetics of oil uptake and moisture loss

A first order kinetics model has been reported by Krokida et al. (2001a) to predict the moisture content and oil content of French fries. Recently, Moyano and Pedreschi (2006) suggested a model describing the kinetics of oil uptake during the frying of potato slices. Under conventional and vacuum frying conditions, the oil uptake and the moisture loss during the frying of potato crisps was described with the first order kinetics model in this study. The simple mass transfer mathematical models have been summarized in frying kinetics equations presenting in following **Sections 3.2.3.1** and **3.2.3.2**.

3.2.3.1 Oil uptake kinetics

The first order kinetics model has been suggested for oil up take during frying process:

$$X_{oil} = X_{oil,\,e}\,[1 - \exp(-k_{oil}\,t)] \qquad \textbf{(3.1)}$$

Where, X_{oil} is the oil content of potato chips (kg/kg db (dry basis)) at time t, t is frying time (min), $X_{oil,e}$ is equilibrium values of oil content (kg/kg db) and k_{oil} is the rate constant for oil content kinetics (min^{-1}).

3.2.3.2 Moisture loss kinetics

The first order model has been suggested for moisture loss during frying process:

$$(X_w - X_{w,e}) / (X_{w,o} - X_{w,e}) = \exp(-k_w t) \qquad \textbf{(3.2)}$$

Where, X_w is the *moisture* content of potato chips at time t (kg/kg db), t is frying time (min), $X_{w,o}$ is the initial moisture content before frying (kg/kg db). $X_{w,e}$ is the equilibrium values of moisture content of potato chips (kg/kg db) and k_w is the rate constant for moisture content kinetics (min^{-1}). The results of kinetics models are summarized in **Table 3.7** and presented in **Figures 3.10** (**a** and **b**) and **Figure 3.14**(**a** and **b**). These results will be described further in the result sections.

3.3 Results and discussion

3.3.1 Oil uptake of Potato crisps

3.3.1.1 Effect of pretreatment techniques (PSSD) on the oil reduction of the fried potato chips under vacuum frying

Table 3.1 and Figure 3.4 show the oil content as a function of time for the fried potato slices prepared at various conditions: (i) pre-dried & no sugar dipping (PNSD), and fried conventionally at 180^{o}C; (ii) pre-dried & no sugar dipping, and vacuum frying at 120^{o}C and 170mbars; (iii) pre-dried, with sugar dipping (PSSD), and vacuum frying at 120^{o}C and 170mbars. There was a significant reduction ($P<0.05$) of the oil content of the potato crisps (approximately 25 wt. % db) when they were fried under the vacuum condition (120^{o}C and 170mbars) compared with the atmospheric condition at 180^{o}C with the same preparation process (pre-dried without sugar dipping) prior to frying. A further reduction in the oil content of the fried potato crisps (approximately 40 wt.% db) was obtained when potato crisps were pre-dried and subsequently dipped in sugar solution (23.1wt%) and fried at the same vacuum conditions, compared with that under conventional conditions (180^{o}C) with pre-drying but no sugar solution dipping.

The oil content of pre-dried and dipped (PSSD) potato crisps vacuum-fried at the pressure of 150mbars were about 19% lower compared to those of the (PSSD) potato crisps vacuum–fried at the pressure of 170mbars **(see Figure 3.5a).** When the frying pressure was reduced to 100 and 50 mbars not a significant change in the oil contents of the potato crisps was observed ($P>0.05$) (see **Figure 3.5b and 3.5c).**

Table 3.1 The oil content of pre-drying potato crisps with different conditions: (i) pre-dried & no sugar solution dipping (PNSD), and frying conventionally at 180°C; (ii) pre-dried with sugar solution dipping, and vacuum frying at 120°C and 170mbars; and (iii) pre-dried, with sugar solution dipping (PSSD), and vacuum frying at 120°C and 170mbars.

Frying time (min)	Conventional frying pre-drying, non-sugar solution dipping		Vacuum frying (120°C, 170mbars) pre-drying and non-sugar solution dipping		Vacuum frying (120°C, 170mbars) pre-drying and sugar solution dipping	
	Oil content (% dry basis)	Stdev	Oil content (% dry basis)	Stdev	Oil content (% dry basis)	Stdev
0	0.00	0.000	0.00	0.000	0.00	0.000
1	57.47	1.233	32.89	0.000	24.06	0.171
2	68.93	4.320	51.52	0.012	37.27	0.001
3	79.89	1.235	55.44	3.497	53.34	5.298
4	75.37	1.422	65.77	1.651	47.08	4.544
5	86.26	1.752	64.25	6.554	52.72	1.528
6	94.36	0.000	92.78	0.000	51.34	5.941

As a result the pressure of 150mbars was found to be appropriate for the vacuum frying in order to reduced the oil content of the PSSD potato crisps.

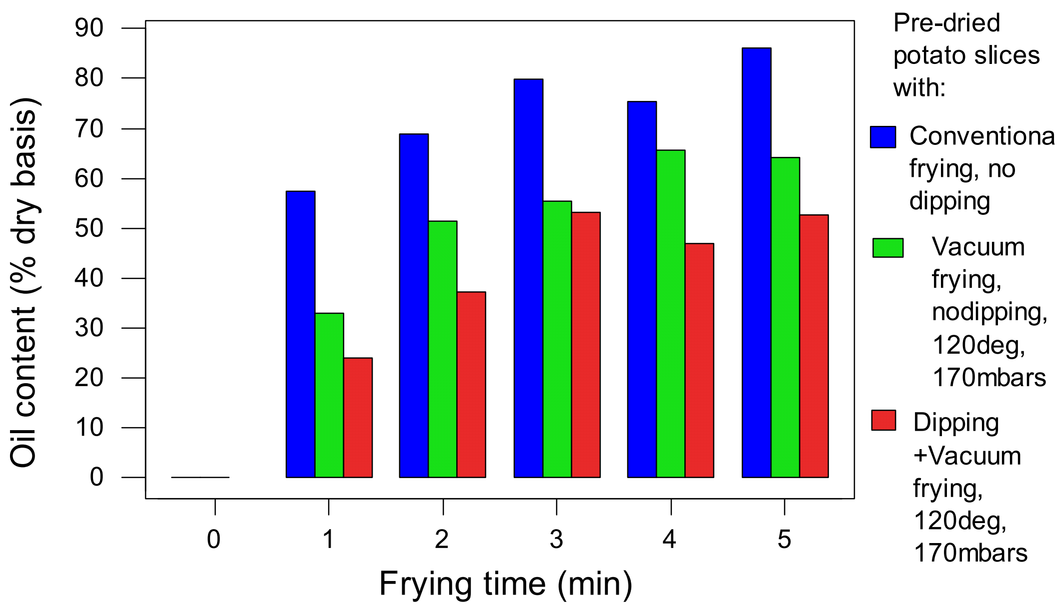

Figure 3.4 Effect of pre-drying with and without sugar solution dipping on the oil content of potato crisps during frying process.

3.3.1.3 Effect of frying oil temperatures on the oil reduction of the PSSD potato crisps with vacuum frying

Figure 3.6 and **Tables 3.2, 3.3** show the oil contents of the PSSD potato crisps, which were fried conventionally at 180°C and vacuum-fried at 120°C and 110°C under the pressure of 150 mbars. There was a significant difference between the oil contents of the conventionally fried and the vacuum-fried potato samples. However, the oil contents of the potato samples vacuum-fried at 110°C were only a small amount less than those of the potato samples vacuum-fried at 120°C. Even though the influence of the frying temperature on the oil content of the vacuum-fried potato crisps was not significant, these results were similar to the results reported by Moyano and Pedreschi (2006) for the NPND potato crisps prepared using conventional frying conditions. Moyano and

Pedreschi (2006) found that the oil content of the potato crisps can be lowered if they were fried at low temperatures.

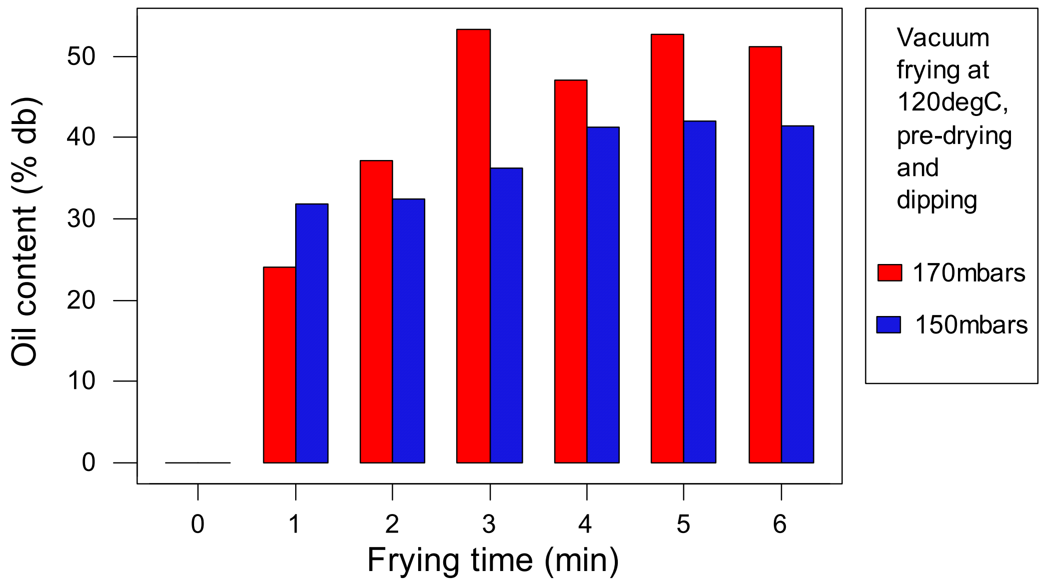

Figure 3.5a The oil content of the pre-dried potato slices and followed by sugar solution dipping and frying under different vacuum frying conditions: 170 and 150mbars, respectively at 120°C.

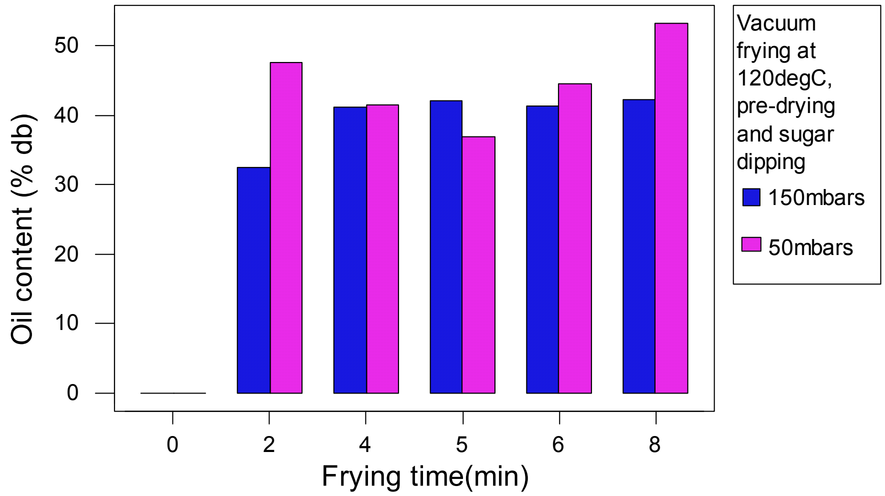

Figure 3.5b The oil content of the pre-dried potato slices and followed by sugar solution dipping and frying under different vacuum frying conditions: 150 and 50 mbars, respectively at 120^{o}C.

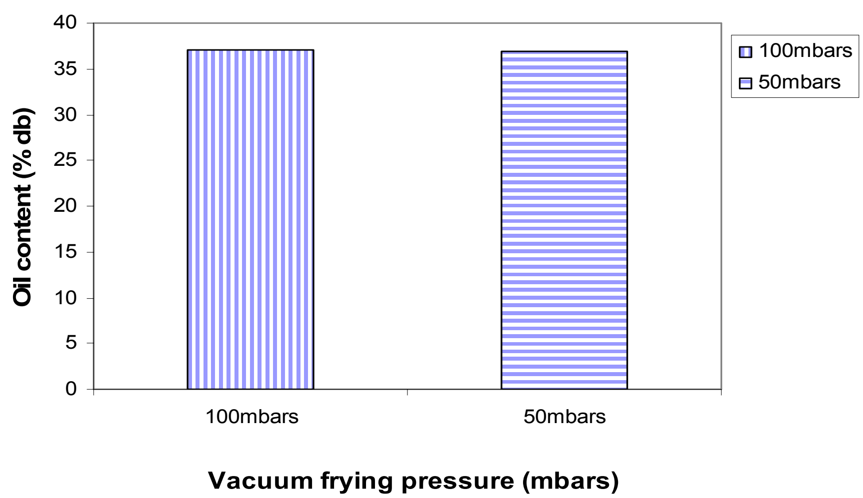

Figure 3.5c Effect of vacuum pressure on the oil content of potato chips pre-dried and followed by sugar solution dipping and frying under different vacuum conditions 100 and 50 mbars, respectively at 120^{o}C after 5 minutes of frying time.

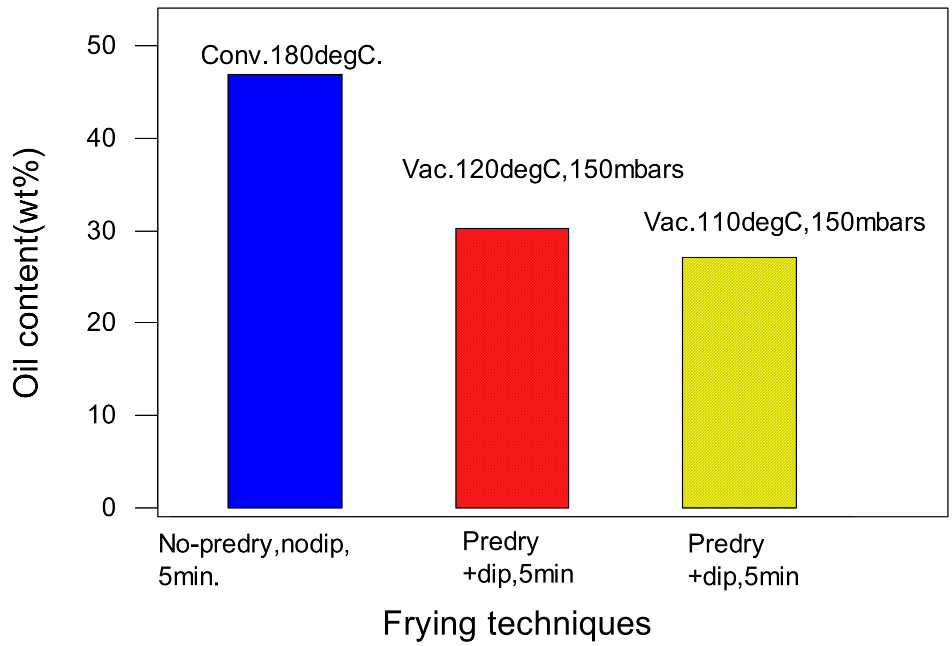

Figure 3.6 Effect of temperature on the oil content of the PSSD potato chips vacuum-fried at 120 and 110^{o}C with 5 minutes at of frying time.

Table 3.2 Oil contents of the potato crisps at 5 minutes frying with different pre-treatments and frying conditions.

Oil content at 5 minutes frying (wt%) or (%wb)		
Conventional frying 180^{o}C – Non pre-drying non-sugar solution dipping (Control samples)	Vacuum frying (120^{o}C, 150mbars)-Pre-drying non-sugar solution dipping	Vacuum frying (110^{o}C, 150mbars)-Pre-drying and sugar solution dipping
46.87	30.19	27.08

Table 3.3 Oil content of the PSSD potato crisps and vacuum frying at 120°C and 110°C respectively under 150mbars.

Frying time (min)	Vacuum frying (110°C, 150mbars) pre-drying and sugar solution dipping		Vacuum frying (120°C, 150mbars) pre-drying and sugar solution dipping	
	Oil content (% dry basis)	Stdev	Oil content (% dry basis)	Stdev
0	0.00	0.000	0.00	0.000
1	29.81	0.566	31.27	0.913
2	33.28	1.276	31.48	0.289
3	35.57	0.545	32.66	0.016
4	44.37	0.025	43.56	0.396
5	40.77	2.500	42.27	0.032
6	37.61	0.116	41.50	0.271

3.3.1.4 Effect of pre-drying technique on the oil reduction of potato chips under vacuum frying

Pre-treatment technique with pre-drying but no sugar dipping had various benefits, which were described in some previous papers (Krokida et al., 2001; Gupta et al., 2000 and Moyano & Pedreschi, 2006). However, most of the papers only presented the effects of pre-drying on fried potato chips prepared under the conventional frying conditions. In this study, the influence of pre-drying technique was investigated for the potato crisps with vacuum frying conditions. **Table 3.4a** & **3.7a**; **Table 3.5** & **Figure 3.8** show the benefits of pre-drying on the oil uptake by the potato crisps under vacuum frying conditions 150mbars at 120°C and 110°C, respectively. **Table 3.4b** and **Figure 3.8b** show the oil content of potato crisps fried conventionally at 180°C.

Table 3.4a Oil content (wt%) of the NPND and PNSD potato crisps under vacuum frying at 120^{o}C and 150mbars (Potato density 1.1045 ± 0.0058 g.ml-1).

Frying time (min)	Non pre-drying (NPND)	Pre-drying (PNSD)
4	37.46	34.49
5	42.84	37.87
6	45.62	32.47

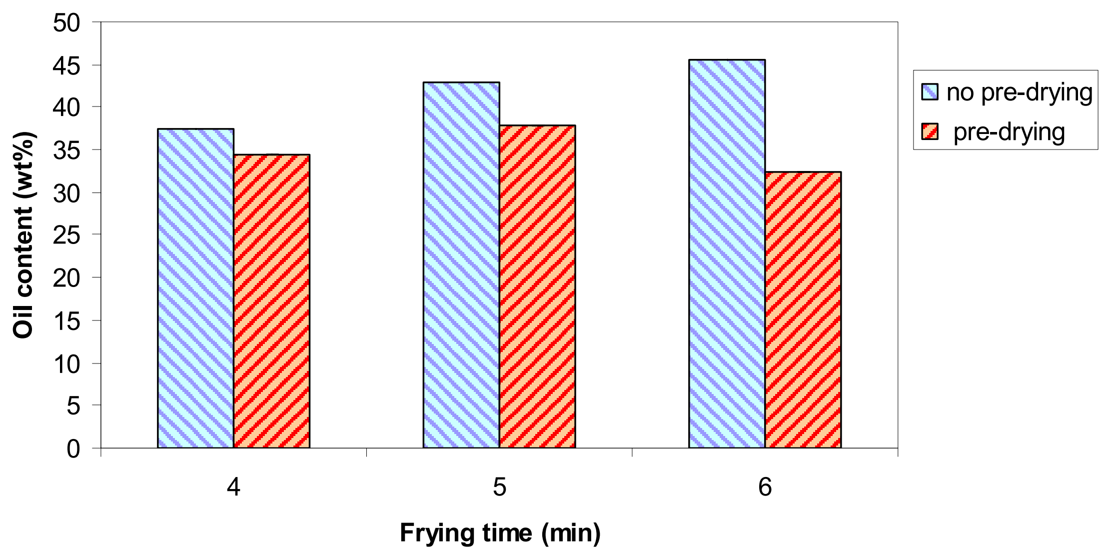

Figure 3.7a Effect of pre-drying on the oil content of potato chips vacuum-fried (150mbars) at 120^{o}C (Density of potatoes = 1.1045 ± 0.0058 g.ml^{-1}).

As can be seen from **Tables 3.4a&b** and **Figures 3.7a&b** the pre-drying treatment reduced the oil content of the vacuum fried potato crisps but it was not efficient for reducing the oil content of the conventional fried potato crisps. The full result of the statistical analysis of the oil content of potato chips is shown on **Table 3.6**. In addition, the oil content of potato crisps frying under vacuum frying at 110^{o}C and 150mbars after frying 5 minutes, is presented in the **Table 3.5** and **Figure 3.8.**

Table 3.4b Oil content (wt %) of the potato crisps under conventional fried (180^{o}C). (Density of potatoes= D= 1.1056 ± 0.0062 g.ml-1).

Frying time (min)	Non-predrying (%wt)	Pre-drying (%wt)
0	0.00	0.00
2	27.56	35.33
3	41.66	38.74
4	42.14	42.60
5	46.87	40.52

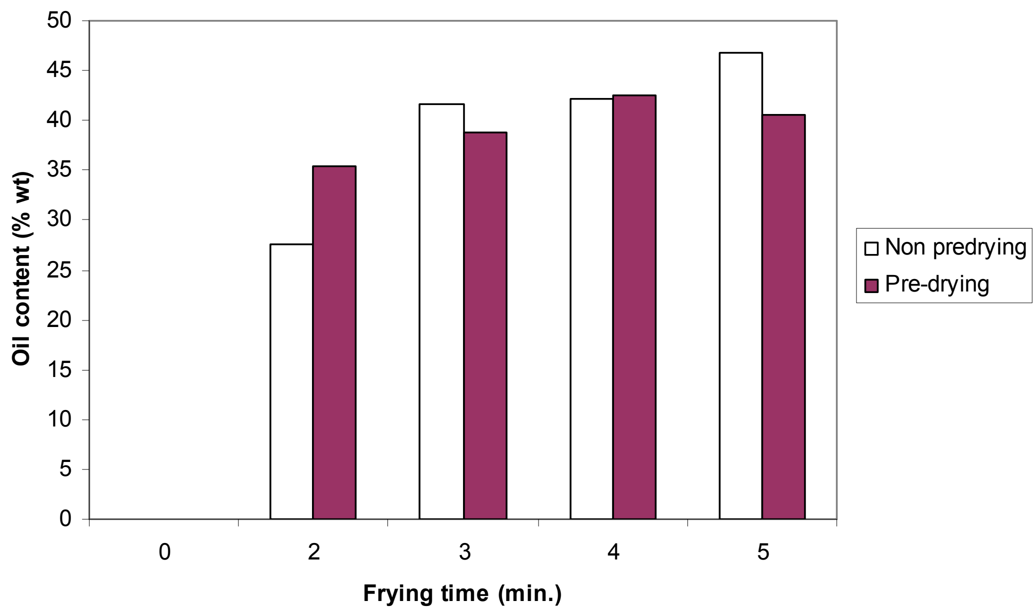

Figure 3.7b Effects of pre-drying on the oil content of potato chips fried conventionally at 180^{o}C; (Density of potatoes= D= 1.1056 ± 0.0062 g.cm^{-3}).

As can be seen from **Table 3.5** and **Figure 3.8,** the oil content of pre-dried (PNSD) samples (28.27 wt %) was much closer to the PSSD potato chips (27.08 wt %) fried at vacuum conditions of 110^{o}C at 150mbars for 5 minutes frying time. This information had not been mentioned previously.

Table 3.5 Oil content of potato crisps with different pretreatment techniques under vacuum frying at 110^{o} C and 150mbars after frying 5 minutes.

Oil content (wt%) at 5 minutes frying of vacuum frying 110^{o} C, 150mbars (D= 1.1056 ± 0.0062 g.ml^{-1})		
No pre-drying no sugar solution dipping	Pre-drying non-sugar solution dipping	Pre-drying and sugar solution dipping
31.78	28.27	27.08

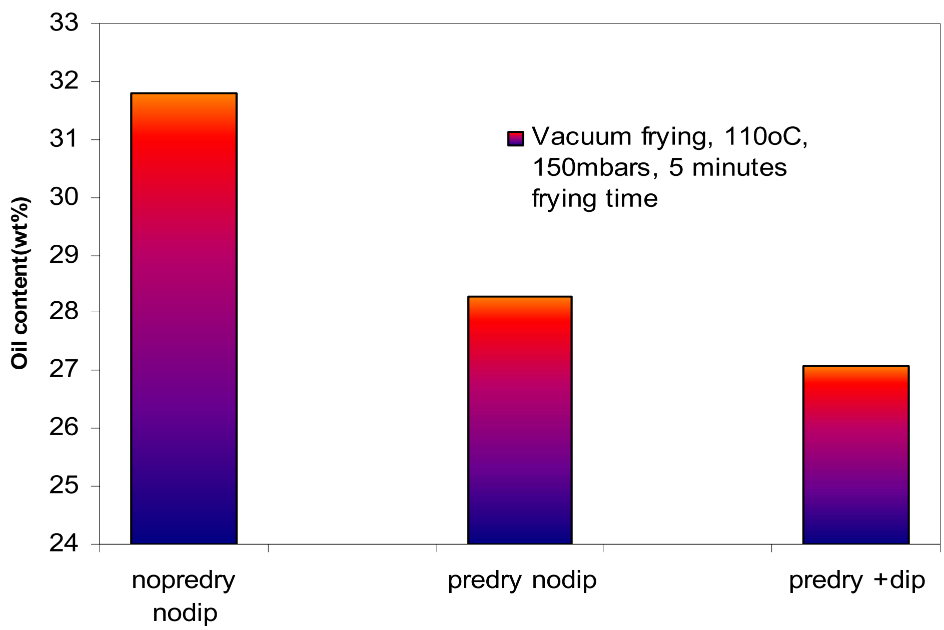

Figure 3.8 Effects of pre-drying and pre-drying & sugar solution dipping on the oil content of potato chips frying under vacuum conditions 150mbars and 110^{o}C after 5 minutes of frying (Density of potatoes= 1.1056 ± 0.0062 g.ml^{-1}).

Table 3.6 Statistical analysis on the results of oil contents

Sample (1)	Sample (2)	Sample testing results Sample (1) vs Sample (2)	Frying time testing results (Frying time is a row factor)
PSSD vacuum frying 120°C, 170mbars	PDND vacuum frying 120°C, 170mbars	SN ($P<0.05$)	SN ($P<0.05$)
PSSD vacuum frying 120°C, 170mbars	PDND conventional frying (180°C)	SN ($P<0.05$)	SN ($P<0.05$)
PDND vacuum frying 120°C, 170mbars	PDND conventional frying (180°C)	SN ($P<0.05$)	SN ($P<0.05$)
PSSD vacuum frying 120°C, 150mbars	PSSD vacuum frying 120°C, 170mbars	NS ($P>0.05$)	SN ($P<0.05$)
PSSD vacuum frying 120°C, 150mbars	PSSD vacuum frying 120°C, 50mbars	NS ($P>0.05$)	SN ($P<0.05$)
PSSD vacuum frying 110°C, 150mbars	PSSD vacuum frying 120°C, 150mbars	NS ($P>0.05$)	SN ($P<0.05$)
PSSD vacuum frying 110°C, 150mbars	Control samples	SN ($P<0.05$)	SN ($P<0.05$)
PSSD vacuum frying 120°C, 50mbars	Control samples	SN ($P<0.05$)	SN ($P<0.05$)
PSSD vacuum frying 120°C, 150mbars	Control samples	SN ($P<0.05$)	SN ($P<0.05$)
PSSD vacuum frying 120°C, 170mbars	Control samples	SN ($P<0.05$)	SN ($P<0.05$)
PDND conventional frying (180°C)	Control samples	NS ($P>0.05$)	SN ($P<0.05$)

3.3.2 Kinetics of oil uptake

As presented in **Section 3.2.3.1,** the Krokida model through equation **(3.1)** was used to calculate the kinetics of oil uptake during the frying process applying in this study**.** In **Figures 3.9a**. and **3.9b.** the plots of ln(1-(X_{oil} /$X_{oil,e}$)) versus frying time (min) give the straight lines with high correlations R-sq (***R^2_{oil}***) and the slopes of -k_{oil} *,* in which k_{oil} *is* the rate constant of oil uptake during the frying process, applying in both conventional and vacuum frying for each condition obtained from this study. The parameters k_{oil} and ***R^2_{oil}*** are presented in **Table 3.7**, where the values of various parameters for models mass transfer **Equation (3.1**) and **(3.2**) are demonstrated.

Figures 3.10a and **3.10b** show the experimental results together with the first order kinetics model prediction for the oil uptake of the potato crisps prepared using different pre-treatment and frying conditions. As mentioned above, the values of parameters of the first order kinetics model are summarized in **Table 3.7.** As can be seen from Figures 3.10a and 3.10b, the oil uptake can be presented by a simple first order kinetics model. The conventionally fried potato samples (the control samples) had the lowest rate constant for the oil uptake kinetics (k_{oil}) and the highest equilibrium oil content ($X_{oil,e}$) value.

The PSSD potato crisps with vacuum frying at 110°C and 150mbars had the highest k_{oil} and the lowest $X_{oil,e}$. As suggested by the Equation (1), the overall oil uptake kinetics of potato samples is controlled by both k_{oil} and $X_{oil,e}$ in order to reduce the oil uptake of potato crisps. The relationships between the specific rate (k_{oil}) and the equilibrium oil content ($X_{oil,e}$) for the potato samples used in this study is shown in **Figure 3.11.** It appears that there is an inverse relationship between k_{oil} and $X_{oil,e}$, that is, in general k_{oil} decreases with increasing $X_{oil,e}$, or vice versa. Therefore, it will not be very meaningful to look at the trend of a single (k_{oil} and $X_{oil,e}$) to explain the overall oil uptake of the fried potato samples.

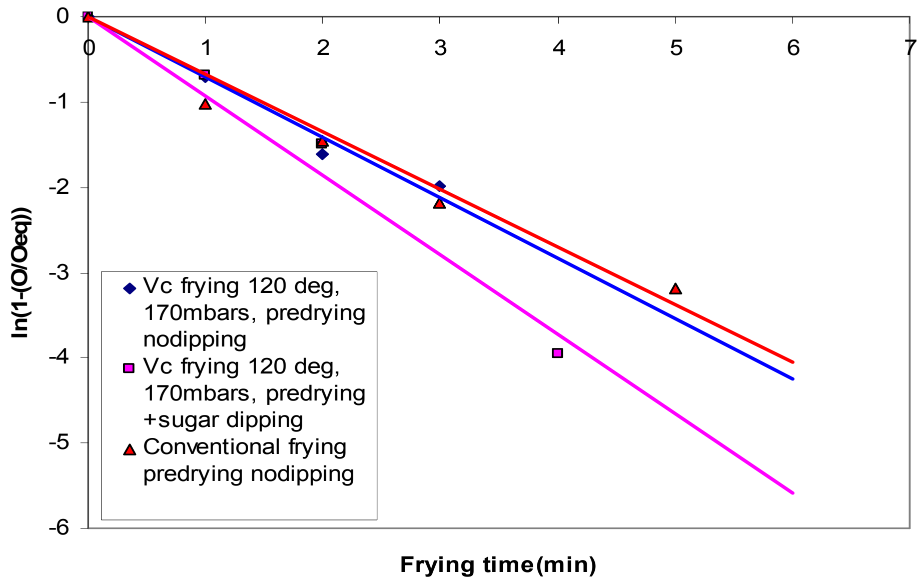

Figure 3.9a First-order reaction kinetics plots for oil uptake of fried potato crisps with different pre-treatment techniques under conventional and vacuum frying conditions (120°C, 170mbars).

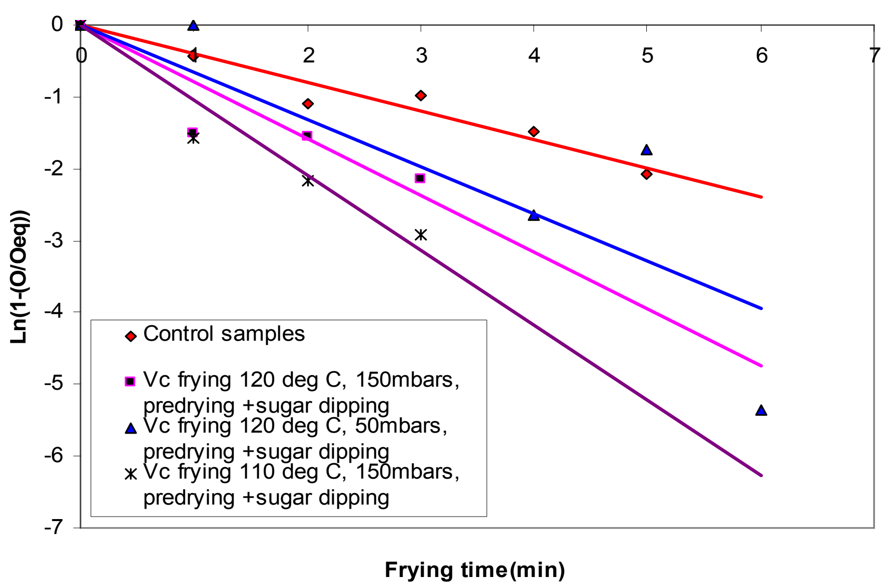

Figure 3.9b First-order reaction kinetics plots for oil uptake of pre-dried and sugar solution dipped potato crisps with different conditions of vacuum frying and control samples.

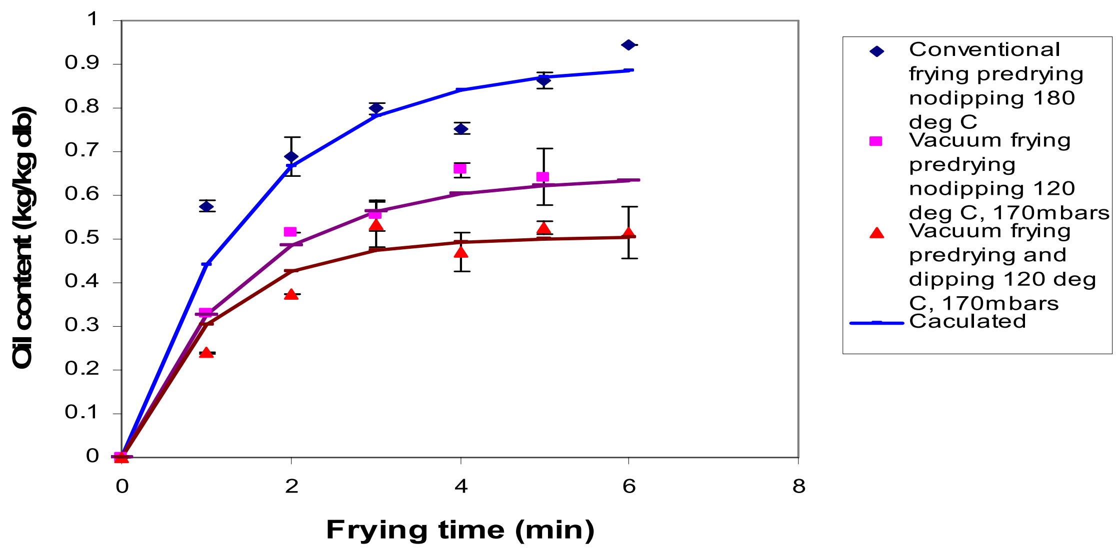

Figure 3.10a

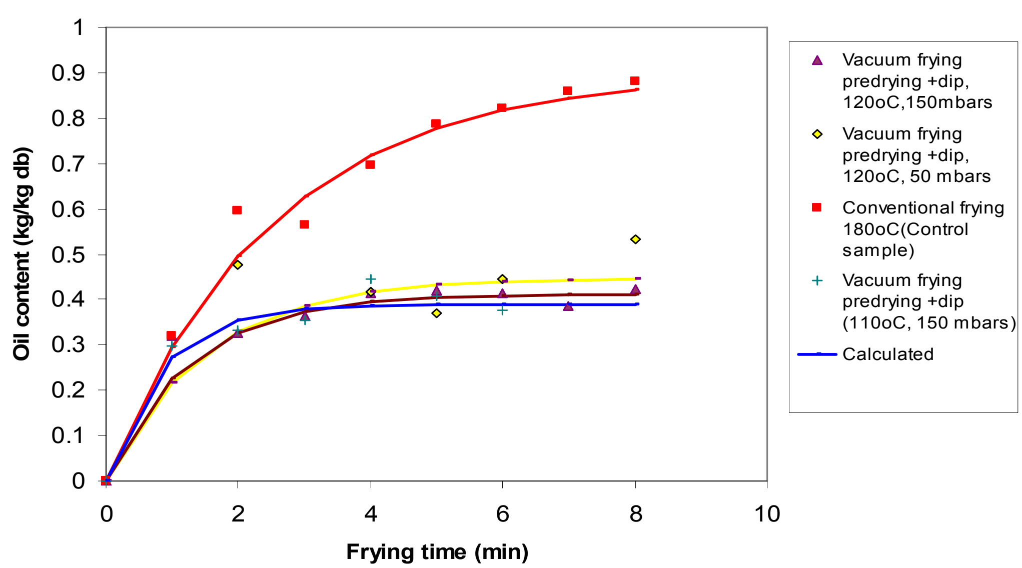

Figure 3.10b

Figure 3.10a and 3.10b Experimental and predicted results for the oil uptake of the potato crisps prepared using different conditions. Symbols represent the experimental results and the solid lines represent the predicted results obtained using Equation (1).

Under vacuum frying conditions, for the PSSD cases, k_{oil} constant increases with rising pressure and decreases with the lowering temperature of frying (**Table 3.8**). That was contrary to the conventional frying where the rate constant increases with frying temperature applying for untreated samples (Moyano and Pedreschi, 2006). The currently observed behavior agrees with the claim that the higher frying temperatures lead to lower absorbed oil applied to the conventional frying process (Talburt et al., 1987).

Vacuum frying and pre-treatments (pre-drying with and without sugar solution dipping), were found to be a good combination for decreasing the oil content of the fried potato crisps. When the potato samples were pre-dried and dipped into the sugar solution and then vacuum fried, the oil content of these samples was reduced significantly. The lowest values (about 60% reduction on dry basis) were observed for the PSSD potato samples, which were vacuum-fried at 110^{o}C and 150 mbars.

Garayo and Moreira (2002) studied the vacuum frying of potato chips, and they found that the final oil content values were significantly different ($p < 0.05$) for the potato chips fried under vacuum (37% db or 27% wb) and atmospheric pressure (66% db or 40% wb). The oil content of the pretreated (pre-drying and sugar solution dipping) potato crisps vacuum fried at 110^{o}C was about 30% db which is less than those of the vacuum fried (31 mbars and 144^{o}C) potato chips (about 37% db) reported by Garayo and Moreira (2002). These observations indicate that pre-drying and subsequently sugar solution dipping can further decrease the oil content of the vacuum fried potato crisps. However, in this study a lower temperature of 110^{o}C and a higher pressure of 150mbars were found to be optimal frying conditions for the preparation of the lowest oil content potato crisps, comparing to the optimal frying temperature of 144 ^{o}C and pressure of 31mbars reported by Garayo and Moreira (2002).

Table 3.7 The parameters for the model equation (3.1) and (3.2)

Frying conditions	$X_{w,o}$	$X_{w,e}$	k_w	R^2_{water}	S_w	$X_{oil,e}$	k_{oil}	R^2_{oil}	S_{oil}
NPND fried conventionally at 180°C	5.66	0.022	1.46	0.98	0.06	0.88 ± 0.05	0.398	0.94	0.016
PNSD fried conventionally at 180°C	2.95	0.020	1.61	0.98	0.02	0.84 ± 0.09	0.68	0.97	0.029
PSSD fried conventionally at 180°C	3.08	0.026	1.71	0.96	0.04	0.47 ± 0.04	0.77	0.98	0.023
PNSD vacuum fried (170mbars) at 120°C	3.00	0.036	1.35	0.96	0.05	0.63 ± 0.04	0.70	0.98	0.04
PSSD vacuum fried (170mbars) at 120°C	2.73	0.053	1.04	0.98	0.10	0.51 ± 0.03	0.93	0.97	0.01
PSSD vacuum fried (150mbars) at 120°C	2.75	0.030	1.01	0.95	0.003	0.41 ± 0.04	0.79	0.78	0.01
PSSD vacuum fried (50mbars) at 120°C	2.75	0.027	1.19	0.98	0.006	0.44 ± 0.07	0.66	0.76	0.03
PSSD vacuum fried (150mbars) at 110°C	2.75	0.047	1.29	0.99	0.011	0.38 ± 0.04	1.05	0.93	0.01

Table 3.8 Effect of frying pressure and oil temperature on the oil uptake rate constant (k_{oil}) in vacuum frying process.

Frying pressure (mbars)	Frying oil temperature (°C)	k_{oil} (min^{-1})
50	120	0.66
150	120	0.79
170	120	0.93
150	110	1.05

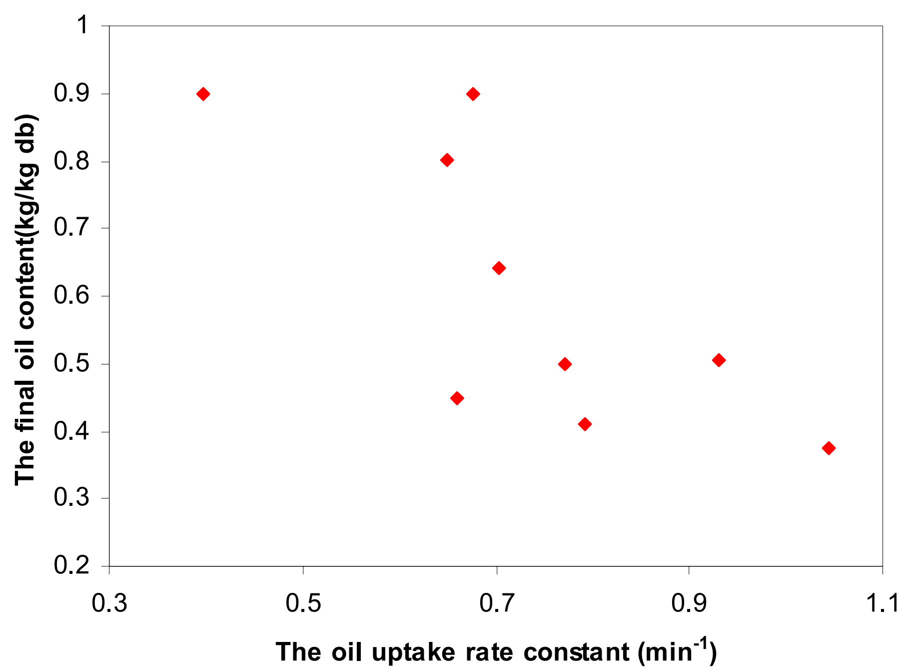

Figure 3.11 The final oil content achieved versus the oil uptake rate constant.

3.3.3 Moisture loss

As mentioned in previous sections, moisture loss and oil uptake have a high correlation and they are considered as the mass transfer mechanism in the frying process. Therefore, when oil uptake has been mentioned, the water loss can not be ignored in the study of the process. Under vacuum frying conditions, the evaporation of moisture in potato chips is associated with frying pressure due to the boiling point temperature of water being related to the frying pressure. In this study, potato chips with pre-treatment pre-drying non-sugar dipping (PNSD) and pre-drying & subsequent sugar dipping (PSSD) techniques are fried at different pressures and temperatures. The effect of pre-treatments on the moisture content of potato chips and the influence of low pressures and low temperatures on the moisture content of PNSD and PSSD potato crisps fried under vacuum conditions are investigated in this study. The comparison with moisture content of potato chips fried conventionally is also determined in this section.

3.3.3.1 Effect of pretreatment PSSD on the moisture content of fried potato crisps under vacuum frying conditions

Table 3.9 shows the moisture content of pre-dried and vacuum fried potato crisps. They were differently pre-treated, one was non-sugar dipped (PDNS) and another was sugar dipped (PSSD) in sugar solution (23.07 wt %) and both of them were fried at an oil temperature of 120^{o}C and a vacuum pressure of 170mbars**.** The results show that there was no significant difference (P> 0.05) on the moisture contents of potato crisps, which were dipped (PSSD) and non-sugar solution dipped (PDNS) and fried at vacuum conditions (120^{o}C, 170mbars). Similar with conventional frying, the pre-treatment PSSD technique was not a significant factor (P>0.05) affecting on the moisture content of pre-dried potato crisps, which were fried at conventional conditions (180^{o}C). **Table 3.10** presents the moisture content of conventionally fried PSSD and PDNS potato crisps; the moisture content of control samples was also presented in this table. The moisture content

Table 3.9 Moisture contents of the pre-dried potato crisps fried under vacuum conditions (120^{o}C and 170mbars).

Frying time (min)	Pre-dried & non-sugar solution dipping				Pre-dried & sugar solution dipping			
	%dry basis		%wet basis		%dry basis		%wet basis	
	average	stdev	average	stdev	average	stdev	average	stdev
0	262.00	1.351	72.00	1.351	275.00	1.052	73.19	1.052
1	57.80	13.911	36.38	5.608	70.87	8.073	41.39	2.832
2	23.58	5.934	18.99	3.890	31.33	0.330	23.85	1.259
3	7.52	0.267	6.99	0.231	11.58	2.914	10.35	2.342
4	6.91	0.010	6.47	0.009	4.82	0.180	4.60	0.165
5	3.84	0.001	3.70	0.001	5.76	0.883	5.44	0.789

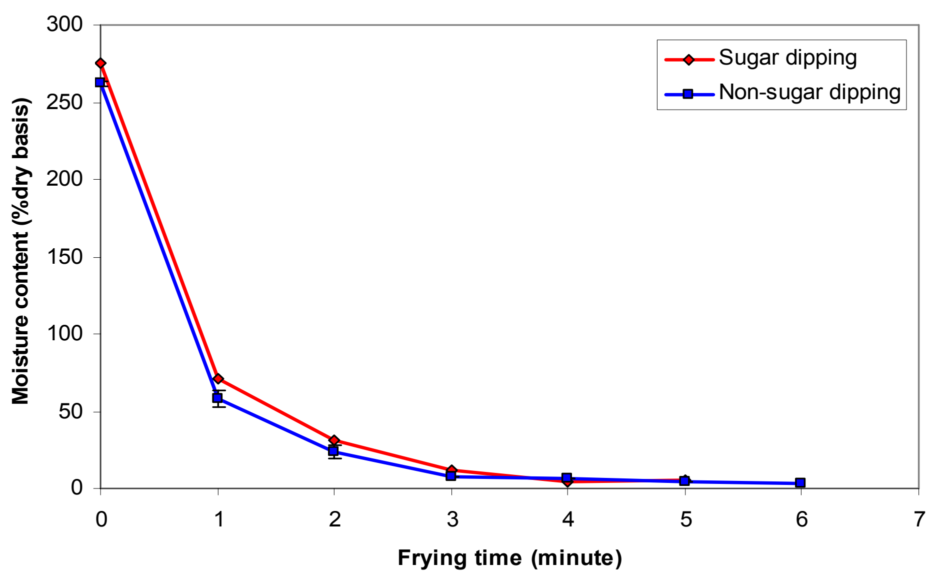

Figure 3.12 Moisture content of the pre-dried potato crisps fried at vacuum conditions (120^{o}C, 170mbars) with different sugar dipping.

Table 3.10 Moisture contents of the conventionally fried potato crisps with different pre-treatment techniques.

Frying Time (min)	Control samples				Pre drying non-sugar dipping				Pre drying & sugar dipping	
	%dry basis		%wet basis		% dry basis		%wet basis		%dry basis	%wet basis
	average	stdev	average	stdev	average	stdev	average	stdev	average	average
0	566.00	1.12	84.58	1.33	292.93	0.23	74.72	0.23	299.29	75.50
1	111.01	7.72	52.59	1.71	65.19	2.06	39.46	0.75	34.15	25.44
2	21.91	10.55	17.68	7.14	23.39	1.37	18.95	0.90	13.13	11.61
3	15.07	1.93	13.09	1.45	5.54	2.89	5.22	2.60	3.58	3.45
4	4.32	0.39	4.14	0.36	2.43	0.20	2.37	0.19	2.92	2.83
5	2.24	0.10	2.20	0.09	2.05	0.13	2.01	0.12	2.86	2.78

of PNSD and PSSD potato crisps in both vacuum and conventional frying were not significantly different (P>0.05) to the control samples. **Table 3.14** shows the full result of the statistical analysis of the moisture content of potato crisps.

3.3.3.2 Effect of pressure on the moisture content of PSSD treated potato chips under vacuum frying conditions

Tables 3.9 and 3.11 show the moisture content of PSSD potato crisps fried at different vacuum pressures 170mbars, 150mbars and 50mbars at the same temperature 120^{o}C. As the results show there was no significant difference on the moisture content of PSSD potato crisps fried at those pressures (**Table 3.14**). Compared with the control samples, the moisture content of potato crisps fried at 120^{o}C with different vacuum pressures 170, 150 and 50mbars respectively was not significantly different from the control samples (**Table 3.14**). Specially, the moisture content of PSSD potato crisps (120^{o}C, 50mbars) with the final moisture content of 2.57 g/g solid was closed to the control samples (2.2 g/g solid). That indicated that pressure was not a significant factor on the final moisture content of vacuum fried PSSD potato crisps.

3.3.3.3 Effect of low temperature on the moisture content of the PSSD treated potato chips under vacuum frying conditions

Table 3.12 shows the moisture content of the PSSD potato crisps fried at vacuum conditions 110^{o}C and 150mbars. Compared to PSSD potato crisps fried at 120^{o}C and 150mbars. There was no significant difference ($P>0.05$) on the moisture content of PSSD potato crisps at frying temperature 110^{o}C and 120^{o}C with the same pressure 150mbars. Similarly, the moisture content of the PSSD potato crisps fried at 110^{o}C and 150mbars was not significantly different to the control samples (**Table 3.14).** It can be concluded that the low temperatures 110^{o}C and 120^{o}C of frying oil did not significantly influence the moisture content in PSSD (and PNSD) potato crisps. In contrast to untreated samples, which were not pre-dried and not sugar solution dipping (NPNS) and fried at 110^{o}C, 150mbars (**Table 3.13**), there was a significant difference ($P<0.05$) in the moisture content of the untreated vacuum fried low temperature potato crisps and control samples and treated vacuum fried samples (**Table 3.15**).

Table 3.11 Moisture contents of the vacuum fried PSSD potato crisps at different frying pressures

Frying time (min)	Vacuum frying 120^{o}C, 50mbars				Vacuum frying 120^{o}C, 150mbars			
	% dry basis		% wet basis		% dry basis		% wet basis	
	average	stdev	average	stdev	average	stdev	average	stdev
0	275.00	1.052	73.19	1.052	275.00	1.052	73.19	1.052
2	20.59	0.001	17.07	0.001	32.20	1.931	24.32	1.131
4	5.17	0.181	4.92	0.164	6.76	0.708	6.33	0.619
5	4.12	0.117	3.93	0.106	4.89	1.555	4.74	0.001
6	2.84	0.001	2.74	0.001	3.33	1.288	3.21	1.204
8	2.57	0.210	2.51	0.199	3.27	0.211	3.24	0.192

Table 3.12 Moisture contents of the PSSD potato crisps and fried at 110^oC and 150mbars.

Frying time (min)	Vacuum frying 110^oC, 150mbars			
	% dry basis		%wet basis	
	average	stdev	average	stdev
0	275.00	1.052	73.19	1.052
1	85.84	0.491	46.19	0.142
2	32.72	0.393	24.65	0.223
3	11.02	0.045	9.92	0.036
4	6.35	0.004	5.97	0.003
5	5.04	0.008	4.80	0.007
6	4.39	0.042	4.21	0.038

Table 3.13 Moisture contents of the untreated samples vacuum fried at 110^oC and 150mbars.

Frying time (min)	Untreated samples vacuum frying 110^oC, 150mbars			
	% dry basis		% wet basis	
	average	stdev	average	stdev
0	566.00	1.118	84.58	1.330
1	318.35	8.602	76.09	0.492
2	221.92	1.304	68.94	0.126
3	120.47	0.774	54.64	0.159
4	56.01	12.182	35.71	5.020
5	34.99	0.915	25.92	0.502
6	12.86	1.824	11.38	1.432

Table 3.14 Statistical analysis on the results of moisture contents.

Sample 1	Sample 2	Sample testing results (sample 1 vs sample 2)	Frying time testing results (Frying time is a row factor)
PNSD vacuum frying 120^{o}C, 170mbars	PSSD vacuum frying 120^{o}C, 170mbars	NS (P>0.05)	SN (P<0.05)
PNSD conventional frying (180^{o}C)	PSSD conventional frying (180^{o}C)	NS (P>0.05)	SN (P<0.05)
PNSD vacuum frying 120^{0}C, 170mbars	PNSD conventional frying (180^{0}C)	NS (P>0.05)	SN (P<0.05)
PSSD vacuum frying 120^{o}C, 170mbars	PSSD conventional frying (180^{o}C)	NS (P>0.05)	SN (P<0.05)
PNSD vacuum frying 120^{o}C, 170mbars	Control samples	NS (P>0.05)	SN (P<0.05)
PSSD vacuum frying 120^{o}C, 170mbars	Control samples	NS (P>0.05)	SN (P<0.05)
Control samples	PNSD conventional frying (180^{o}C)	NS (P>0.05)	SN (P<0.05)
Control samples	PSSD conventional frying (180^{o}C)	NS (P>0.05)	SN (P<0.05)
PSSD vacuum frying 50mbars, 120^{o}C.	PSSD vacuum frying 150mbars, 120^{o}C	NS (P>0.05)	SN (P<0.05)
PSSD vacuum frying 50mbars, 120^{o}C	Control samples	NS (P>0.05)	SN (P<0.05)
PSSD vacuum frying 150mbars, 120^{o}C	Control samples	NS (P>0.05)	SN (P<0.05)
PSSD vacuum frying 110^{o}C,150mbars,	PSSD vacuum frying 120^{o}C, 150mbars,	NS (P>0.05)	SN (P<0.05)
PSSD vacuum frying 110^{o}C,150mbars,	Control samples	NS (P>0.05)	SN (P<0.05)

The results from **Table 3.15** show that there was a significant difference in the moisture content in vacuum fried untreated samples to control samples ($P<0.05$) and pre-treated samples ($P<0.05$). Whereas the moisture content in vacuum fried pre-treated samples was not significantly different to the control samples (**Table 3.14).** That indicated that pre-treatment PSSD including PNSD techniques are advantageous techniques applied in vacuum frying as these techniques did not significantly affect the final moisture content in potato crisps applied to different vacuum pressures and low temperatures as described in previous sections.

Table 3.15 Statistical significance of the results on the moisture contents in untreated samples fried under vacuum conditions and other samples.

Sample 1	**Sample 2**	**Sample testing results (sample 1 vs sample 2)**	**Frying time testing results (Frying time is a row factor)**
NPND vacuum fried 110^{0}C, 150mbars	Control samples	SN ($P<0.05$)	SN ($P<0.05$)
NPND vacuum fried 110^{0}C, 150mbars	PSSD vacuum fried 110^{0}C,150mbars	SN ($P<0.05$)	SN ($P<0.05$)
NPND vacuum fried 110^{0}C, 150mbars	PSSD vacuum fried 150mbars, 120^{0}C	SN ($P<0.05$)	SN ($P<0.05$)

3.3.4 Kinetics of moisture loss

As presented in **Section 3.2.3.1,** the kinetics of water loss during the frying process applied in this study were calculated through equation **(3.2). Figure 3.13.a**. and **3.13.b** show the first order kinetics of oil uptake during the frying process. In **Figures 3.13.a**. and **3.13.b.** the plots of ln$[(X_w - X_{w,e})/(X_{w,o} - X_{w,e})\}$ versus frying time (min) give straight lines with high correlations R-sq ($\boldsymbol{R^2_{water}}$) and the slopes of $-k_w$. The parameter k_w is a

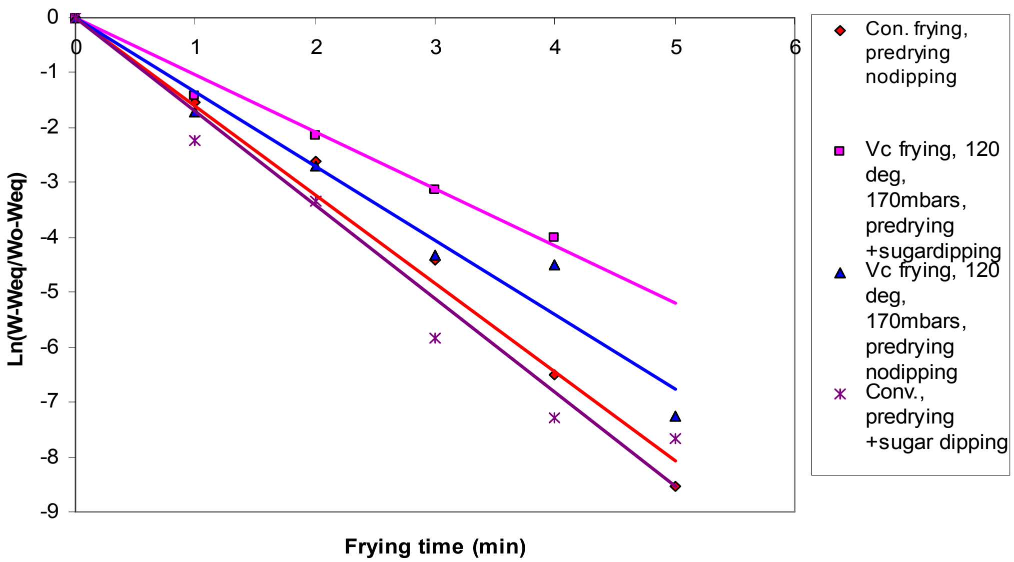

Figure 3.13a First-order reaction kinetics plot for moisture loss of fried potato crisps with different pre-treatment techniques followed by either conventional or vacuum frying processes (120°C, 170mbars).

special rate constant of moisture loss during frying process. The parameters k_w and $\boldsymbol{R^2_w}$ are presented in **Table 3.7.**

As shown in **Figures 3.14a and 3.14b**, the pre-drying and pre-drying with sugar solution decreased the initial moisture content of potato crisps. For the same frying time, the moisture contents of the fried potato samples were not different from each other. The final moisture contents of the potato samples ranged from 0.02 to 0.05 kg/kg db (see **Table 3.7).** The lowest moisture content was for the samples prepared using the conventional frying at 180°C with PNSD technique (about 0.02 kg/kg db). The moisture contents of the vacuum-fried PSSD samples were between 0.027 to 0.053 kg/kg db, when

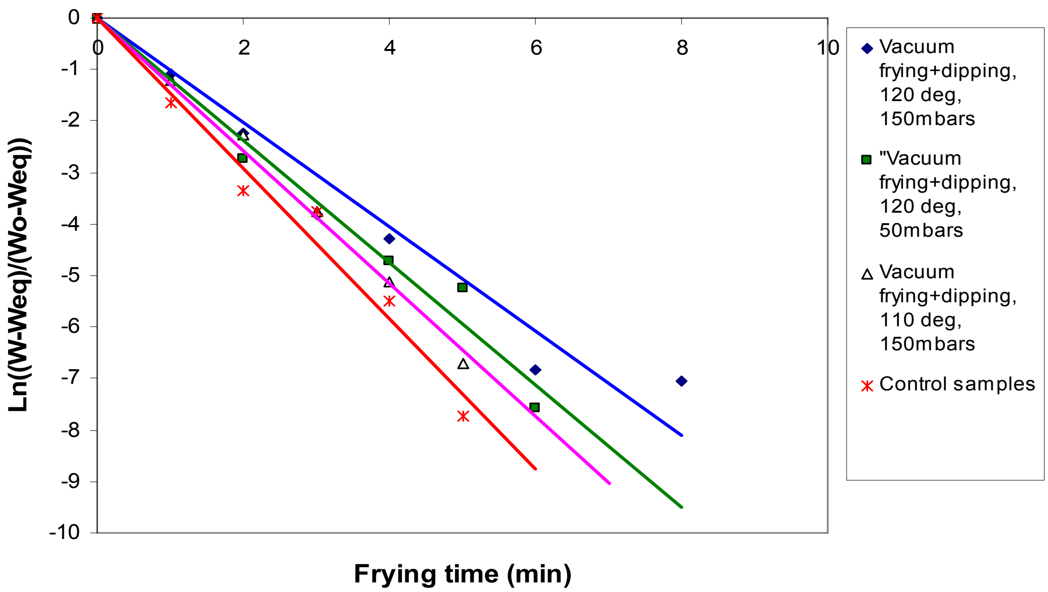

Figure 3.13 b First-order reaction kinetics plot for moisture loss in pre-dried and sugar solution dipped potato crisps followed by different conditions of vacuum frying compared to control samples.

pressure was increased from 50 mbars to 170 mbars while the same oil temperature of 120^{o}C was employed. Garayo and Moreira (2002) observed the similar behaviour.

They found that the rate of moisture loss was affected significantly ($P<0.05$) by the vacuum pressure treatment. There was an inverse relationship between vacuum pressure and rate of moisture loss at the same oil temperature. This means that the more pressure is reduced; the more water in potato crisps is evaporated, due to the boiling reduction. The water content of the potato samples fried at 110^{o}C was 0.047 kg/kg db and that of the sample fried at 120^{o}C was 0.03 kg/kg db. The moisture contents of the PSSD samples fried conventionally at 180^{o}C and the PSSD samples vacuum-fried at 120^{o}C and 50 mbars were very similar 0.026 and 0.027 kg/kg db, respectively (see **Table 3.7**).

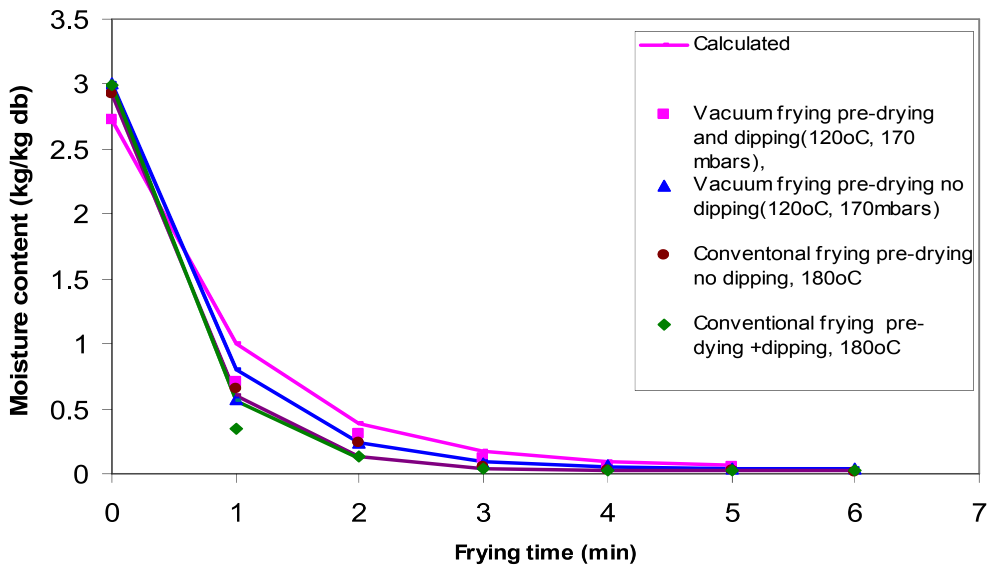

Figure 3.14a

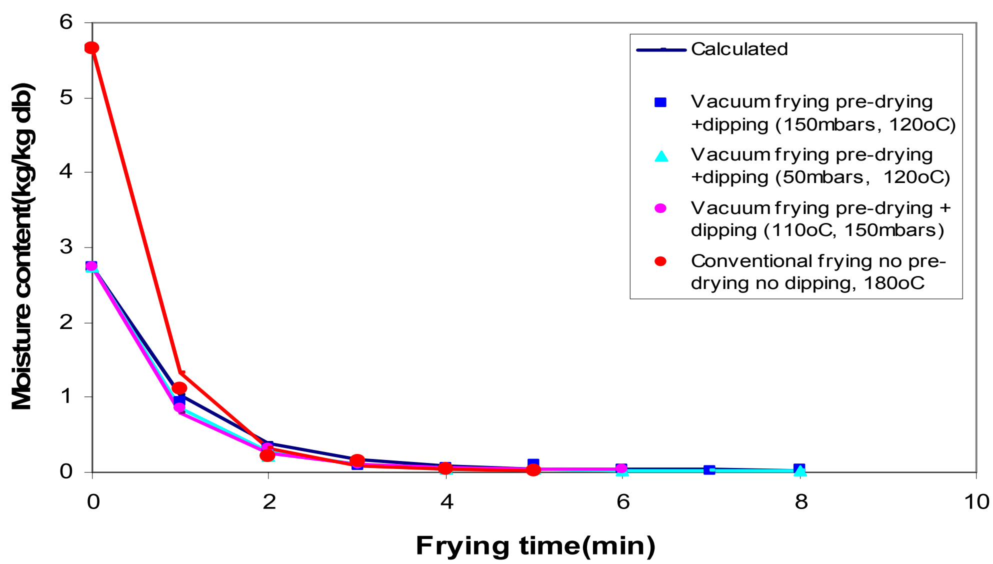

Figure 3.14b

Figure 3.14a and 3.14b Effects of pre-drying with and without sugar solution dipping on the moisture contents of potato crisps during vacuum and conventional frying processes. Symbols represent the experimental data and the solid lines are the predicted results using equation (3.2).

3.3.5 Shrinkage

Figure 3.15 represents the degree of volume shrinkage in potato crisps in correlation to frying time under vacuum and conventional frying with different pretreatment techniques, pressures and temperatures. The highest degree of the shrinkage was found in potato crisps fried under vacuum at 150mbars at an oil temperature of 110°C. Next, was vacuum frying at 170mbars and 120°C, and last was the control sample, which had the highest oil content compared the others. The moisture content differences between those samples were small compared to the large differences in the oil contents.

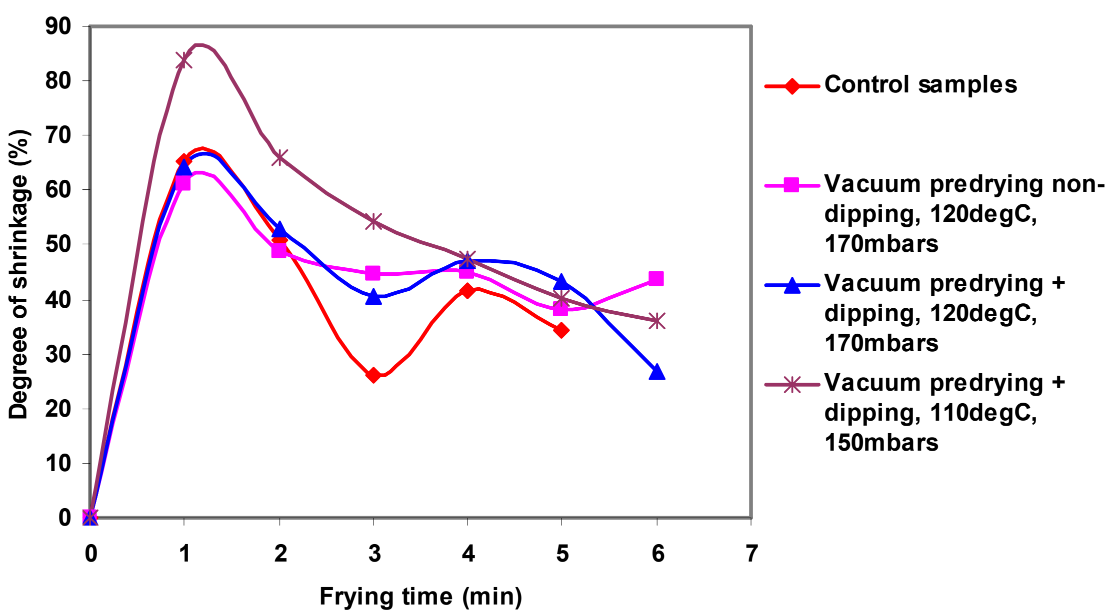

Figure 3.15 Effect of pre-drying (PNSD) and pre-drying followed by dipping in sugar solution (PSSD) on the shrinkage of potato crisps during vacuum and conventional frying (the control) processes.

3.4 Conclusions

The pre-drying and subsequently sugar dipping (PSSD) and followed by vacuum frying significantly affect the oil content and moisture content of potato chips. Lower oil contents for the potato crisps can be obtained by applying PSSD under vacuum frying conditions comparing with conventional frying. The optimum conditions for vacuum frying are 110^{o}C and 150mbars obtained from this study. There was more than 55% oil reduction on dry basis when potato slices were fried under these conditions compared with oil content of control samples. The present study has shown the promise of significant oil content reduction (thus improving the health outlook of the fried potato crisps to the public) at least technically. Full economic analysis of the processes would be necessary for large-scale productions.

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4. COLOUR CHANGES OF POTATO CRISPS DURING DEEP FAT FRYING- EFFECTS OF PRETREATMENT TECHNIQUES AND VACUUM FRYING.

4.1. Introduction

Colour is another important factor in processing quality food products. It is generally the first impression the user makes about the product (Gould, 1983). In fried potatoes, the color of potato chips is one of the most significant quality factors of acceptance for fried products. Therefore, the food industries have established specific values of lightness for acceptable potato chips (Krokida et al., 2001). In this study, the colour of potato crisps, which were produced in both conventional and vacuum frying, especially with pre-treatments: pre-dried & sugar and non-sugar solution dipping; the colour of products was investigated and presented in this chapter.

Factors that affect the colour of potato crisp

There have been some studies carried out over the years on the factors affected the color of fried potato chips. A summary is given below.

- Variety, irrigation, rainfall, date of harvest and soil temperature:

Variety, irrigation, rainfall, date of harvest and soil temperature and source and rate of potash application influence the color of potato chips (Smith, 1959 and 1960). There is a good relation between soil and air temperature and chip color. Chips were very light from harvests where soil and air temperatures were in the sixties and fifties for a week preceding harvest (Smith, 1960).

- Specify gravity of potatoes

Specific gravity of potatoes was also affected by variety, irrigation, rainfall, date of harvest and source and rate of potash application (Smith, 1960). Therefore, the different specify gravity may involve the colour of potato chips.

- The tuber reducing sugar content:

The tuber reducing sugar content is an important factor in determining the colour of oil-fried chips (Talburt and Smith, 1987). Reducing sugars (glucose and fructose) interact with amino acids, ascorbic acid, and some other organic compounds during deep-frying, producing an unacceptable burned (caramelized) flavor and dark coloration (Beukema and van der Zaag 1990). Therefore, tubers with high reducing sugar contents are undesirable.

- Storage time:

Chip color can also be affected by changes in the tuber starch to sugar ratio during storage. It has been published that the reducing sugar content increases with storage time (Watada and Kundel, 1954; Hyde and Morrison, 1964).

- Storage temperature:

During low temperature (< 8 °C) storage, reducing sugar content of potato tubers increases due to starch hydrolysis. Accumulation of reducing sugars in tuber results in excessive browning of French fries and potato chips.

Glucose content affects the color of potato chips. Various methods were used to treat glucose content in potato tubers to obtain the better color of potato chips. Sodium bisulfite and sulfur dioxide gas were used with storage potato slices before frying to obtained acceptable light color chips after six months storage (Smith, 1960). Tubers are usually held or reconditioned at about 21°C for 1 to 3 weeks in order to reduce the reducing sugars before frying (Heinze, Kilpatrick, & Dochterman, 1955; Kirkpatrick, Heinze, Craft, Mountjay, & Falatko, 1956) or blanched to leach out soluble sugars (Brown & Morales, 1970).

- Frying conditions

Temperature of frying oil and frying time are disturbing factors on the colour of fried potato chips. The lightness (L value) decreased while the redness (a value), yellowness (b value) and total changing in colour (ΔE value) increased as oil temperature and frying time increased (Nourian and Ramaswamy, 2003).

Vacuum conditions also influence the colour of potato chips. Sijbring and Velde (1969) used vacuum frying after conventional pre-frying when the moisture content of the potato reached about 10% to maintain the colour of potato chips. Yousif et al. (1999) also found that in vacuum microwave drying, non-enzymatic browning is minimized due to low processing temperatures.

The effects of sugar on the colour of potato chips

There have been various papers discussed on the influence of sugar on the colour of potato chips, Marquez and Añon (1986) investigated the influence of reducing sugars on the color of fried potatoes. Authors found that fructose has a greater effect on the final color of French fries compared with the addition of the same amount of glucose. Whereas, sucrose did not modify the final color appreciably with a similar increase of amount. These results are in agreement with previous studies carried out in model systems (Ashoor and Zent, 1984). However, Leszkowiat et al., 1990, confirmed that the presence of sucrose contributed to the no enzymatic browning in potato chips. Authors mentioned that the presence of sucrose alone also led to colour development.

The objective of this chapter is to investigate the colour of potato crisps with different pre-treatment techniques, pre-dried non-sugar solution dipping and sugar solution dipping and following with conventionally and vacuum frying respectively. The effects of sugar dipping on the colour of potato crisps were much more focused in each condition of frying. The effect of vacuum pressure on the sugar dipping potato crisps is evaluated. The visual pictures of frying potato crisps are also illustrated in this study.

4.2. Materials and methods

4.2.1 General view

There have been various papers using color metering to measure the surface colour of potato chips (Marquez and Añon, 1986; Coffin et al., 1987; Krokida et al., 2001; Mayano et al., 2002). The colour of fried potatoes has been measured usually in units $L^* a^* b^*$, which is an international standard for colour measurements, adopted by the Commission International d'Eclairage (CIE) in 1976. L^* is the luminance or lightness component, which ranges from 0 to 100, and parameter a^* (from green to red) and b^* (from blue to yellow) are the two chromatic components, which range from -120 to 120 (Papadakis et al., 2000).

In food products, the $b*$ value gave a good estimation of the β-carotene content in white fleshed sweet potatoes (Ameny and Wilson, 1997). In fried potatoes, higher $b*$ parameter values gives more yellow products, which is desirable for fried products (Krokida et al., 2001). However, Parameter "*a*" increase is not desired because that means *a* more red product, which is not acceptable for fried potatoes (Krokida et al., 2001). Pedreschi et al. (2005) found a good linear correlation (R^2 = 0.9569) between the acrylamide concentration and "a" parameter in fried potato chips. Acrylamide, a chemical compound created in fried potato products, has been classified as probably carcinogenic in humans; related information about acrylamide is described in **Chapter 6.**

4.2.2 Colour measurement and evaluation

In this study, potato crisp colour was measured by a Chroma Meter (Minolta Co., Japan). The chroma meter instrument is composed of two components, which are the Data processor DP-301 and measuring head **(Figure 4.1)**. The calibration needs to be performed before measuring the colour of potato crisps by placing the tip of the measuring head flat against the surface of the white calibration place. The calibration data was obtained when the measure button was pressed. The second calibration was immediately followed when the tip of measuring head flat was against the Petri dish, which was placed over the white paper and considered as surface measurement for the potato crisp samples. The three colour parameters *L, a, b* of the sample were generated from the data processor when the potato crisp sample was displayed on the Petri dish and at the bottom of the measuring head with a close surface contact and the measure or measuring head's measuring button was pressed. Measurements were taken for 10 crisps for each condition and averaged.

Figure 4.1 The colour meter instrument (Minolta Co., Japan).

The total colour change, ΔE, of each crisp was calculated as:

$$\Delta E = [(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2]^{1/2} \quad \textbf{(4.1)}$$

Where L_o, a_o and b_o are the lightness, redness and yellowness color score, respectively, at time zero. The L, a and b represented the instantaneous individual readings during frying (Nourian and Ramaswamy, 2003).

4.2.3 Kinetics of colour change

Nourian and Ramaswamy (2003) discussed the kinetics of the colour change first-order model, based on changes occurring between the initial and a maximum or a minimum value:

$$k = - [\ln (C_m - C_t) / (C_m - C_o)] / t \qquad \textbf{(4.2)}$$

Where C_t is the colour value of potato crisps after frying at t(time) > 0, C_o is the initial colour value, C_m is the maximum value (m = max) or is the minimum value (m = min) of the colour parameter, t is the time (min) and k is the reaction rate constant at a particular condition (dipping or without dipping), calculated as the slope of the $\ln_e[(C_{max} - C_t) / (C_{max} - C_o)]$ vs. time (t).

4.3 Results and discussions

4.3.1 Effects of sugar concentrations on the colour of pre-drying potato crisps under conventional frying conditions

As described in previous Chapters **(Chapter 2** and **Chapter 3),** dipping sugar solution played an important role in reducing the oil content of potato crisps, in both conventional and vacuum frying. Consideration of the higher sugar concentration solution is an interesting objective in the investigation process. However, the influence of higher sugar concentration may affect the colour of potato crisps as a result of the Maillard reaction when potato chips are frying at high temperature. Therefore, the effect of different sugar concentrations on the colour; the most attractive appearance of quality of potato crisps could not be ignored in this study.

4.3.1.1 Effect of sugar concentration on the lightness of pre-dried and fried potato crisps

Table 4.1 and Figure 4.2 show the lightness of frying potato slices after pre-drying and subsequently (PSSD) dipping in different solutions, which are 23.07wt% and 30 wt% The lightness of pre-drying potato slices without sugar dipping are also presented in **Table 4.1 and Figure 4.2.**

As shown in **Figure 4.2 and Table 4.1,** the lightness of potato crisps decreases with frying time in three conditions of sugar concentrations. The lightness of potato crisps with sugar dipping solution 23.07 wt % is not significantly ($P > 0.05$) different compared with pre-drying and non-sugar dipping (PNSD) potato crisps. Whereas, the crisps dipped in sugar solution 30 wt% had a significant difference ($P < 0.05$) on the lightness with crisps dipped in 23.07wt % sugar solution one and PNSD frying potato slices The lightness of potato crisps with sugar solution dipping 30wt % was lower compared with crisps with

Table 4.1 The lightness of the pre-dried potato crisps treated in different sugar solutions.

(Standard "*L*" colour number =95.29)

Frying time (min)	Without dipping		Dipping with sugar 23.07% (w/w)		Dipping with sugar 30% (w/w)	
	Lightness	Stdev	Lightness	Stdev	Lightness	Stdev
0	77.46	1.761	77.46	1.761	77.46	1.761
1	72.97	2.467	72.04	3.710	72.54	1.800
2	68.56	5.012	71.45	2.490	72.10	2.931
3	68.22	3.236	72.46	3.057	63.68	2.575
4	67.00	2.897	68.11	3.725	59.47	4.250
5	68.08	2.313	65.55	2.153	52.55	2.070
6	64.77	1.720	61.09	3.134	52.89	3.886

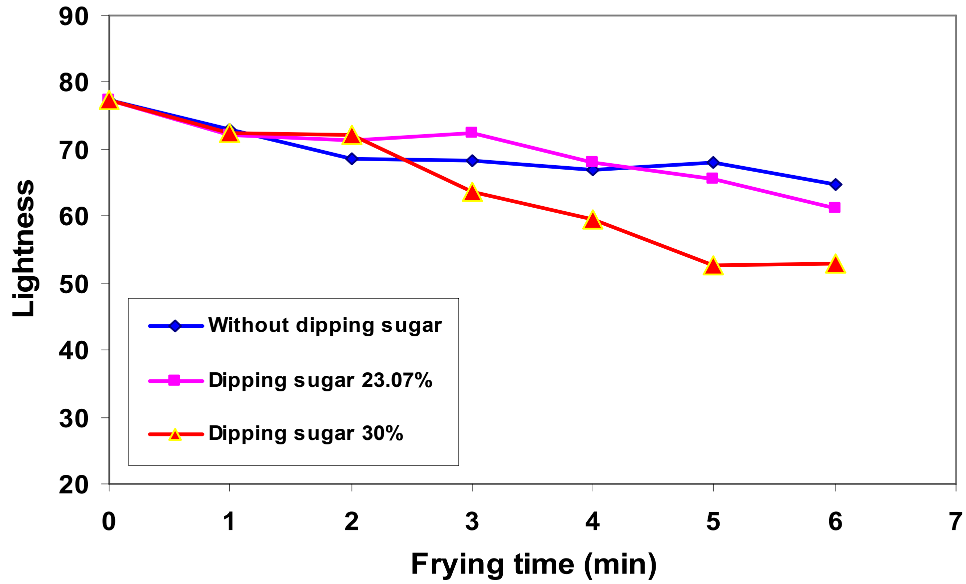

Figure 4.2 The lightness of pre-dried potato crisps with different sugar concentrations.

23.7 wt% sugar solution dipping. The mean values, which were obtained from the statistical analysis, the lightness of potato crisps with sugar solution dipping 30wt % and 23.7wt % are 64.4 and 69.7, respectively.

4.3.1.2 Effect of sugar concentration on the redness of pre-dried and fried potato crisps

In colour analysis, parameter "*a*" indicated the redness of the sample. The "*a*" parameter of potato crisps after pre-drying, non dipping, and dipped in two sugar solutions 23.07% and 30% (w/w) is presented in **Table 4.2**.

As shown in **Figure 4.3 and Table 4.2,** the redness of potato crisps increased with frying time in three conditions of concentration of sugar solutions, including without dipping sugar (concentration of sugar = 0%). The highest number of parameter "*a*" was found at the highest concentration of dipping sugar solution. Parameter "*a*" increase is not desired because that means a more red product, which is not acceptable for fried potatoes (Krokida et al., 2001). In statistical analysis**,** the parameter "*a*" was found at the highest concentration of dipping sugar solution. Parameter "*a*" increased significantly (P< 0.05) per each minute frying time in all three cases: non-dipping, dipping 23.07% and 30 wt % sugar solution potato crisps. There is no significant difference between the redness, "*a*" parameter of frying potato slices with dipping in sugar solution of 23.07% compared with the non-dipping one (P >0.05). In contrast, there was a significant difference between the potato crisps with sugar solution dipping 30wt% and non-dipping sugar solution potato crisps. Similarly, the crisps with 23.07% and 30 wt % sugar dipping are significantly different in redness (P< 0.05) and the higher number appeared for the crisps with dipping sugar 30 wt % solution **(Table 4.2 and Figure 4.3).**

Table 4.2 The redness of the pre-dried potato crisps treated in different sugar solutions.

(Standard "*a*" colour number = + 0.01)

Frying time (min)	Without dipping		Dipping with sugar 23.07% (w/w)		Dipping with sugar 30% (w/w)	
	Parameter "*a*"	Stdev	Parameter "*a*"	Stdev	Parameter "*a*"	Stdev
0	-2.53	0.232	-2.53	0.232	-2.53	0.232
1	-1.91	0.395	-1.62	0.545	-0.95	0.330
2	-0.83	0.723	-1.17	0.323	0.93	1.580
3	2.01	1.149	0.87	2.148	6.61	2.361
4	3.76	2.049	4.38	2.516	9.51	2.049
5	4.46	1.796	7.22	1.365	9.87	1.543
6	5.16	1.471	8.58	1.984	9.74	1.385

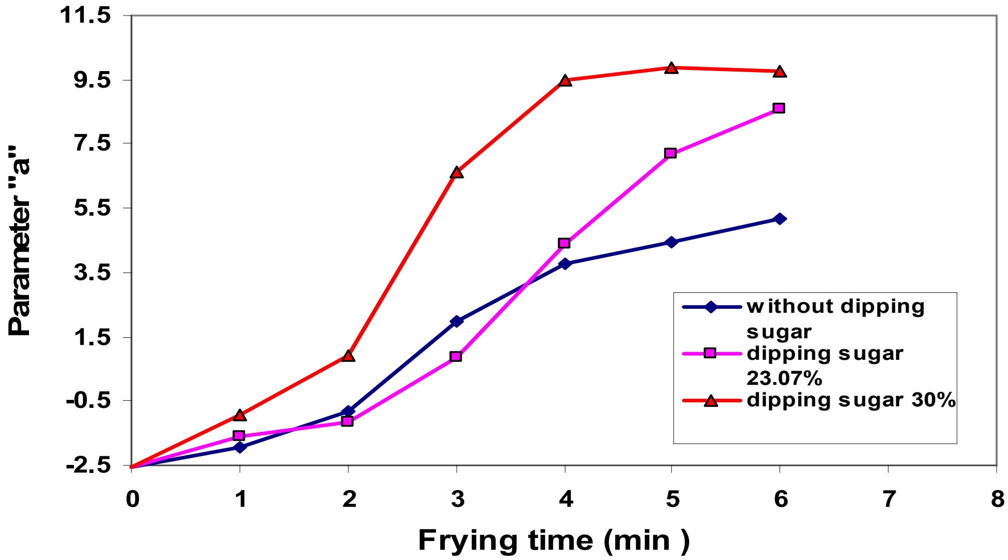

Figure 4.3 The redness of potato crisps with different sugar concentrations.

4.3.1.3 Effect of sugar concentration on the yellowness of pre-dried and fried potato crisps

The yellowness of food product is specified by the parameter "*b*" in colour measurement. **Table 4.3** and **Figure 4.4** present the yellowness of potato crisps, which were pre-dried and subsequently dipped in different concentrations of sugar solutions before frying. The data presents the yellowness of crisps from 10 slices measurement for each condition. In general, higher "*b*" parameter values give more yellow products, which is desirable for fried products (Krokida et al., 2001). From **Table 4.3** and **Figure 4.4,** the results show that the yellowness of potato crisps dipping with sugar solution of 23.07% and 30% were not significantly different ($P>0.05$) with the crisps non-dipping. However, the mean value "*b*" parameter of fried potato slices with pre-drying and dipping in the sugar of 23.07 wt% and 30 wt% was slightly less compare with PNSD one, which had the "*b*" value of 16.8, compare with others PSSD frying chips are 15.89 and 15.6, respectively.

Table 4.3 The yellowness of the pre-dried potato crisps treated in different sugar solutions.

(Standard “*b*” colour number = +2.45)

Frying time (min)	Without dipping		Dipping with sugar 23.07% (w/w)		Dipping with sugar 30% (w/w)	
	Parameter “*b*”	Stdev	Parameter “*b*”	Stdev	Parameter “*b*”	Stdev
0	6.25	0.815	6.25	0.815	6.25	0.815
1	10.94	1.182	11.67	1.305	15.16	1.325
2	14.48	1.791	14.45	2.613	18.79	6.769
3	20.55	2.894	16.78	6.561	21.77	3.015
4	22.42	1.660	19.00	3.932	18.65	2.545
5	19.21	6.045	21.88	3.998	14.82	3.699
6	23.77	2.855	21.20	2.263	13.70	3.476

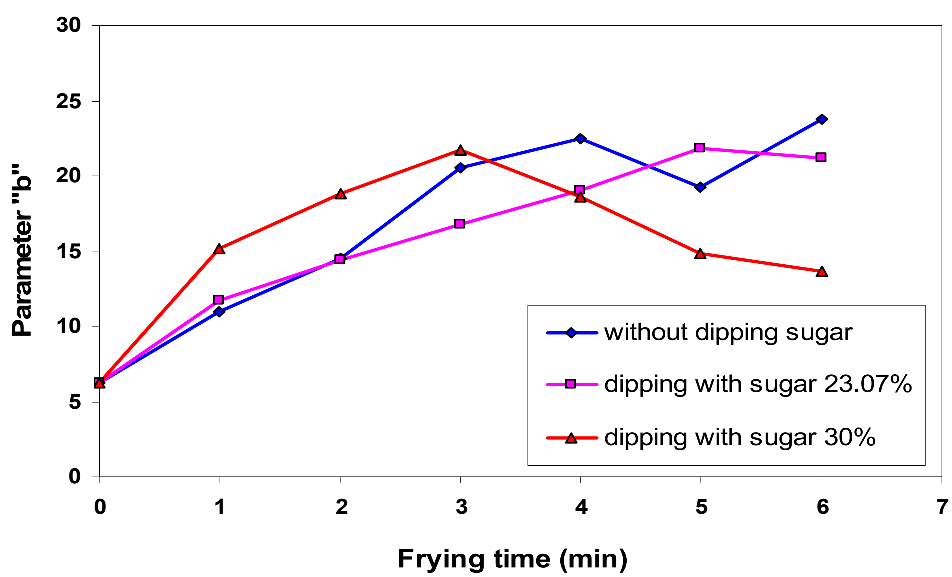

Figure 4.4 The yellowness of pre-dried potato crisps with different sugar concentrations.

4.3.1.4 Effect of sugar concentration on the total colour change of pre-dried and fried potato crisps

The total colour change (ΔE) of potato crisps was calculated based on the equation (6.1). **Table 4.4** and **Figure 4.5** present the ΔE value in frying process of pre-drying potato slices and dipping in the different concentration sugar solutions before frying.

As seen on the **Table 4.4**, the total colour change (ΔE) of pre-drying potato slices are significantly different ($P<0.05$) after each minute of frying, in both cases of sugar solution dipping (23.07wt% and 30wt% sugar solution) and non-dipping potato crisps. There is no significant difference ($P >0.05$) between the ΔE value of potato crisps with sugar solution dipping 23.07 wt% and non-dipping potato crisps. Whereas, the total colour change of potato with dipping 30 wt% sugar solution is significantly different ($P =0.015 <0.05$) compared with non-dipping.

Table 4.4 The colour changes of the pre-dried potato crisps treated in solutions of different sugar concentrations.

(Standard colour number "*L*"=95.29, "*a*" = + 0.01, "*b*"= +2.45)

Frying time (min)	Without dipping	Dipping with sugar solution 23.07wt%	Dipping with sugar solution 30wt%
	ΔE Value	ΔE Value	ΔE Value
0	0.00	0.00	0.00
1	6.53	10.47	10.30
2	12.25	13.97	14.07
3	17.62	16.66	22.68
4	20.26	17.00	24.95
5	17.46	17.61	29.12
6	22.96	21.14	28.47

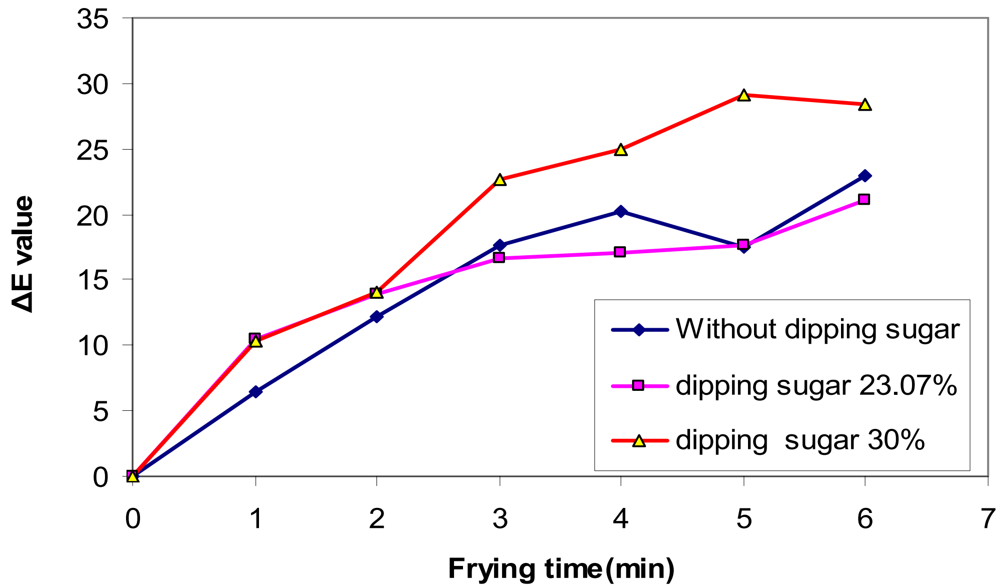

Figure 4.5 The total colour change of pre-dried potato crisps with different sugar concentrations

From the results obtained**,** the chosen sugar concentration is 23.07 wt% as the concentration of sugar dipping solution for pre-drying potato slices applied in this study.

4.3.2 Colour changes of potato crisps under conventional frying

The colour of potato slices without pre-drying and non-dipping sugar (NPNS) during frying process considered as the colour of control samples, which are frying under the atmospheric condition and 180^{o} C, are presented in **Table 4.5**.

Figure 4.6 show the total colour change of control samples. The total colour change of pre-drying non-sugar dipping (PNSD), pre-drying & subsequently sugar dipping (PSSD) samples are also illustrated in this Figure. Similarly as described in the **section 4.3.1.4**, the total colour change of control samples, non pre-drying and non-sugar dipping conventional frying at 180^{o}C, is also significantly different after each minute of frying time.

Table 4.5 The colour of the control potato crisps (non pre-dried and non sugar solution treated (NPNS)) during conventional frying process (180^{o}C).

(Standard colour number "*L*"=90.22, "*a*"=1.58, "*b*"=-5.44)

Frying time (min)	Lightness		Redness		Yellowness	
	Parameter "*L*"	Stdev	Parameter "*a*"	Stdev	Parameter "*b*"	Stdev
0	74.77	0.904	-8.38	0.415	6.25	1.671
1	76.62	1.478	-7.01	0.509	15.16	2.759
2	76.51	2.646	-4.95	1.059	18.79	1.297
3	77.19	1.899	-3.15	1.545	21.77	2.641
4	72.66	3.592	2.94	3.185	18.65	2.880
5	70.16	5.007	5.29	3.866	14.82	3.046

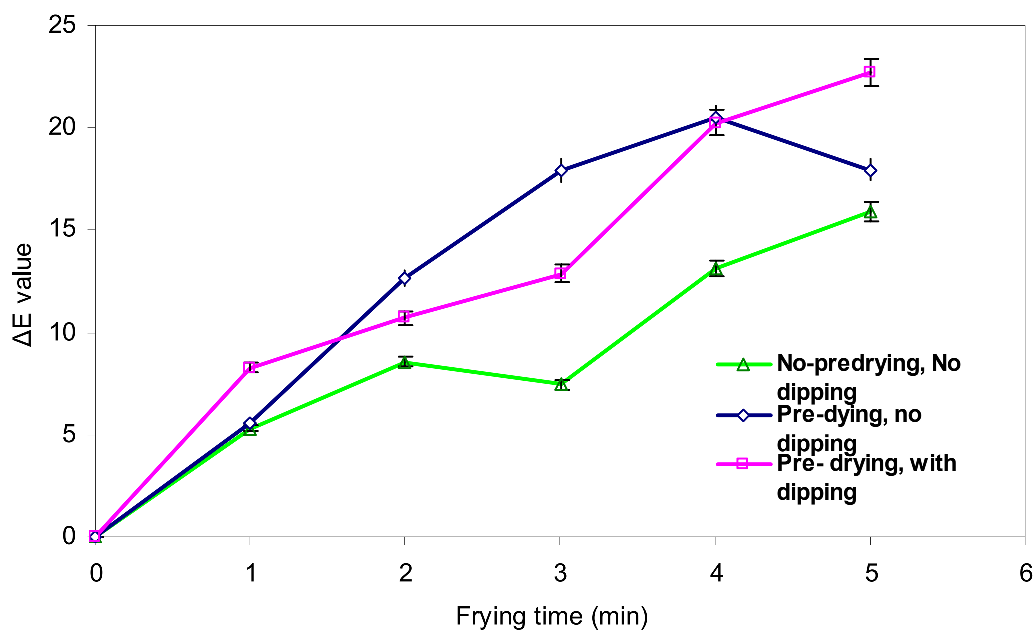

Figure 4.6 Changes in colour of treated and untreated potato crisps during conventional frying at 180^{o}C. *ΔE* value for the total changing in colour.

There was no significant difference in the total colour change between the control sample and PNSD samples ($P > 0.05$). However, there was a significant difference in the total colour change between the control sample and PSSD samples ($P < 0.05$). That means the dipping sugar concentration (23.07wt%) had a significant affect on the colour of potato crisps compared with the control samples when frying at conventional frying with high frying oil temperature 180^{o}C.

4.3.3. Colour changes of potato crisps under vacuum frying

There have been various papers which have discussed the colour of potato chips under conventional frying. Nourian and Ramaswamy (2003) investigated the effect of temperature on the colour of potato chips frying at high temperature at atmospheric condition. Krokida et al. (2001) studied the influence of frying conditions on the colour changes during deep fat frying of french fries. Garayo and Moreira (2002) presented the colour of non-pretreatment potato slices under vacuum frying. However, the colour of potato crisps, which were pre-dried & sugar dipped and fried under vacuum conditions have not been mentioned in the published papers. The objective of this section is to present the effect of sugar solution dipping on the colour of pre-drying & sugar dipping (PSSD) and pre-drying & non-sugar dipping (PNSD) potato crisps with different density of tubers under vacuum frying and compare with the control samples (NPND). The effects of pressure on the colour of PSSD and PDND frying potato slices are also investigated in this study.

4.3.3.1 Colour of potato crisps with vacuum frying- Effects of sugar dipping

The colour of potato crisps may be affected by the density of a tuber as mentioned in **Section 4.1**. There were two densities, which are D = 1.087 ± 0.005 g.ml^{-1} and D = 1.1052 ± 0.0021005 g.ml^{-1} of potato tubers investigated in this study. The effects of sugar dipping and non-sugar dipping on the lightness, redness, yellowness and total colour change of pre-drying potato slices during vacuum frying (120^{o}C, 170mbars) at the densities of potato tuber D=1.087± 0.005 g.ml^{-1} are shown in **Figure 4.7a, b, c, d**; **Table**

4.6, 5.7 and **4.8.** The effects of sugar dipping and non-sugar dipping on the colour of pre-dried potato slices with the same vacuum conditions (120°C, 170mbars) at different densities of potato tuber D = 1.1052 ± 0.0021 g.ml^{-1} are illustrated in **Figure 4.8a, b, c, d**; **Table 4.10** and **4.11.** The colour of control samples, which are sliced potatoes non-pre-dried and non-sugar dipped (NDNS) and fried conventionally at 180°C is presented in the **Figure 4.7a, 4.7b, 4.7c, 4.7d** as well as **Table 4.8** and **4.9.**

From the data presented in **Table 4.9** and **Figure 4.7d,** there was no significant difference (P = 0.050) in the total colour change of potato crisps sugar solution dipped and non-sugar solution dipped at the vacuum frying of 120°C and 170mbars with the density of potato tuber (D = 1.087 ± 0.005 g.ml^{-1}). The ΔE value of potato crisps with non-sugar solution dipped with the mean of 23 is higher than potato crisps with sugar

Table 4.6 The colour of the pre-dried and non sugar solution treated (PDNS) potato crisps during vacuum frying process (120°C, 170mbars).

(Standard colour number "*L*"= 96.41, "*a*"=0.22, "*b*"= 2.04)

Potato density = 1.087 ± 0.005 g.ml^{-1}

Frying time (min)	Lightness		Redness		Yellowness	
	Parameter "*L*"	Stdev	Parameter "*a*"	Stdev	Parameter "*b*"	Stdev
1	91.77	1.865	0.34	0.601	15.03	1.505
2	98.95	4.182	1.79	1.587	-7.05	5.648
3	99.77	6.263	3.65	1.951	-10.24	5.929
4	98.01	5.882	6.67	3.555	-18.01	7.804
5	99.27	2.430	5.40	3.639	-14.50	9.884

Table 4.7 The colour of the pre-dried and sugar solution treated potato crisps during vacuum frying process (120^{o}C, 170mbars).

(Standard colour number "*L*"= 96.41, "*a*"=0.22, "*b*"= 2.04)

Potato density = 1.087 ± 0.005g.ml^{-1}

Frying time (min)	Lightness		Redness		Yellowness	
	Parameter "*L*"	Stdev	Parameter "*a*"	Stdev	Parameter "*b*"	Stdev
1	90.98	7.360	-0.98	2.906	15.60	18.143
2	94.64	4.240	1.85	0.988	4.91	3.350
3	94.27	4.485	3.19	1.501	2.28	3.910
4	89.75	9.324	7.54	2.358	-12.35	8.329
5	93.34	3.802	8.64	2.432	-9.49	9.296

Table 4.8 The colour of non pre-drying and non sugar solution treated potato crisps during conventional frying process (180^{o}C).

(Standard colour number "*L*"= 96.41, "*a*"=0.22, "*b*"= 2.04)

Potato density = 1.087 ± 0.005g.ml^{-1}

Frying time (min)	Lightness		Redness		Yellowness	
	Parameter "*L*"	Stdev	Parameter "*a*"	Stdev	Parameter "*b*"	Stdev
1	95.85	2.313	0.68	0.627	1.39	3.833
2	95.52	4.204	1.20	1.066	4.24	4.631
3	99.17	2.690	3.19	0.802	6.55	2.209
4	96.98	2.146	4.63	1.107	9.21	1.516
5	92.24	2.979	7.57	0.937	9.92	1.544

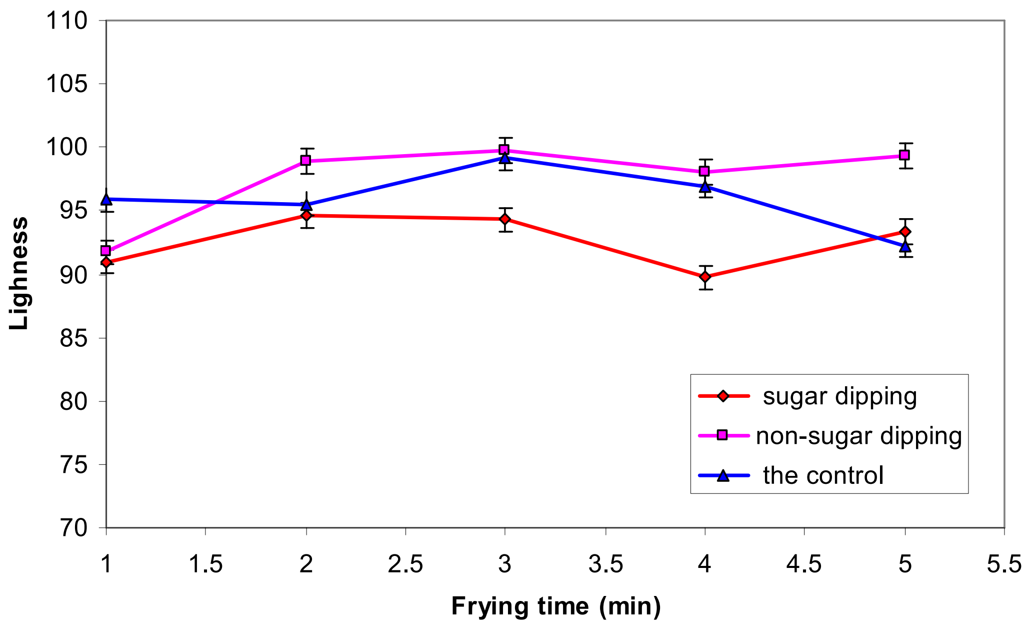

Figure 4.7a Effects of sugar solution dipping on the lightness of the pre-dried potato crisps vacuum fried at 120°C and 170mbars (Potato density=1.087 ± 0.005g.ml^{-1}).

dipping with the mean of 16.4. That means that sugar solution dipping is not a significant factor for the total colour change of potato crisps under vacuum frying (170mbars) at low temperature at 120^0 C obtained from this study with the density of potato tuber 1.087 ± 0.005 g.ml^{-1}.

As mentioned in **Section 4.1,** the colour of potato chips may be influenced by the density of tubers. In this study, the lightness and redness of potato slices under vacuum frying had a contrary result from two tuber densities, which are 1.087±0.005 and 1.1052±0.0021 g.ml^{-1}. The potato slices with the density of 1.087±0.005 g.ml^{-1} displayed a significant difference in lightness but did not display a significant difference in redness of PSSD and PNSD potato crisps vacuum fried. Whereas, potato crisps with the density of 1.1052± 0.0021g.ml^{-1} were not significantly different in lightness, but they were significantly different in redness of PSSD and PNSD potato crisps vacuum fried **(Table 4.10, Figures 4.8a-4.8c).** Probably, greater density may be caused by a larger content of solids, which

Table 4.9 The colour changes of the potato crisps treated with different pre-treatments and frying conditions (Potato density=1.087 ± 0.005g.ml^{-1}).

(Standard number colour *L*= 96.41, *a*=0.22, *b*= 2.04)

Frying time (min)	Non pre-drying non-sugar dipping and conventional frying at 180^0 C (control sample)	Pre-drying non-sugar dipping and vacuum frying (120^0 C, 170mbars)	Pre-drying & sugar dipping and vacuum frying (120^0 C, 170mbars)
	ΔE Value	ΔE Value	ΔE Value
1	4.57757E-16	3.34996E-06	5E-06
2	2.92	23.26	11.66
3	6.63	26.71	14.35
4	8.83	34.21	29.25
5	11.55	30.88	26.97

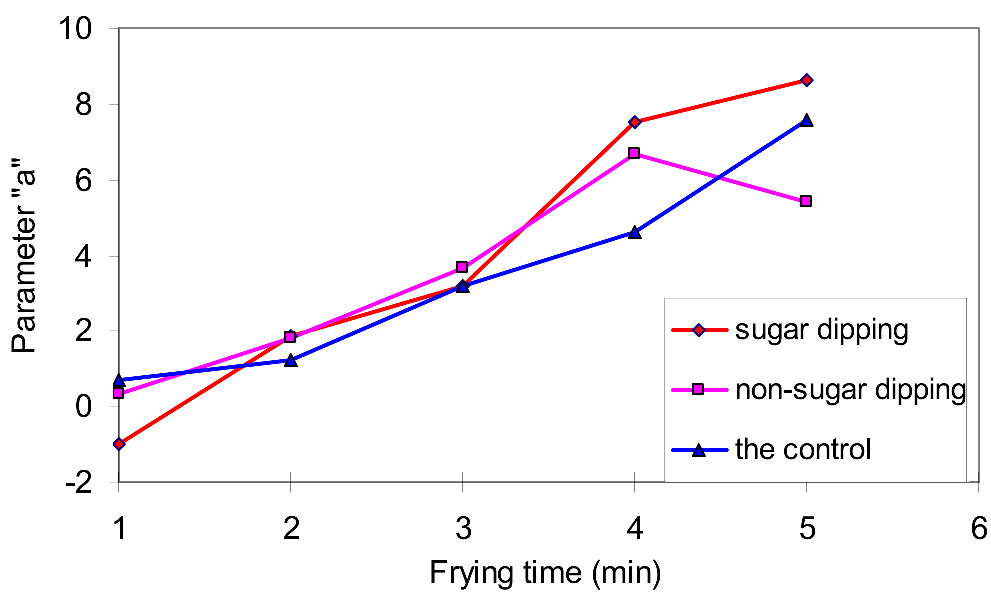

Figure 4.7b Effects of sugar solution dipping on the redness of pre-dried potato crisps vacuum fried at 120°C, 170mbars (Potato density=1.087 ± 0.005g.ml^{-1}).

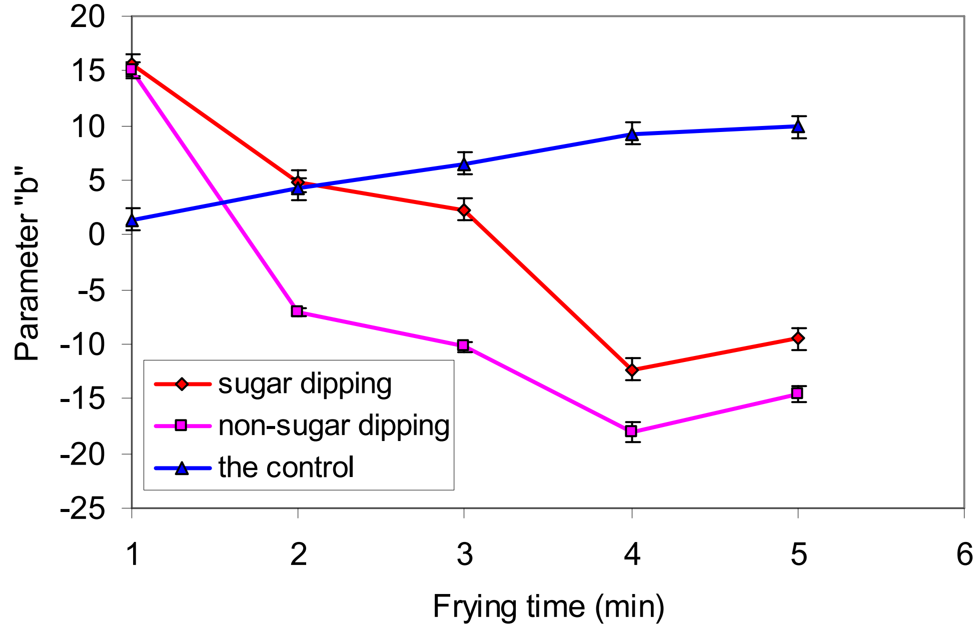

Figure 4.7c Effects of sugar solution dipping on the yellowness of pre-dried potato crisps vacuum fried at 120°C, 170mbars (Potato density =1.087 ± 0.005g.ml^{-1}).

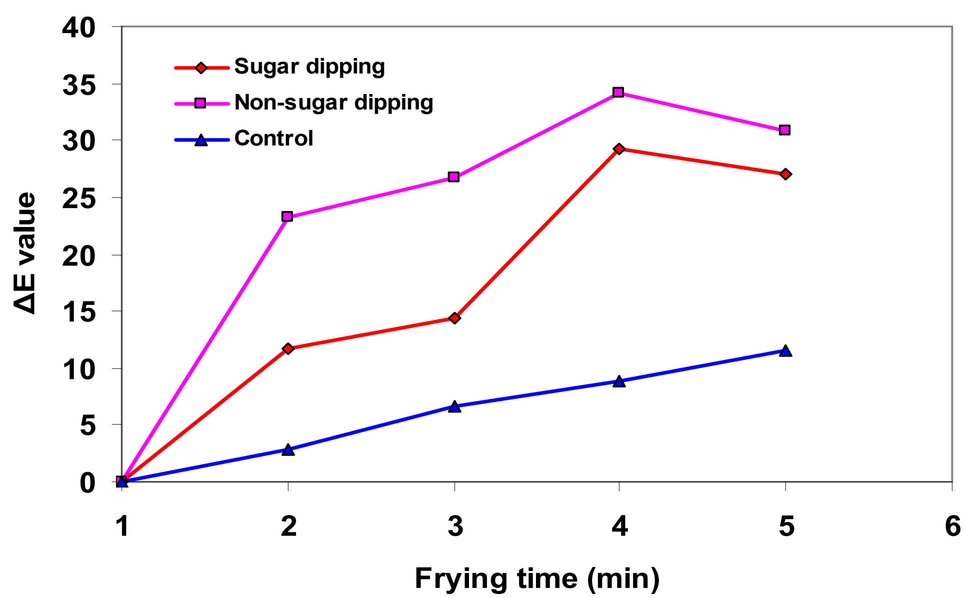

Figure 4.7d Effects of sugar solution dipping on the total colour change of pre-dried potato crisps vacuum fried at 120°C, 170mbars (Potato density =1.087 ± 0.005g.ml^{-1}).

Table 4.10 The colour of the pre-dried and non-sugar solution treated potato crisps during vacuum frying process (120°C, 170mbars).

(Standard colour number *L*= 96.41, *a*=0.22, *b*= 2.04)

(Potato density = 1.1052 ± 0.0021g.ml^{-1}).

Frying time (min)	Lightness		Redness		Yellowness	
	Parameter "*L*"	Stdev	Parameter "*a*"	Stdev	Parameter "*b*"	Stdev
0	84.82	1.404	-7.48	0.773	37.33	2.804
1	75.35	3.694	-4.25	1.155	37.06	3.413
2	76.56	2.407	-2.75	0.491	35.42	6.855
3	72.51	4.107	-2.29	0.907	36.43	3.080
4	73.57	3.080	-4.23	0.602	34.96	3.062
5	76.54	2.994	-3.33	0.745	36.94	1.614
6	73.83	3.844	-2.47	0.553	32.76	3.775

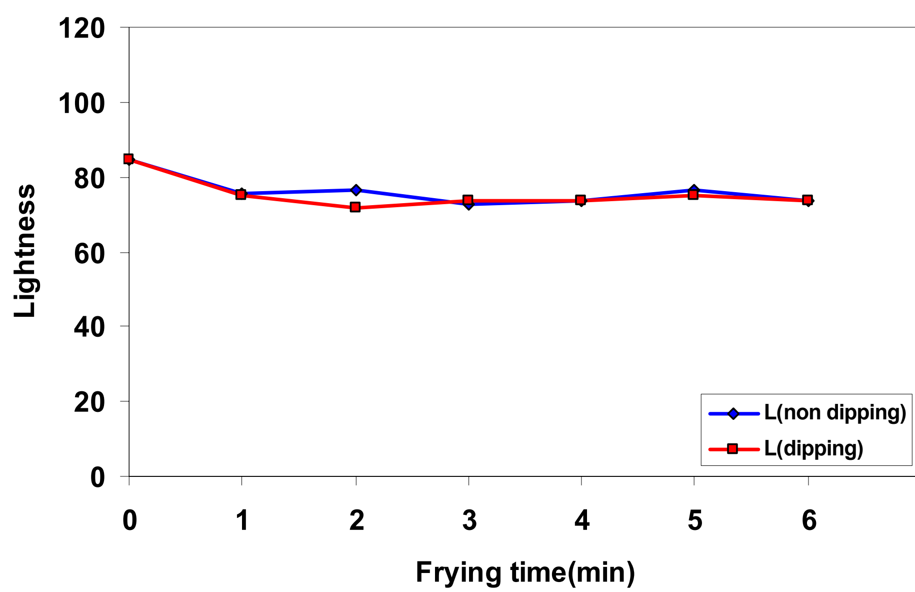

Figure 4.8a Effects of sugar solution dipping on the lightness of pre-dried potato crisps vacuum fried at 120°C, 170mbars (Potato density = 1.1052 ± 0.0021 g.ml^{-1}).

Table 4.11 The colour of the pre-dried and sugar solution treated (PSSD) potato crisps during vacuum frying process (120°C, 170mbars).(Standard colour number *L*= 96.41, *a*=0.22, *b*= 2.04 and potato density = 1.1052 ± 0.0021 g.ml^{-1}).

Frying time (min)	Lightness		Redness		Yellowness	
	Parameter "*L*"	Stdev	Parameter "*a*"	Stdev	Parameter "*b*"	Stdev
0	84.82	1.404	-7.48	0.773	37.33	2.804
1	75.15	3.120	-3.47	0.998	38.04	1.960
2	71.89	5.436	-2.33	0.492	33.92	3.963
3	73.63	2.437	-2.27	0.596	32.72	2.126
4	73.83	3.233	-1.67	0.522	30.52	3.506
5	74.85	2.731	-3.34	0.251	32.28	2.237
6	73.42	2.576	-0.18	0.547	30.27	4.035

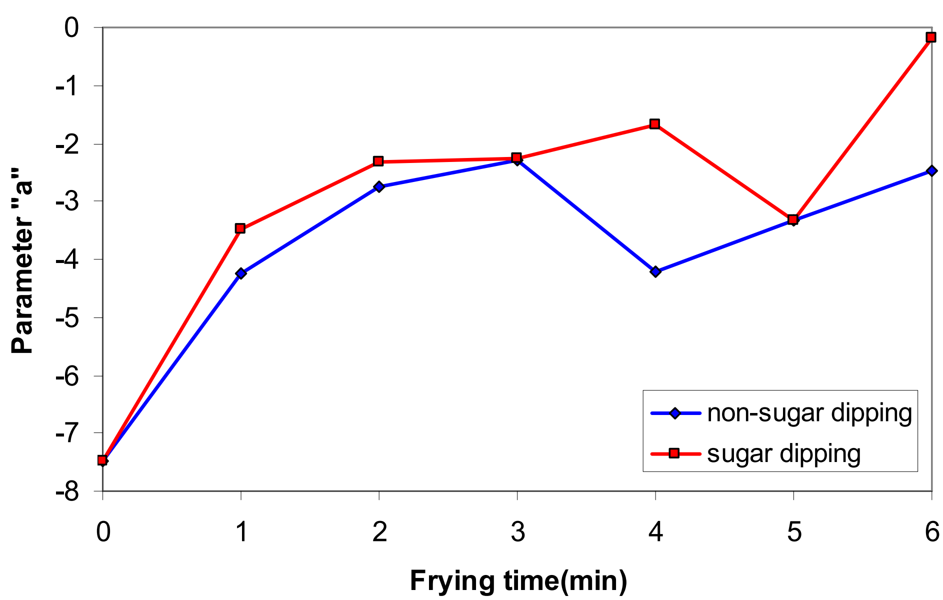

Figure 4.8b Effects of sugar solution dipping on the redness of the pre-dried potato crisps vacuum fried at 120°C and 170mbars (Potato density = 1.1052 ± 0.0021 g.ml^{-1}).

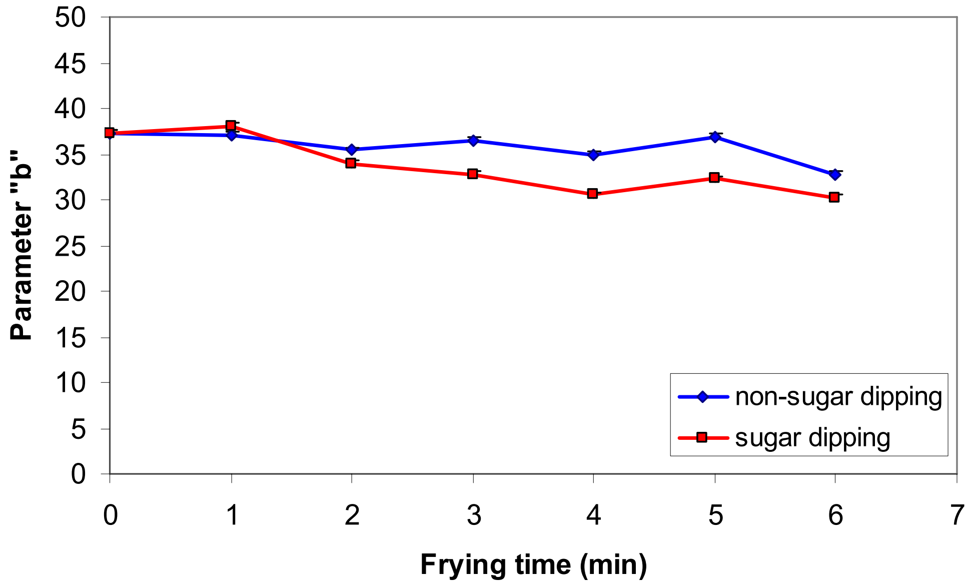

Figure 4.8c Effects of sugar solution dipping on the yellowness of the pre-dried potato crisps vacuum fried at 120°C, and 170mbars (Potato density = 1.1052 ± 0.0021 g.ml^{-1}).

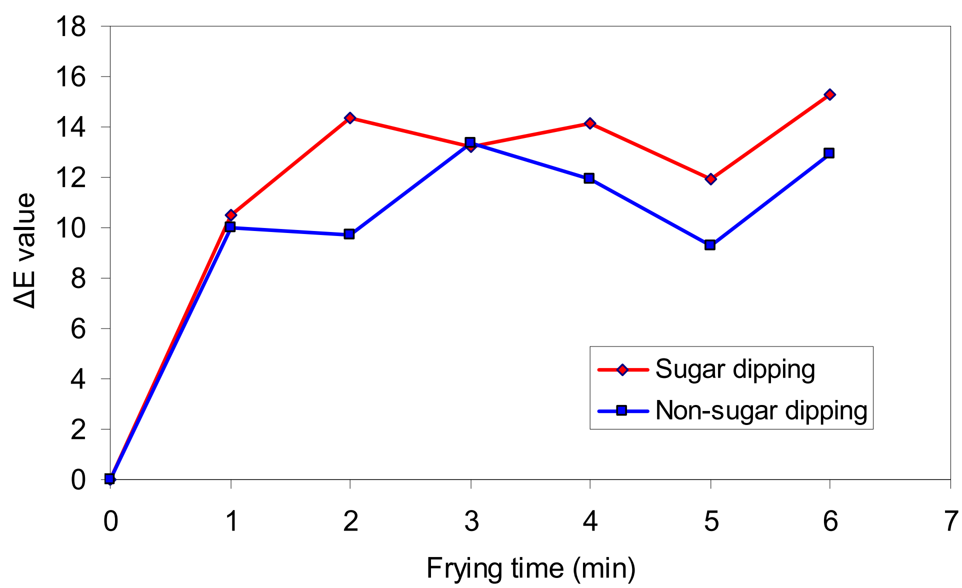

Figure 4.8d Effects of sugar solution dipping on the total colour change of the pre-dried potato crisps vacuum fried at 120°C and 170mbars (Potato density = 1.1052 ± 0.0021 g.ml^{-1}).

are composed of larger reducing sugars, protein and enzymes may cause the Mallard reaction and caramel production affected the redness of potato crisps.

Therefore, a significant difference in redness can be observed in this case. With a density of 1.1052 ± 0.0021 g.ml^{-1}, there was a significant difference ($P=0.039 <0.05$) in the total colour change of PSSD and PNSD potato crisps during vacuum frying at 120^{o}C and at 170mbars. In contrast, with the density of 1.087 ± 0.005 g.ml^{-1}, there was no significant difference in the total colour change of PSSD, PNSD and the control samples respectively.

At 5 minutes frying time with the same one potato tuber

The density of the tuber and the storage conditions may affect the colour of the potato crisps. To achieve comparable data potato crisps prepared from one tuber (density of 1.08 g.ml^{-1}) were fried for 5 minutes at either vacuum conditions (120^{o}C, 170mbars) or under conventional frying conditions at 180^{o}C (see **Figure 4.9)**. The results show that the

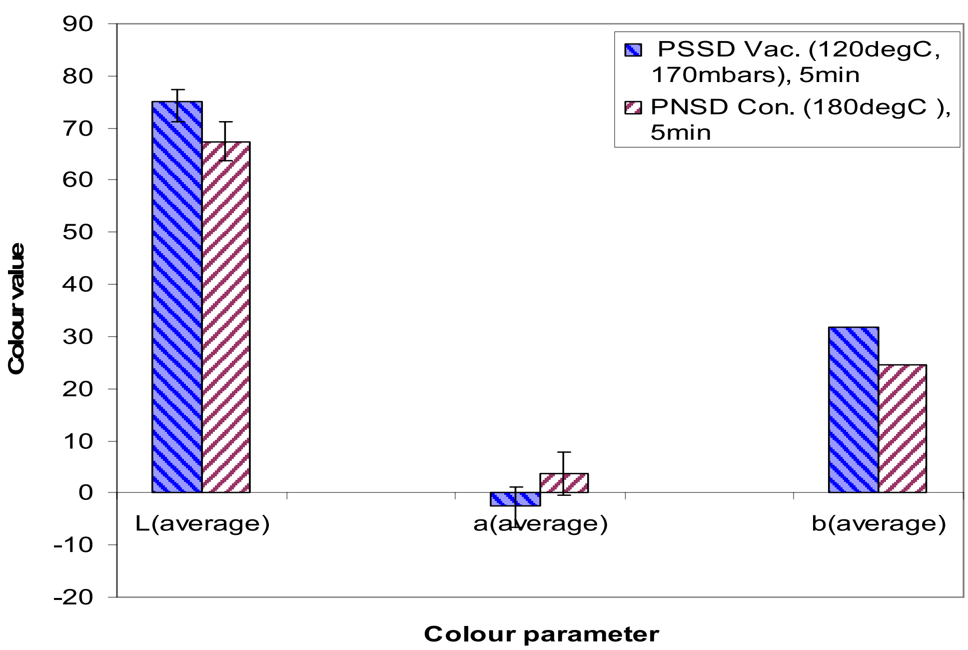

Figure 4.9 Colour of potato crisps fried at 5 minutes under either the conventional or the vacuum frying conditions.

vacuum fried PSSD potato crisps were advantageous compared to PNSD potato crisps fried in the conventionally way. Obviously, the lightness and yellowness of the PSSD potato crisps (vacuum fried) were higher while the redness ("*a*" value) was lower than that of PNSD conventionally fried. In the previous experiments, which were presented in **Sections 4.3.1 and 4.3.2,** the colour values and the total color changes of the PNSD treated samples and the control samples (NPND) were not significantly different compared to the conventional frying. The data seems to confirm that the vacuum frying with the pre-treatment PSSD presents an advantage in colour appearance compared to the control sample and that of the PNSD during conventional frying.

4.3.3.2 Effect of vacuum pressure on the colour of pre-dried and sugar solution dipped, vacuum fried potato slices

The colour data of pre-dried and sugar dipped potato slices fried at 120^0C with vacuum pressures 50mbars, 150mbars are presented in **Tables 4.12 and 4.13**, respectively.

Table 4.12 Colour of the pre-dried and sugar solution treated potato crisps during vacuum frying process (120^oC, 50mbars).

(Standard colour number "*L*"= 96.41, "*a*"=5.3, "*b*"= -3.27)

D = 1.0871 ± 0.0050 $g.ml^{-1}$

Frying time (min)	Lighness		Redness		Yellowness	
	Parameter "*L*"	Stdev	Parameter "*a*"	Stdev	Parameter "*b*"	Stdev
0	84.82	1.404	-7.48	0.773	37.33	2.804
2	79.41	2.166	-0.61	0.371	36.26	2.057
4	77.11	3.115	0.32	0.811	29.49	2.664
5	73.39	3.232	1.52	0.310	29.70	3.019
6	73.76	1.995	1.22	0.404	28.97	2.570
8	74.88	3.815	2.30	0.706	26.73	5.732

Table 4.13 Colour of the pre-dried and sugar solution treated potato crisps during vacuum frying process (120^{o}C, 150mbars).

(Standard colour number "*L*"= 96.41, "*a*"=5.3, "*b*"= -3.27)

Density of potatoes = 1.0871 ± 0.0050g.ml^{-1}

Frying time (min)	Lighness		Redness		Yellowness	
	Parameter "*L*"	Stdev	Parameter "*a*"	Stdev	Parameter "*b*"	Stdev
0	84.82	1.404	-7.48	0.773	37.33	2.804
1	78.31	1.544	-2.71	0.367	30.26	2.481
2	77.05	2.022	0.42	0.816	35.26	2.051
3	76.16	2.221	2.33	0.537	32.88	2.242
4	73.50	3.615	2.79	0.748	31.11	2.232
5	76.03	2.279	3.20	0.584	27.31	4.041
6	73.01	2.222	3.78	1.064	29.45	1.950
7	72.96	3.359	4.11	0.657	27.72	3.521
8	73.36	3.344	4.34	1.117	28.28	2.341

Figures 4.10a, 4.10b and **4.10c** also illustrate the same data under both vacuum pressures 50mbars and 150mbars respectively. **Figure 4.10d** and **Table 4.14** show the total colour changes of the pre-dried and sugar solution dipped potato crisps (fried at 120^{0}C under vacuum pressures 50mbars, 150mbars).

From the statistical analysis shown in **Table 4.14**, potato crisps fried under two different vacuum pressures 50mbars and 150mbars respectively display a significant difference in the total colour change ($P<0.05$). This difference was probably caused by the significant difference in the "*a*" value ($P<0.05$); whereas "*L*" and "*b*" values did not change so significantly between them. The mean value of the parameter "*a"* with vacuum pressure 50mbars was smaller (-0.48) compared to 150mbars pressure, which had a mean value of

1.18. This result suggests that vacuum frying with "*a*" lower vacuum pressure may produce lower contents in acrylamide toxin in potato crisps. This is due to the high correlation of parameter "*a*" with acrylamide concentration formation in potato crisps as mentioned above in early part of **Section 4.2.**

Figure 4.11a demonstrates the resulting colour of the pre-dried and sugar solution dipped potato crisps after 5 minutes of frying at 120^0C and under different pressures 50 mbars, 100 mbars and 150mbars respectively**.** The lightness and yellowness of potato crisps were only slightly different (P>0.05) for different pressures and for the same frying time (5min). The redness was significantly different (P<0.05) when potato slices were fried at different pressures (50, 100 and 150mbars) for the same frying time of 5 minutes. This indicates that the pressure is a significant factor here. The lowest value of redness was observed for the lowest pressure (50mbars) used, and the highest value in parameter "*a*" was observable for the highest pressure (150mbars). It seems that for a smaller value of "*a*" parameter, the samples need to be fried at a lower pressure (**Figure 4.11b**).

Table 4.14 Statistical analysis on the results for the colour of the pre-dried and sugar solution treated potato crisps during vacuum frying at 120^{o}C under different pressures (50 and 150 mbars).

(Standard colour number "*L*"= 96.41, "*a*"=5.3, "*b*"= -3.27

and density of potatoes= 1.0871 ± 0.0050g.ml^{-1})

Parameters	Mean value 50 mbars	Mean value 150 mbars	Samples	Frying time
L	77.23	76.30	NS (P=0.338>0.05)	SN (P=0.004<0.05)
a	-0.46	1.18	SN (P=0.009<0.05)	SN (P=0.000<0.05)
b	31.41	31.46	NS (P=0.948>0.05)	SN (P=0.001<0.001)
ΔE	12.10	13.63	SN (P=0.021<0.05)	SN (P=0.021<0.05)

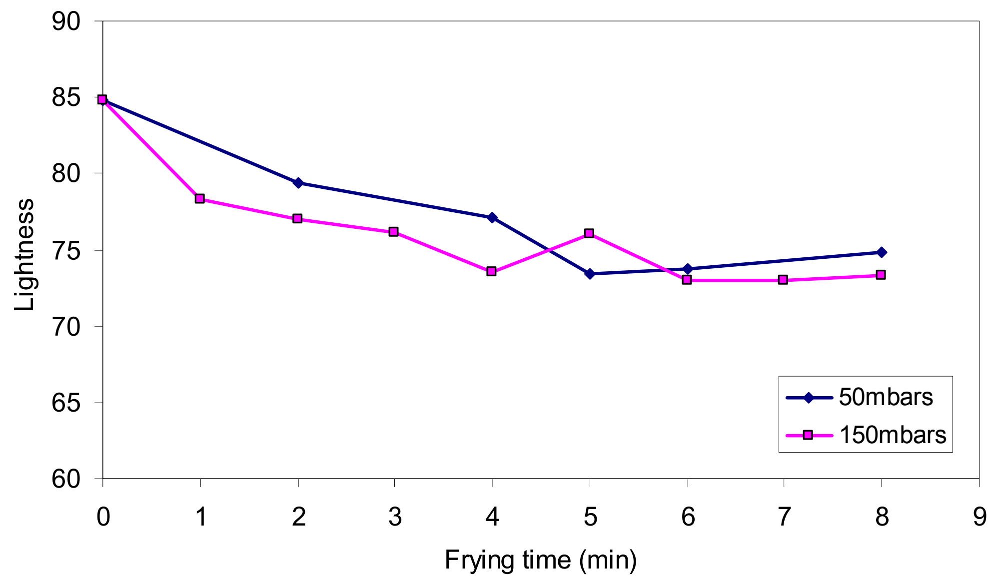

Figure 4.10a Effects of pressure on the lightness of the PSSD potato crisps, followed by vacuum fried at 120°C (Potato density = 1.087 ± 0.005g.ml^{-1}).

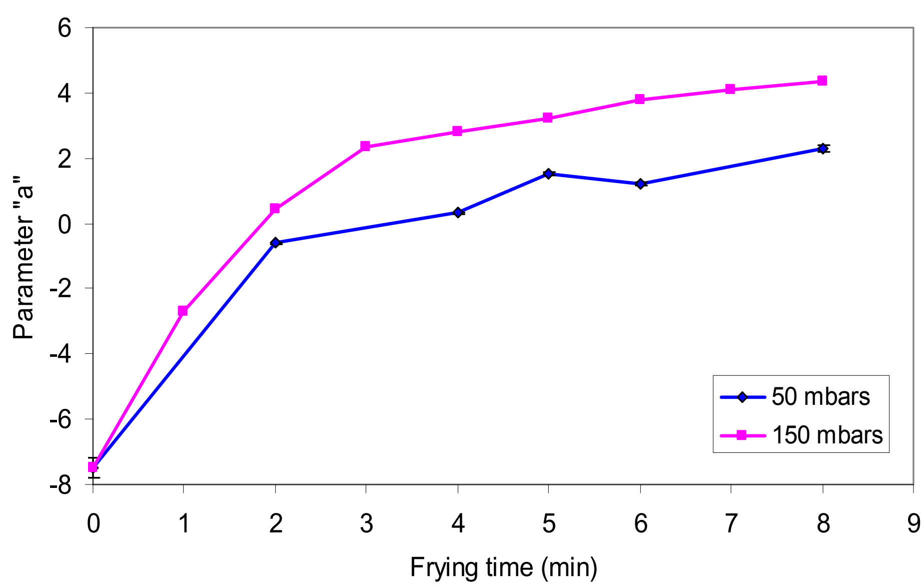

Figure 4.10b Effects of pressure on the redness of the PSSD potato crisps followed by vacuum fried at 120°C (Potato density = 1.087 ± 0.005g.ml^{-1}).

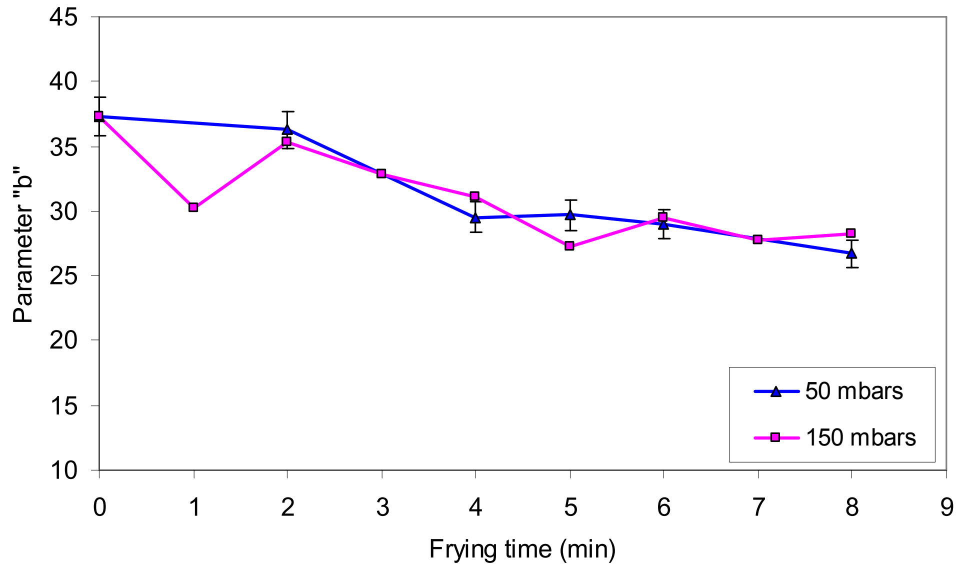

Figure 4.10c Effects of pressure on the yellowness of the pre-dried and sugar solution dipped potato crisps followed by vacuum fried at 120°C (Potato density = 1.087 ± 0.005g.ml^{-1}).

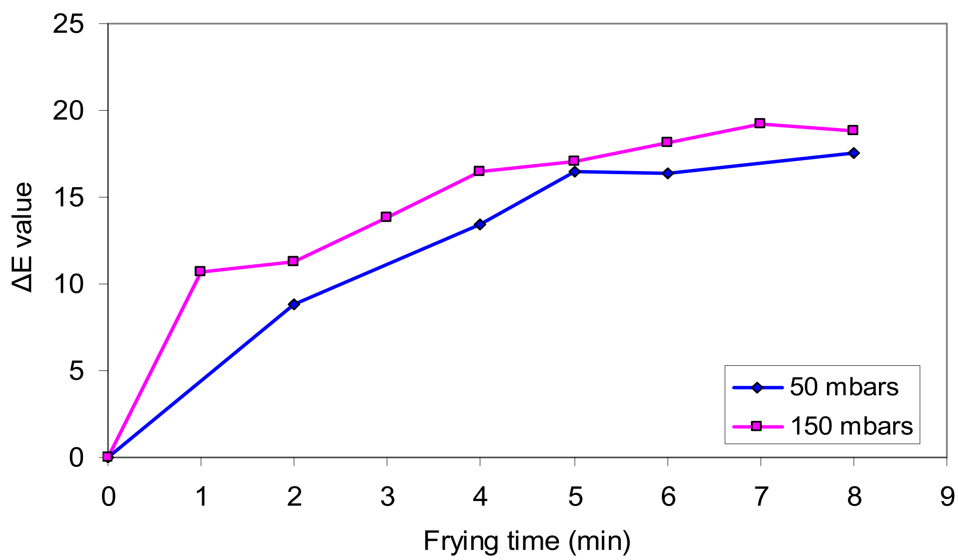

Figure 4.10d Effects of pressure on the total colour change of the pre-dried and sugar solution dipped potato crisps followed by vacuum fried at 120°C (Potato density = 1.087 ± 0.005g.ml^{-1}).

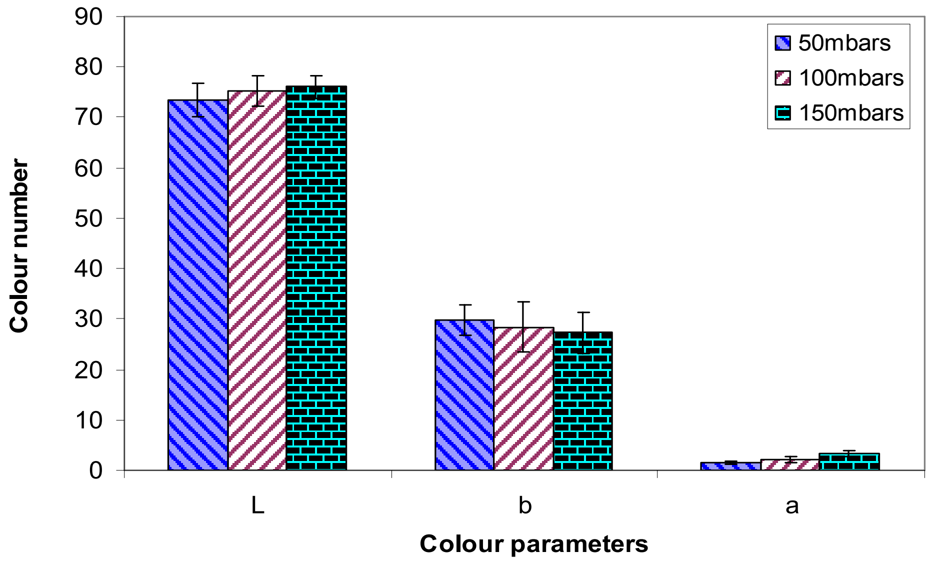

Figure 4.11a Colour parameters of the pre-dried and sugar solution dipped potato crisps after 5 minutes of frying time at 120°C and under different pressures 50 , 100 and 150mbars respectively.(Standard number "*L*"= 96.41, "*a*"=5.3, ""*b*= -3.27; Potato density = 1.087 ± 0.005g.ml^{-1}).

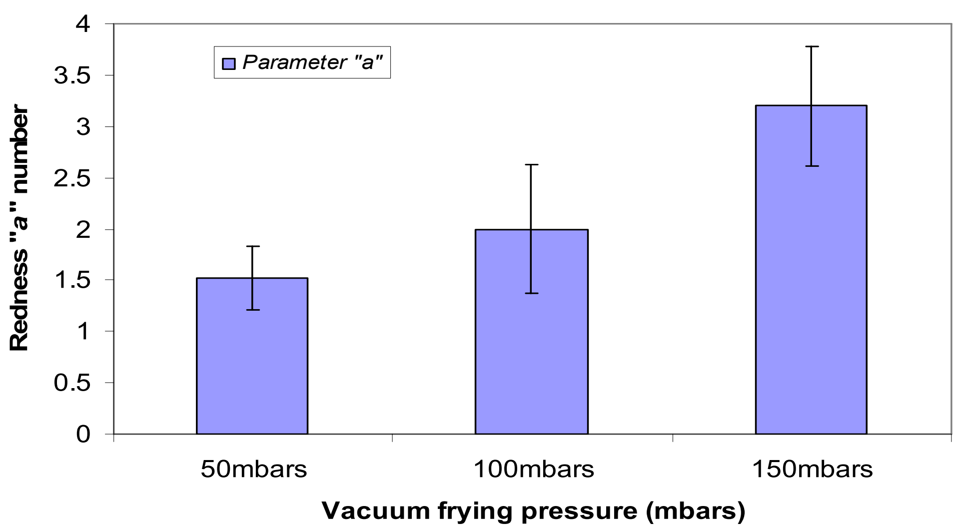

Figure 4.11b Colour parameters "*a*" of pre-dried and sugar solution dipped potato crisps after 5 minutes of frying time at 120°C and under different pressures 50 , 100 and 150mbars respectively.(Standard number "*L*"= 96.41, "*a*"=5.3, "*b*"= -3.27; Potato density = 1.087 ± 0.005g.ml^{-1}).

4.3.4 Colour changes of potato crisps presented using colour photos

4.3.4.1 Conventional frying

Conventional frying at the start (0 frying time)

Figure 4.12a Photo of potato crisps just after blanching.

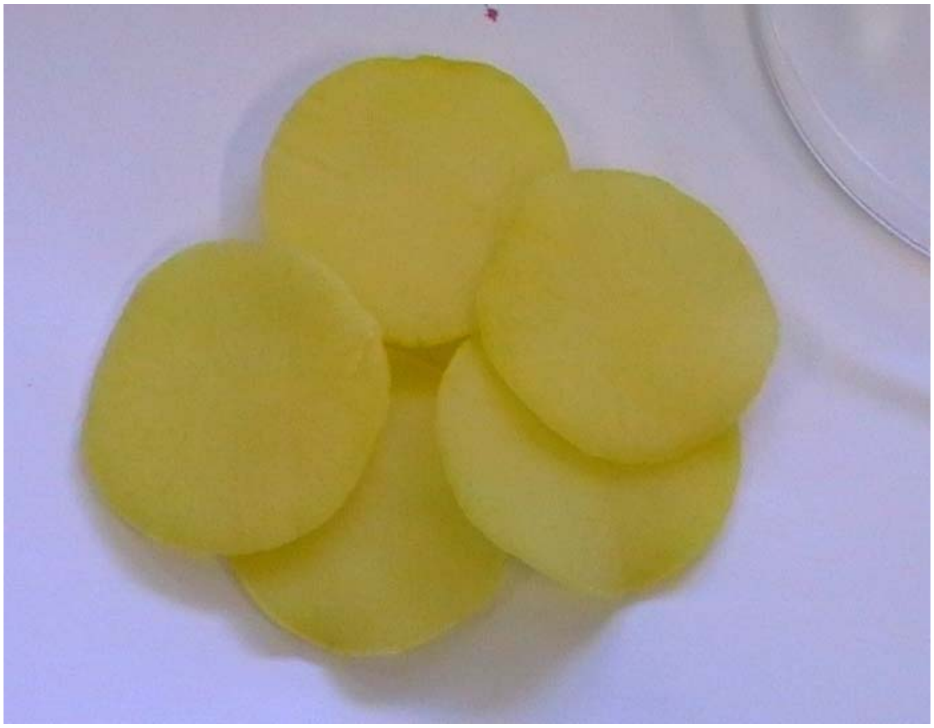

Figure 4.12b Potatoes after drying

Conventional frying for 1 minute

Figure 4.13a Control sample crisps after 1 minute of frying.

Figure 4.13b Potato crisps pre-dried, no-sugar solution dipping, fried for 1 minute.

Figure 4.13c Potato crisps pre-dried and sugar solution dipped after 1 minute of frying.

Conventional frying for 2 minutes

Figure 4.14a Control sample crisps after 2 minutes of frying.

Figure 4.14b Potato crisps pre-dried, no sugar solution dipping fried for 2 minutes.

Figure 4.14c Potato crisps pre-dried and sugar solution dipped fried for 2 minutes.

Conventional frying for 3 minutes

Figure 4.15a Potato crisps (control samples) no pre-dried and no sugar solution dipping fried for 3 minutes.

Figure 4.15b Potato crisps pre-dried, no sugar solution dipping fried for 3 minutes.

Figure 4.15c Potato crisps pre-dried and sugar solution dipped fried for 3 minutes.

Conventional frying for 4 minutes

Figure 4.16a Potato crisps (control samples) no pre-dried, no sugar solution dipping, fried for 4 minutes.

Figure 4.16b Potato crisps pre-dried, no sugar solution dipping fried for 4 minutes.

Figure 4.16c Potato crisps pre-dried and sugar solution dipped, fried for 4 minutes.

Conventional frying for 5 minutes

Figure 4.17a Potato crisps (control samples) no pre-dried, no sugar solution dipping, fried for 5 minutes.

Figure 4.17b Potato crisps pre-dried, no sugar solution dipping, fried for 5 minutes.

Figure 4.17c Potato crisps pre-dried and sugar solution dipped, fried for 5 minutes.

4.3.4.2 Vacuum frying

Vacuum frying for 1 minute

Figure 4.18a Potato crisps pre-dried, no sugar solution dipping, fried for 1 minute at 120^{o}C and 170mbars.

Figure 4.18b Potato crisps pre-dried and sugar solution dipping, fried for 1 minute at 120^{o}C and 170mbars.

Vacuum frying for 2 minutes

Figure 4.19a Potato crisps pre-dried, no sugar solution dipping, fried for 2 minutes at 170mbars and 120^{o}C.

Figure 4.19b Potato crisps pre-dried, sugar solution dipping, fried for 2 minutes at 170mbars and 120^{0}C.

Vacuum frying for 3 minutes

Figure 4.20a Potato crisps pre-dried, no sugar solution dipping, fried for 3 minutes at 170mbars and 120^{o}C.

Figure 4.20b Potato crisps pre-dried, sugar solution dipping, fried for 3 minutes at 170mbars and 120^{o}C.

Vacuum frying for 4 minutes

Figure 4.21a Potato crisps pre-dried, no sugar solution dipping, fried for 4 minutes at 170mbars and 120^{o}C.

Figure 4.21b Potato crisps pre-dried, sugar solution dipping, fried for 4 minutes at 170mbars and 120^{o}C.

Vacuum frying for 5 minutes

Figure 4.22a Potato crisps pre-dried, no sugar solution dipping, fried for 5 minutes at 120^{o}C and 170mbars.

Figure 4.22b Potato crisps pre-dried, sugar solution dipping, fried for 5 minutes at 120^{o}C and 170mbars.

4.3.4.3 Vacuum frying for 5 minutes under different vacuum pressures

Figure 4.23a Potato crisps pre-dried, no sugar solution dipping, fried for 5 minutes at 120°C and 170mbars.

Figure 4.23b Potato crisps pre-dried, no sugar solution dipping, fried for 5 minutes at 120°C and 100mbars.

Figure 4.23c Potato crisps pre-dried, no sugar solution dipping, fried for 5 minutes at 120°C and 50mbars.

4.3.5 Kinetics of the colour changes

The kinetics of total colour changes with different pre-treatment techniques as a function of frying time are fitted with high correlation coefficients (R^2= 0.8-0.9) under conventional frying using the model suggested by Nourrian and Ramaswamy (2003) (**equation 4.2**) (Krokida et al., 2001). **Figure 4.24** presents the kinetics of total colour changes of potato crisps with different pre-treatment techniques during frying under conventional conditions.

The brown colour of potato chips is formed by a reaction between reducing sugars and amino acids (Sijbring and Velde, 1969). This brown colour of potato chips is formed when the moisture content decreases to below 6-12 wt%. The starting point of the discoloration depends on the frying oil temperature and on the content of reducing sugar in the potatoes. However, in the final product fried in the conventional fryer to the moisture content below 2 wt% the browning is more or less independent of the frying oil temperature but depends on the reducing sugar content of the potatoes.

In this study, the pre-dried potato crisps were dipped in the sugar solution before frying. The total change in colour of potato crisps during frying with different condition treatments are presented in **Figure 4.6** and the kinetics plots shown in **Figure 4.24**. The total colour change of potato crisps (**Figure 4.6)** was directly related to the processing time and the treatment techniques. Obviously, the potato crisps with pre-dried treatment and sugar solution dipped (PSSD) had greater change in colour compared with the control samples, probably cause by the addition of sugar. Whereas, the pre-dried potato crisps without dipping (PNSD) displayed different behaviour compared to PSSD samples in different periods of frying time, probably caused by the effects of moisture content and sugar content in each sample, as Sijbring and Velde (1969) mentioned before. At 4-6 minutes (240 seconds) frying time the final moisture content of both pre-dried un-dipped and dipped samples were less than 2%. The change in colour depends on the reduced sugar content, which was obtained from the sucrose hydrolysation (Leszkowiat et al., 1990). Moreover, removal of water during frying could limit sucrose hydrolysis (Leszkowiat et al., 1990). These phenomena can explain the behavior of the pre-dried sugar dipped samples, which had less change of color compared to the pre-dried, un-dipped during the period of time from 1.30 to 4 minutes (90 to 240 seconds), where the rate of water loss is greater in sugar solution dipped samples compared to the un-dipped samples **(Figure 2. 8).**

The kinetics of the total colour change of the fried potatoes has been shown to follow a modifed first-order model (see **Figure 4.24**). The k values, the reaction rate constants at the particular conditions (which are control, dipping and without dipping) are 0.36; 0.39 and 0.41 (min^{-1}), respectively, with reasonably high correlation coeffcients (R^2 are 0.82, 0.90 and 0.81, respectively).

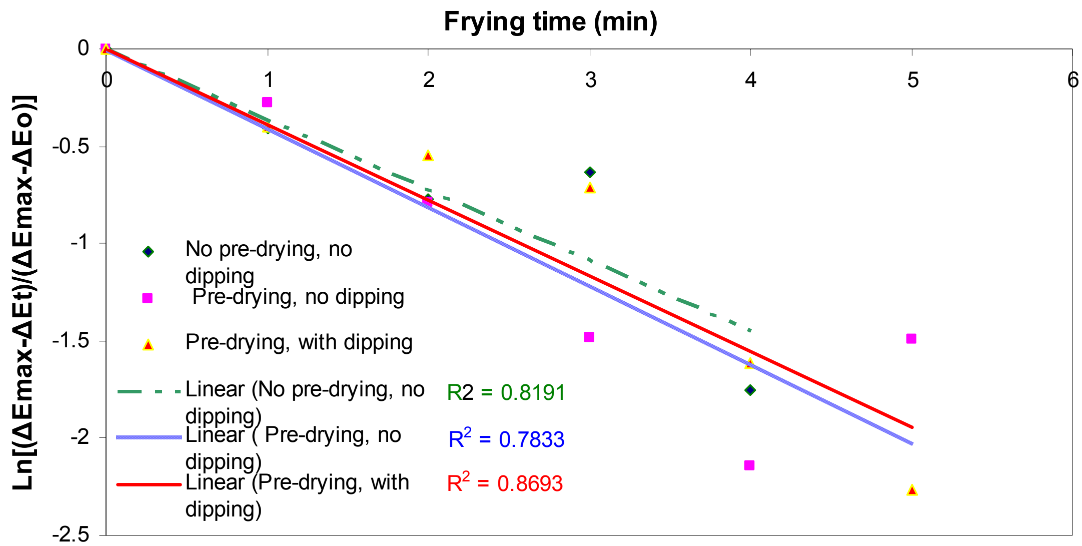

Figure 4.24 The kinetics of the colour changes of the potato crisps during frying with different pretreatment techniques under conventional frying conditions.

4.4 Conclusions

The sugar solution concentration, the pre-treatment technique, the condition of frying (conventional and vacuum) and the density of potato tubers all affect the colour change of the fried potato chips. Under vacuum conditions, the frying pressure affects the colour of the PSSD potato crisps.

The concentration of sugar solution used for dipping the pre-dried potato crisps before frying affects the colour of potato chips. The higher concentration of sugar solution the more significant effect on the color of pre-dried potato crisps under conventional frying. Therefore, the concentration of 23.07 wt % was chosen for the sugar solution for dipping pre-treatment for reducing oil content of potato crisps applied in this study. Under the vacuum frying conditions of 120°C and 170mbars, there was no significant difference between the colour of potato crisps with sugar solution dipping (PSSD) and the control, and PNSD potato crisps (for a potato tuber density of $1.087 \pm 0.005 g.ml^{-1}$). At 5 minutes of frying time, the colour of PSSD potato crisps fried in vacuum conditions improves with an increased lightness and yellowness, but reduced redness compared to that without the sugar dipping (PNSD) when conventional frying was used. However, under conventional frying with high frying oil temperature (180^{o}C), there was a significant difference in the colour of the PSSD and the control samples. The high density of tuber ($1.1052 \pm 0.0021 g.ml^{-1}$) was a significant factor for the total color change of the PSSD and the PNSD potato crisps fried under vacuum conditions (120^{o}C and 170mbars). Under vacuum frying conditions, the frying pressure affected the colour of the PSSD fried potato crisps. Smaller changes in the total color change (ΔE) of potato crisps is due to the lower frying vacuum pressure (50mbars) compared to a higher pressure of 150mbars at the same frying temperature of 120^{o}C. From the colour measurement and the pictures presented it can be concluded that vacuum frying at low temperatures presents a preferable technique further improving the colour of the pre-dried and sugar solution dipped and fried potato crisps.

4.5 References

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5. THE TEXTURE PROPERTIES OF POTATO CRISPS WITH DIFFERENT PRE-TREATMENTS- FOLLOWED BY EITHER THE CONVENTIONAL OR THE VACUUM FRYING

5.1. Introduction

Texture plays an important role in the overall acceptance of food as well as in the enjoyment of eating (Thybo and Martens, 1998). The definition of texture can be expressed as "Texture is a composite of those properties which arise from the structural elements of food and the manner in which it registers with the physiological senses" (Szczesniak, 1963). In potato chips, texture is a major quality factor. The crispiness is a perception that is one of the most important sensory attributes of the product (Bourne et al., 1966).

The texture of the foods we eat is contributed by either the naturally occurring properties of high polymers such as starch, pectin, cellulose, and hemicelluloses or their denatured states of these components. In a potato, the cellulose, hemicelluloses, and pectic substances, which occurred primarily as calcium pectinate, are probably the principal constituents of the cell walls (Smith, 1987). These substances are present as "polymeric gels".

There have been various methods to improve the crispness of potato chips. Pre-drying potato crisps by vacuum microwave method has been shown to be able to produce crisps with expected crispy texture. This is due to the tissue of the potato being expanded by the rapid conversion of water to vapour within the potato slices (Durance and Liu, 1997). Potato strips have been found to increase their crispiness after soaking in the solution of

NaCl (3wt %) for 50 minutes before frying (Bunger , Moyano and Rioseco, 2003). A small amount of sodium acid pyrophosphate added in the frying oil also results in an increased crispness of potato chips (Smith, 1962). However, due to the acid imparted to the chips, a darker colour is resulted. It also reduced frying time by more than 0.5 min and lowered the oil content of potato chips by using this additive (Smith, 1987).

The factors that influence the crispness of the potato crisps

There have been some studies carried out over the years on the texture of fried potato products. A summary is given below.

- Tuber composition affects chip texture. In particular, peak force correlated significantly with tuber specific gravity and the compositions such as starch, moisture, reducing sugar, and soluble carbohydrate content. The tuber amylase content does not affect the peak force. Cultivars with low specific gravity and starch components produced chips with lower breaking force requirement (Lefort et al., 2003). For these reasons, tuber cultivar influences the crispness of the potato chips. Chip peak force differs significantly between yellow fleshed cultivars and red skin cultivars (Lefort et al., 2003).

- Post-harvest changes affect the tissue structural components. Scanlon (1996) has suggested that during tuber storage, cell wall and middle lamella and/or tissue turgor pressure could cause changes in the texture of the processed potatoes.

- Pre-blanching technique also affects the tissue of a fried potato. Blahovec et al. (1999) have studied the influence of pre-blanching of crisps in different salt solutions (Na, K, Ca and Mg clorides) on objective texture properties of the end product. These authors have found that the modulus of elasticity (EM), which was used by de Waelee and Eijk (1996) as a measure of the fried potato tissue crispness, being the most important crisp texture parameter increases with increasing concentration ratio of monovalent ions over bivalent ions (Na + K /Ca + Mg).

- During the frying process, the texture of the potato chip changes. Moisture content is an indicator or predictor of texture. For potatoes with the same moisture content, the maximum breaking force is dependent on the specific gravity of the raw potatoes as the feed. For potatoes with the same specific gravity, the maximum breaking force is not only dependant on the frying oil temperature but also to the frying time (Segnini et al., 1999a). Maximum breaking force was obtained when the moisture content of potato chips is 2.5wt%. Before that point the maximum breaking force was proportional to moisture content, and after this point the maximum breaking force had a tendency to decrease when moisture increased (Segnini et al., 1999a).

- Water activity (a_w) affects the sensory crispness and mechanical deformation of snack foods (Katz and Labuza, 1981). The existence of water affects the texture of dry snack foods by plasticizing and softening the starch/protein matrix which alters the mechanical strength of the product. In this investigation; the critical water activity ($a_{w,c}$) values were defined from 0.35 to 0.5 as the critical zone where the products became organoleptically unacceptable due to either a lack of crispness or poor overall texture. The suggestion from the authors is that the a_w of acceptable and good crispness of potato chips should not exceed the critical water activity in particularly a_w less than 0.52. **Figure 5.1** shows the relationship of a_w and moisture content (g water/g solids) of potato chips (adapted from Katz and Labuza, 1981). From this study, the good snap breaking pattern of potato chips occurs with moisture content less than approximately 0.06 (g water/g solids) (see **Figure 5.1**).

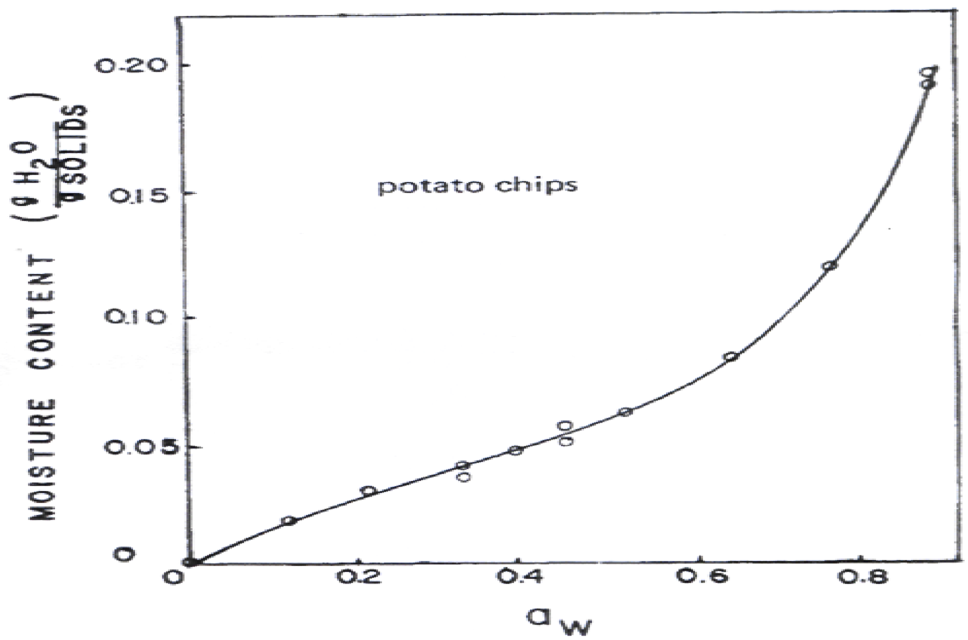

Figure 5.1 Moisture content versus water activity at 20°C of fried potato chips (adapted from Katz and Labuza, 1981).

5.2. Materials and methods

5.2.1 Measurement and calculations

The texture and the crispness of potato crisps or slices were evaluated for various properties: breaking force, the slope, the distance and the area under the force-deformation curve. The stiffness, hardness and softness of potato chips can be calculated from those parameters obtained from the force-deformation curves. From literature review, to evaluate the texture and crispiness of potato chip there are various methods:

- Lefortf Duran and Upadhyaya (2003) have studied the texture of vacuum microwave-dried (VMD) potato chips. The sample texture was evaluated using a TA.XT2 Texture Analyzer. Potato chips were centered above an open cylinder (3 cm high and 3 cm in diameter). A round–tipped probe (6 mm diameter) was used to break the chips to produce a force-deformation curve (**Figure 5.2**); measuring the peak force (N), slope (N mm^{-1}), and the distance (mm) through the force–deformation curve. From this study, Lefort et al. (2003) found that the **peak force** had a high correlation coefficient ($R^2 = 0.752$) with the sensory rating, whereas the slope and distance did not significantly correlate with the sensory ratings. The VMD chips with high sensory ratings, that were deemed "too crispy", appeared with high mean peak force. From this study, they suggested that the peak force obtained from force-deformation analysis is a good parameter to assess the VMD chip texture (Lefort et al., 2003).

- In a similar testing method, in mechanical deformation studies and in the case of potato crisps, **the slope of the curve** is a good measure of chip crispiness, and therefore a good predictor of its texture (Bourne et al., 1966). In this paper, authors suggested measuring the area; in the other words, **the area** under a force-distance curve is a measure of the work done during the test. A lower area under

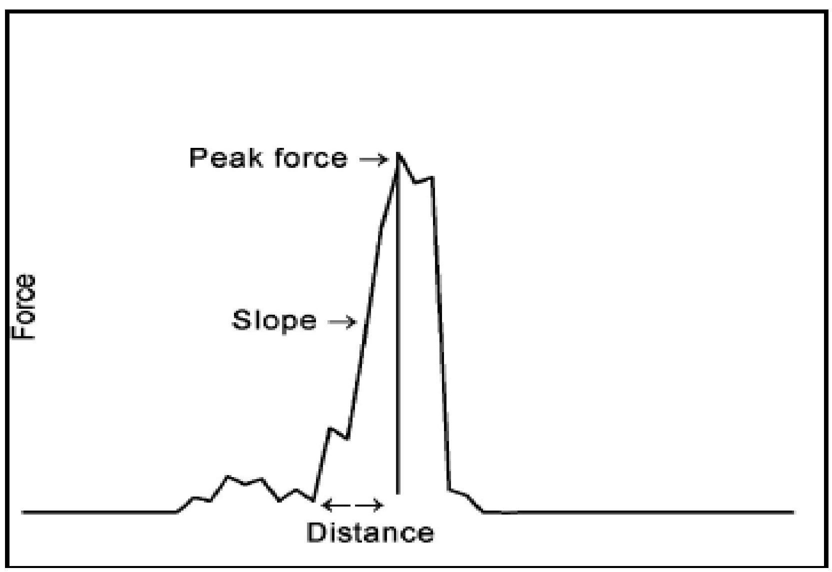

Figure 5.2 Force-deformation curve representing data quantified by the TA.XT2 Texture Analyzer from the fracturing of a potato chip (adapted from Lefort et al., 2003).

the curve, from a crisp potato chip, will be crunched up easily between the teeth. Whereas, a larger area under the curve, from a limp chip, will be chewy and require much more effort from the jaw muscles for mastication (Bourne et al., 1966).

- However, due to large variations in slope among samples, **peak force** of chip breakage has been suggested to be a more reliable measure of chip texture (Demetriades et al., 1995). Similarly, the texture analysis of potato chip, by using an Instron punch test with three-point support of a potato chip, Segnini et al. (1999a) have proposed the use of **maximum breaking force** to quantify texture of potato chips.

- In the measurement of the texture of fried potato tissue as affected by pre-blanching in some salt solutions, Blahovec et al. (1999) used a 4464 Instron Universal Testing Machine with three-point bending regime to deform the

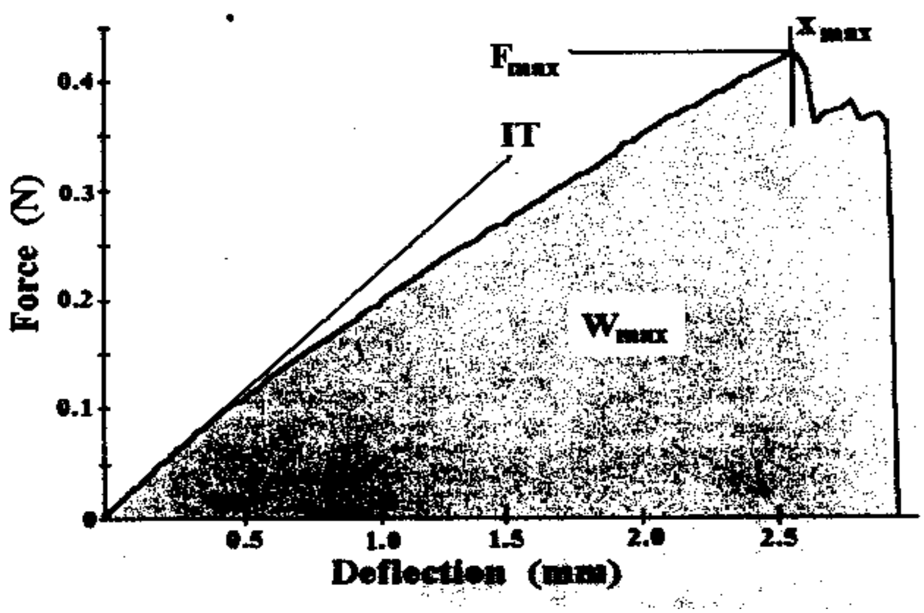

Figure 5.3 Example of a deformation cure obtained in a three-point bending test of a planar fried potato crisp. Determined test parameters: SIT (slope of initial tangent); F_{max} (maximum force), x_{max} (maximum deflection) and W_{max} (total deformation work) (adapted from Blahovec et al., 1999).

samples to rupture. A typical deformation curve is shown in **Figure 5.3**. Four results were determined from the deformation cure: *SIT* (slope of initial tangent), F_{max} (maximum force), x_{max} (maximum deflection) and W_{max} (total deformation work). They were used to calculate these four texture parameters:

(1) Surface energy: $$SE(J.m^{-2}) = 10^3 \frac{W_{max}}{2 w_i . t_h} \quad \textbf{(5.1)}$$

Where w_i and t_h are the width and thickness of the sample.

(2) Maximum relative deflection: $$MRD = \frac{x_{max}}{l} \quad \textbf{(5.2)}$$

where l is the distance between the supporting rods.

(3) Elastic modulus: $$EM\ (N.mm^{-2}) = \frac{SIT.l^3}{4.w_i..t_h^3} \quad \textbf{(5.3)}$$

(4) Maximum tensile stress: $$MTS(N.mm^{-2}) = \frac{3.F_{max}.l}{2.w_i.t_h^2} \quad \textbf{(5.4)}$$

In which, elastic modulus (EM) is the parameter that was used by de Waele and van Eijk (1996) as a measure of the **fried potato tissue crispness**. Elastic modulus and maximum tensile stress were using calculated by Baltsavias et al., 1997 in testing the properties of the biscuits they made.

- In the same field as potato chips, to evaluate the texture of fried slice potato chips with different frying temperatures, Nourian and Ramaswamy (2003) used Lloyd Universal Testing Machine with a similar method as described above. The textural properties of fried potato were evaluated through three parameters:

  1. Hardness = Maximum force (N) / Maximum deformation (mm):

$$H\ (\text{N.mm}^{-1}) = \frac{F_{max}}{x_{max}} \quad \textbf{(5.5)}$$

2. Stiffness = (Force/Cross section area)/ (Deformation/ Initial length):

$$S_t\ (\text{N.mm}^{-2}) = \frac{F}{Ao}\frac{l}{x} \quad \textbf{(5.6)}$$

3. Firmness = Slope of the linear section of the curve (N.mm^{-1}). **(5.7)**

5.2.2 Kinetics of the texture change

A first-order equation was suggested as the kinetic model for texture changes during frying (Nourian and Ramaswamy, 2003):

$$\frac{dC}{dt} = -kC \quad \textbf{(5.8a)}$$

Where C is the concentration of the reactant, t is the frying time, and k is the rate constant with a unit of time^{-1}. Transposing and integrating gives:

$$\ln C = -kt + \ln C_o \quad \textbf{(5.8b)}$$

where C_o is the initial concentration of the reactant at time zero. A plot of ln C versus time will be linear for a first order reaction. The slope of the line gives the rate constant k, and the intercept on the ordinate at time zero gives ln $C_{o.}$

D value, which is the time required at a particular temperature to reduce the quality factor to one-tenth of the original value, is calculated as:

$$D = 2.303 / k \quad \textbf{(5.9)}$$

In potato French fries, the kinetics of textural changes of potato chips during frying have been suggested by Pedreschi and Aguilera (2001) to follow:

$$F_{max} = e^{-ks.t} + k_h.\ t \quad \textbf{(5.10)}$$

Where:

F_{max} = Maximum force

t = time (min)

k_s = kinetics constant of the potato tissue softening process during frying (min^{-1})

k_h = kinetics constant of the crust hardening process during frying (min^{-1})

***The Arrhenius equation*:**

The rate constant normally follows the Arrhenius equation (Nourian and Ramaswamy, 2003) :

$$\ln k = \ln A - E_a/RT \qquad \textbf{(5.11)}$$

Where A is a preexponential constant,

E_a is the activation energy (kJ/mole),

R is the universal gas constant (8.314 J/mole K)

T is the temperature (K)

5.2.3 Experimental set up for texture analysis

In this study, the crispiness and texture analysis of potato crisps were performed at Department of Chemical and Materials Engineering, The School of Engineering, The University of Auckland, New Zealand by using an Instron Universal Testing Machine (model 5567-H 1566, made in England). Punch test was performed on each slice, mounted over a 3-point support (15mm between points) and using a punch Ø 5mm (**Figure 5.4). Figure 5.5** shows the overall set up in the Instron Universal Testing Machine chamber for texture-crispiness analysis of the potato crisps in our study. **Figures 5.6 and 5.7** present the experimental set up with the three-point support used to measure texture of potato crisp and the testing in process. The crosshead speed was 2mm/min. Force at fracture (N), and at 1mm of deformation (stiffness, N/m) were the texture parameters evaluated. Means and standard error of the means were calculated from 10 replicates for each condition. That was for fresh blanched potato slices. With potato after frying and crispness, maximum break in force and deformation were measured from the force-deformation curve (**Figure 5.8**), which was recorded using a PC and LabView (for Windows 95) software. When the crisp was cracked **(Figure 5.7**), at the same time the force-deformation curve dropped in a straight line (**Figure 5.8).** There were 10 tests for each type of crisp sample in this study.

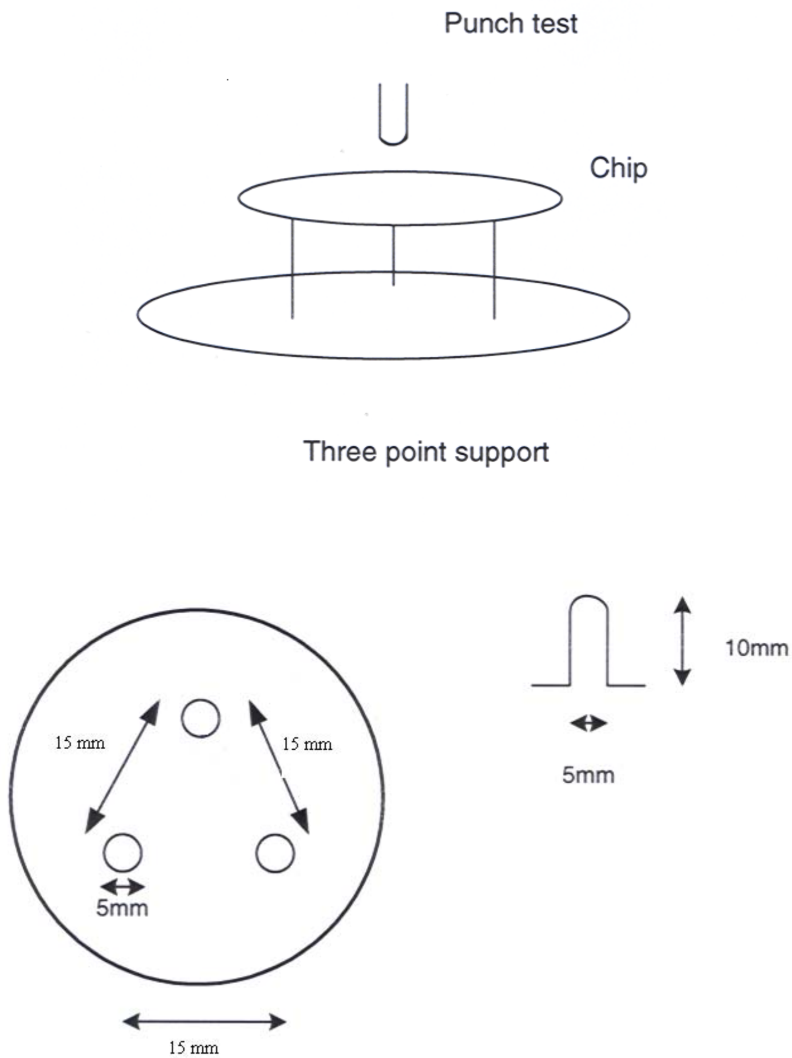

Figure 5.4 The texture measurement set-up for the three-point support applied in the current study.

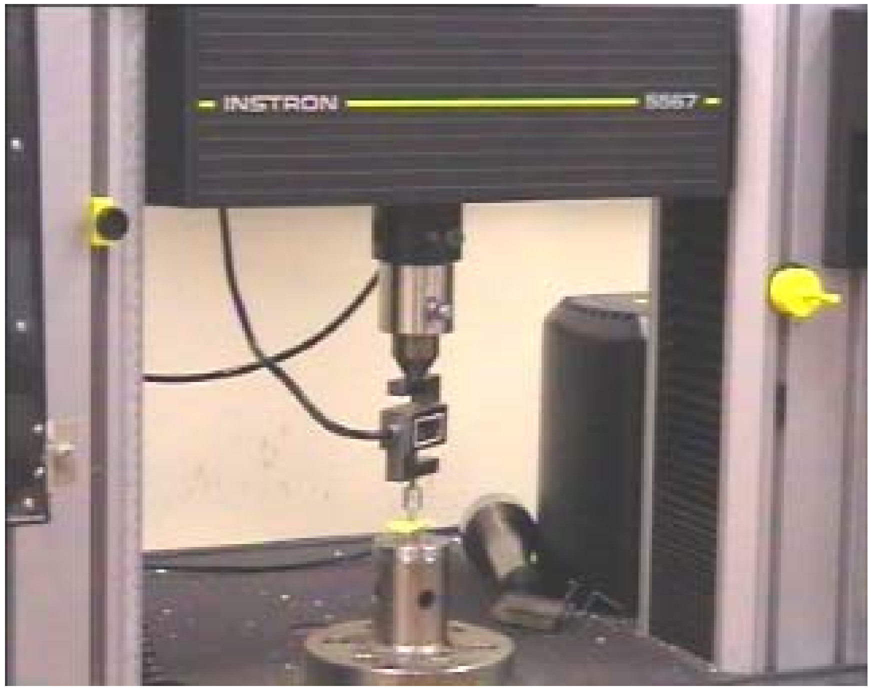

Figure 5.5 The experimental setup in the Instron testing chamber for texture measurement of the potato crisps.

Sample preparation After frying under different conventional and vacuum conditions as described in **Chapter 2** and **3**, the samples were kept in desiccators and tested immediately at the first hour after frying. Fresh potato slices after blanching and with different pre-treatment techniques were also tested in this study.

Statistical analysis Statistical analyses were done using Minitab Release 12 for Windows (Minitab Inc, USA). All the instrumental tests for texture were performed with 10 replicates, and the mean and standard error were calculated. Analysis of variance (ANOVA) was done for significant difference with $p < 0.05$.

Calculations Mathematical software MATLAB 7.0.1 program was used to calculate the total deformation work with the function “trapz” used.

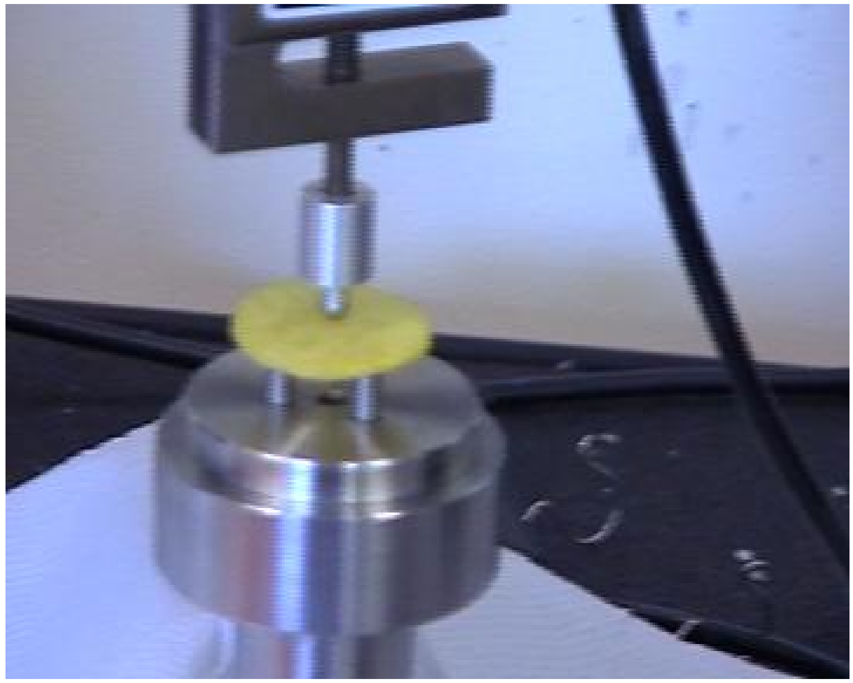

Figure 5.6 Texture testing in progress

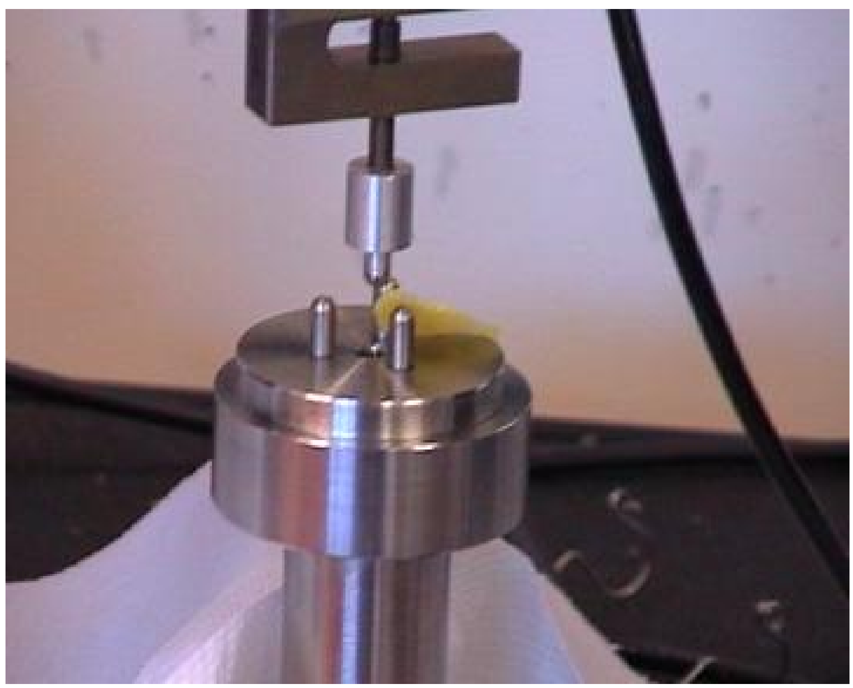

Figure 5.7 When the crisp is cracked.

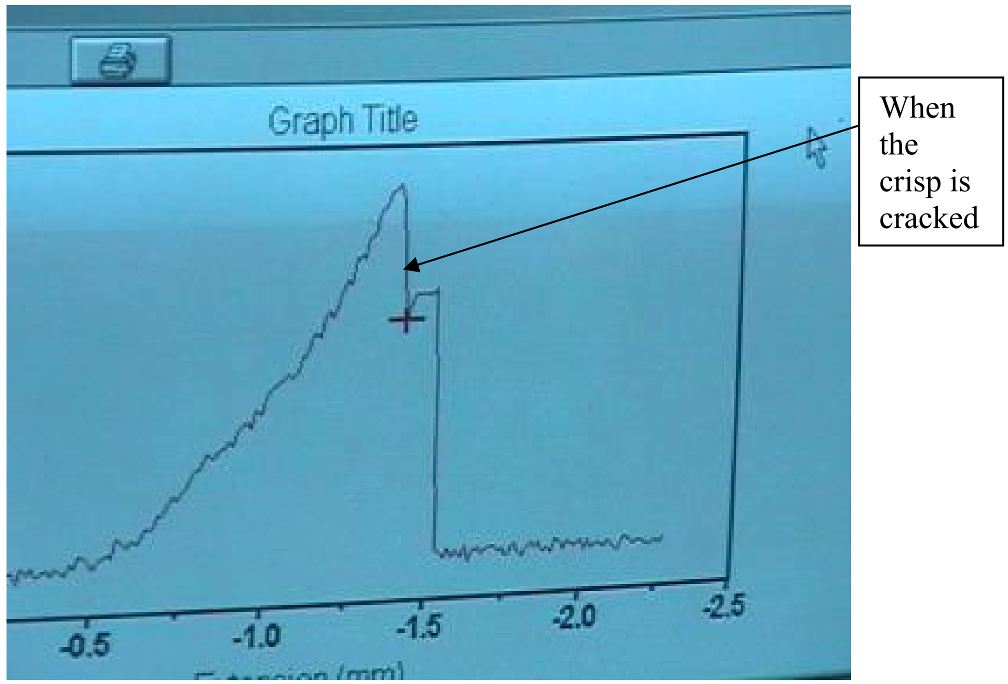

Figure 5.8 Force-deformation curve recorded using the Instron Universal Testing Machine at Chemical & Materials Engineering Department.

5.3. Results and Discussion

5.3.1 The changing deformation curve with frying time

Figures 5.9 to **5.14** show the force- deformation curve from fresh potato after blanching before frying (at time =0) to 5 minutes frying time of control samples (frying at 180^0 C under conventional condition). There was little difference in the shape of the force-deformation curves for frying time from 0 to 2 minutes (**Figures 5.9** to **5.11).** The change of shape started at 3 minutes of frying (**Figure 5.12).** The samples that were cracked by the Instron testing machine for the 4 minutes frying samples gave the force- deformation curves as shown in **Figure 5.13** and **Figure 5.14** demonstrating the rapid drop in force when the samples were snapped.

The changing shape of the force-deformation curve was probably due to the gelatinization of starch in the heating process, which was related to the moisture removal and oil uptake process. The microstructure of potato tissue was changed and associated with the texture quality effects. Extended heating, as in the frying process, brings about further changes in the starch matrix and a breakdown of cell walls. Texture is greatly influenced by cell wall integrity (Stanley and Tung, 1976).

The percentage of samples that were snapped by the Instron machine were different at various frying times, pre-treatments and conditions of frying. For example, with control samples 75% testing samples were cracked at 4 minutes frying samples, 78% testing samples were cracked with samples fried for 5 minutes and not much higher in percentage when testing with samples fried for at 6 minutes, where their moisture contents were at 4 to 2% (in db). With CF & PNSD samples, all the samples were snapped at 3 to 4 minutes of frying times when their moisture contents were already at 2% (see **Table 2.3**

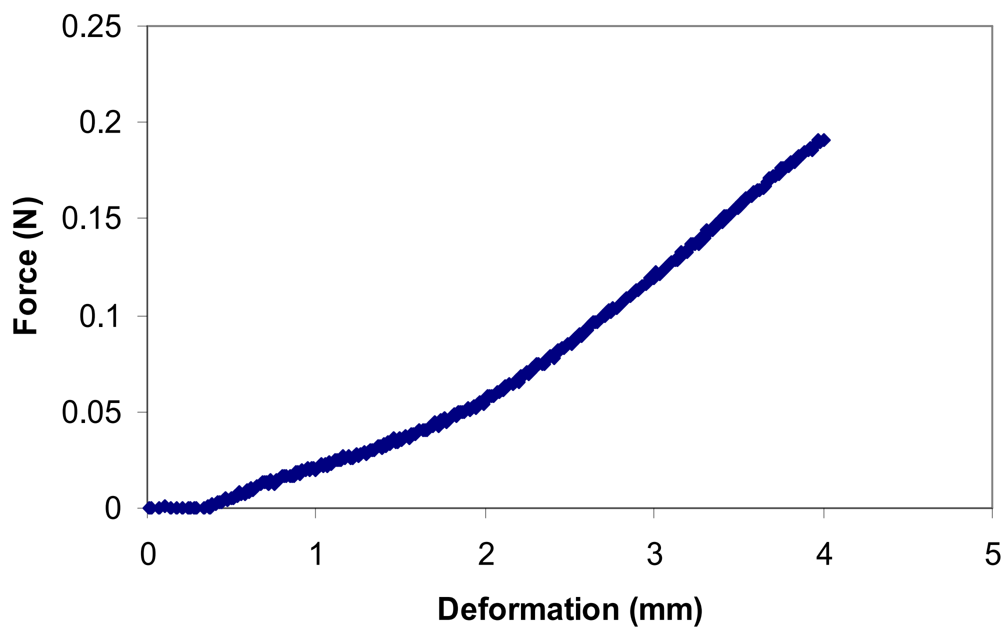

Figure 5.9 The deformation curve of the control sample before frying (Fresh potato after blanching, NPNS at t = 0 min).

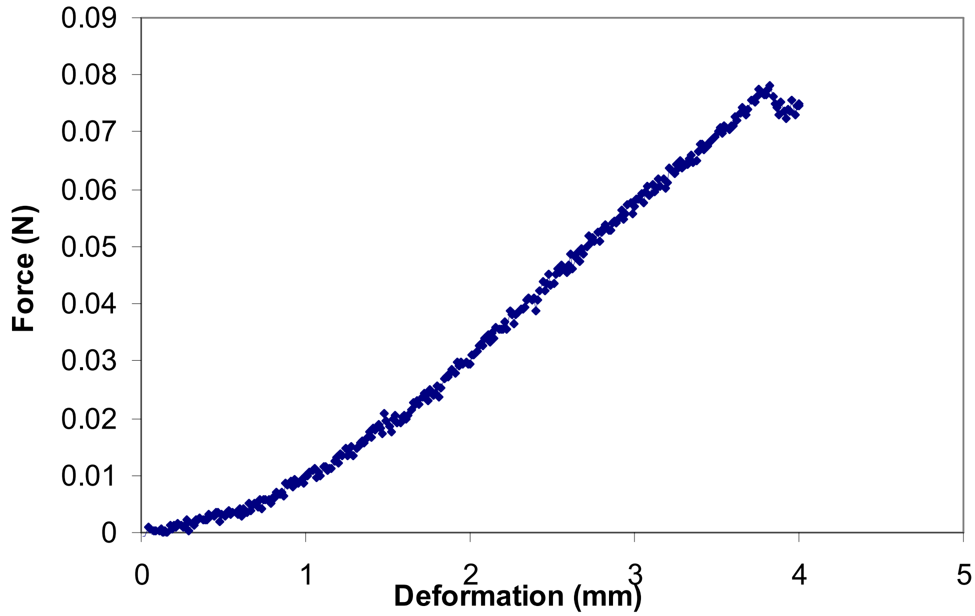

Figure 5.10 The deformation curve of the control sample after frying for 1 minute.

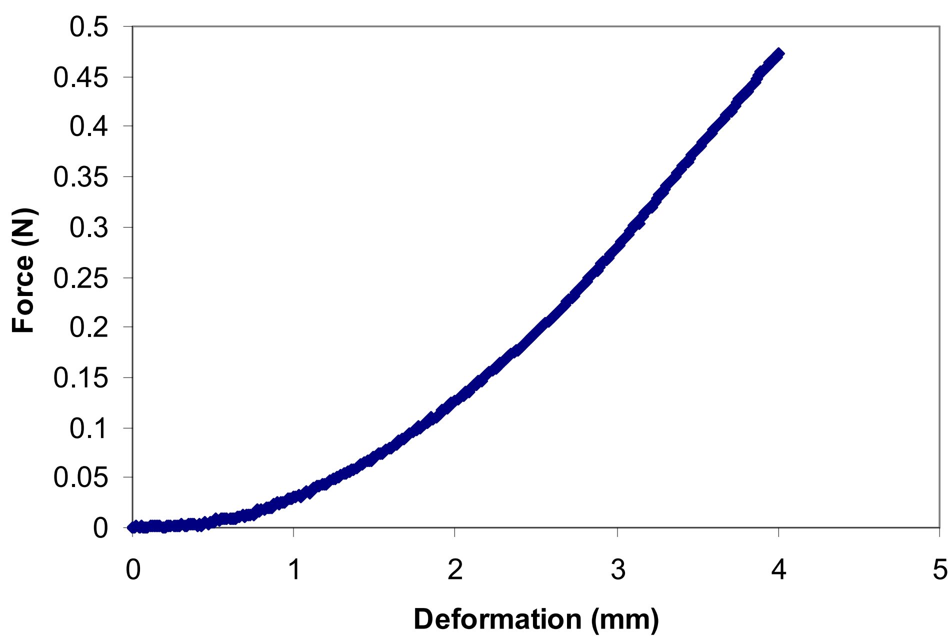

Figure 5.11 The deformation curve of the control sample after frying for 2 minutes.

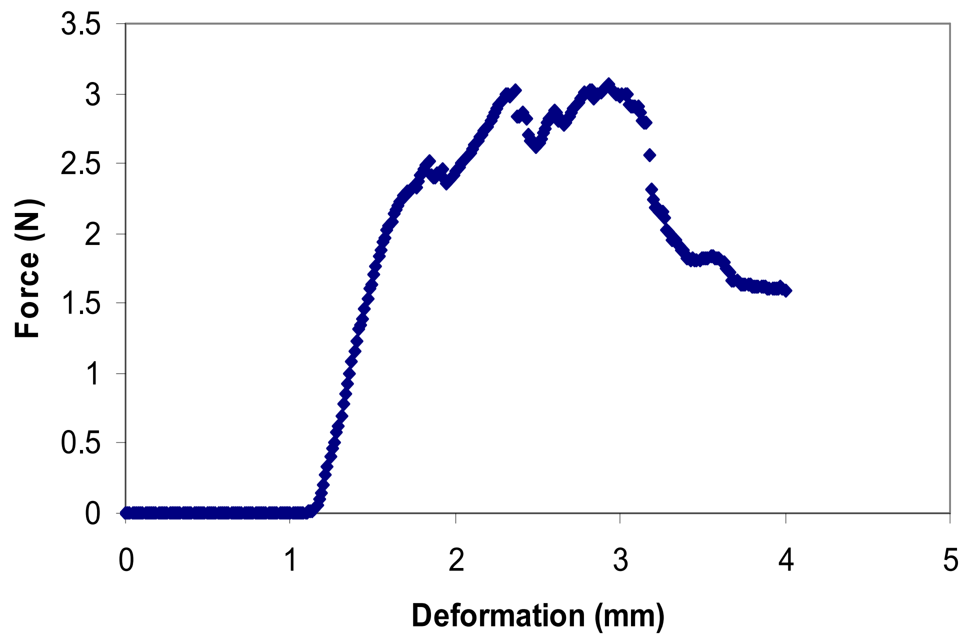

Figure 5.12 The deformation curve of the control sample after frying for 3 minutes.

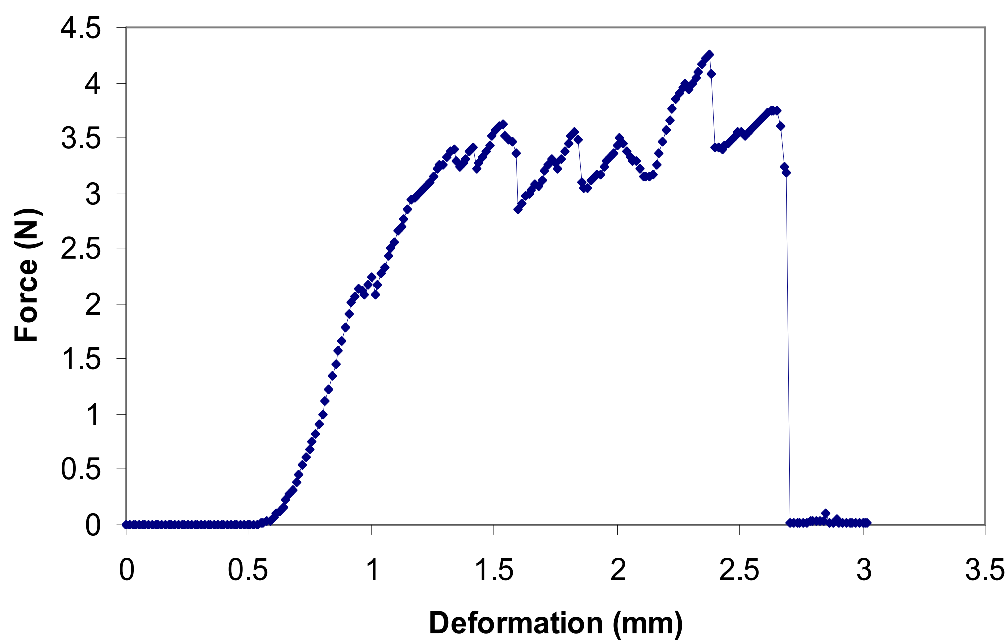

Figure 5.13 The deformation curve of the control sample after frying for 4 minutes.

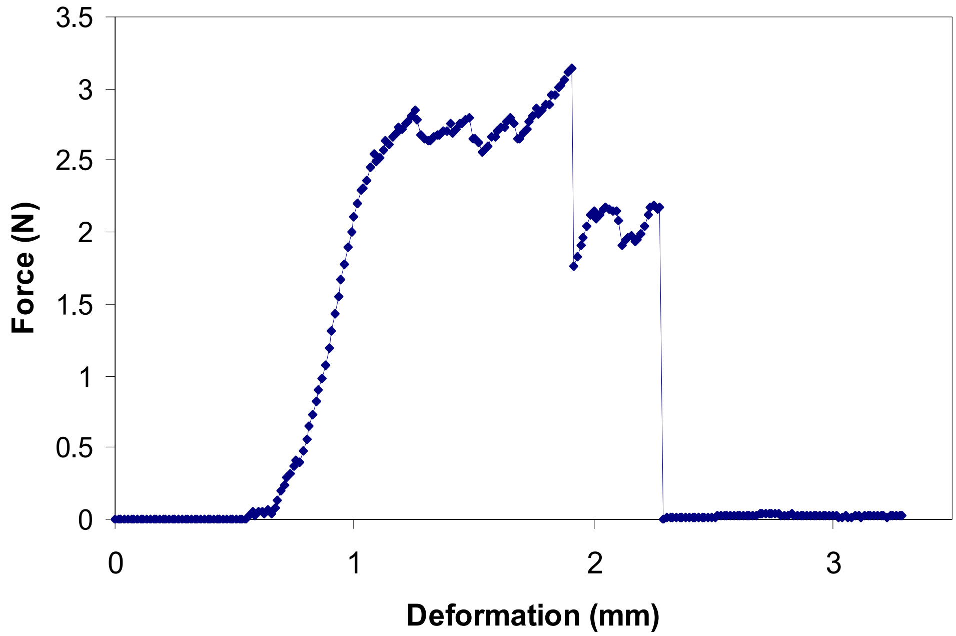

Figure 5.14 The deformation curve of control sample after frying for 5 minutes.

and **Table 5.1**). There were 10 samples were tested for each frying condition. However, the samples were only broken 63.6% in the total number of testing samples when their moisture content was at 5.54 ± 2.89 % db at 2 minutes of frying. **Table 5.1** shows the percentage of cracked samples for each pre-treatment in both conventional and vacuum frying. The difference was also probably dependant on the moisture content when the crispiness occurred in each sample. The formation of crispness in potato occurs at the end of frying in the agreement of the work by Smith (1987).

5.3.2 Texture parameter analyses

5.3.2.1 The crunchiness

The crunchiness was defined as the crispness and the sharp sound when the chip is bitten (Segnini et al., 1999b). The fracture force (F_{max}) is considered as the texture parameter representing the crunchiness of potato crisps as illustrated by Segnini et al. (1999b) through the equation:

$$\text{Crunchiness} = 1.22 + 0.509\ (\text{Force}) \qquad (R^2 = 0.68) \qquad \textbf{(5.12a)}$$

Table 5.1 also shows the three parameters with their standard deviations obtained from force- deformation curves in our study: maximum force (F_{max}), maximum deformation (x_{max}) and total deformation work (W_{max}) as explained in **Figure 5.3**. From the results of F_{max} values obtained, statistical analyses were carried and **Table 5.2** shows the statistical significance between the control and potato chips samples, which had the different pretreatment techniques in vacuum and conventional frying. The comparison between those pre-treatment samples in the values of maximum force was also demonstrated in **Table 5.2.**

As denoted in **Table 5.2,** most of the samples, which had the upper letter "a" were significantly different in the maximum force (F_{max}) compared with control samples. Unless CF- PDNS (conventional frying-pre-drying non-sugar dipping) samples were not significantly different from the control samples. As a result of investigation of **Equation (5.12a),** which demonstrated a positive relationship between the crunchiness of potato crisps from panel testing and maximum force from instrument testing, it appeared that there was an improvement in the crunchiness of potato chips samples, which were PSSD at CF and PNSD & PSSD at VF (vacuum frying) conditions. Consequently, the evaluation given the best crispiness devoted to PSSD potato crisps vacuum frying at 6 minutes, 110^0C, 150 mbars.

Beside the suggestion of maximum force as a predicting texture parameter for crunchiness of potato chips, the initial slope (*SIT*) obtained from force- deformation curves was also offered as a good texture parameter for crispness evaluation. Bourne et al. (1966) measured potato chip texture using a universal testing machine, and found that the initial slope of the force-deformation curve appeared to increase with increasing crispness. **Table 5.3** shows not only the mean values of *SIT (*slope of initial tangent) obtained from the force- deformation curves but also illustrates the surface energy values calculated from equation **(5.1)** of potato crisps at different pre-treatment techniques with conventional and vacuum frying. The statistical analyses were also approved in **Table 5.4** on the *SIT* values of control samples among with others pre-treatment samples under VC and CF conditions.

Table 5.1 The percentage of the snapped samples and the mean values of three texture parameters (F_{max}, x_{max}, W_{max}) for potato crisps treated with different pre-treatment techniques under conventional and vacuum frying conditions respectively.

Frying Con-dition	Pre-treatment	Frying time (min)	Snapp-ed Samp-les (%)	F_{max} (N)		x_{max} (mm)		W_{max}(N.mm)	
				Aver.	stdev	Aver.	stdev	Aver.	stdev
Conven-tional Frying	Control samples	4	75	4.04	0.897	1.51	0.571	5.36	1.402
		5	78	4.15	1.843	1.54	0.740	5.43	3.671
		6	75	4.11	1.231	1.16	0.429	2.75	1.317
	PNSD	2	64	5.19	2.210	1.61	0.927	5.99	2.212
		3	100	4.89	1.715	1.10	0.436	4.17	1.796
		4	100	4.47	1.931	0.83	0.499	2.24	0.842
	PSSD	2	50	4.34	1.769	2.13	0.901	7.23	2.900
		2.5	100	6.67	1.496	0.78	0.198	4.09	2.828
		3	90	6.85	2.244	1.04	0.532	5.59	4.331
		3.20	100	6.60	1.992	0.62	0.150	2.99	0.914
		4	100	6.68	1.870	1.06	0.409	5.84	3.683
Vacuum Frying (150 mbars)	NPNS (120^0C)	5	20	3.37	1.346	3.03	1.153	7.31	0.643
		6	80	6.02	2.216	1.28	0.681	5.13	4.072
	PNSD (120^0C)	4	50	5.74	3.422	1.80	0.826	9.72	3.102
		5	80	7.35	2.106	1.96	1.094	7.44	2.283
		6	100	6.19	1.128	0.88	0.200	4.41	1.426
		6.5	100	6.04	0.889	1.03	0.622	4.67	2.874
	PSSD (120^0C)	5	100	6.72	2.401	0.67	0.163	3.81	2.971
	PSSD (110^0C)	5	70	5.37	1.308	1.61	1.132	5.74	3.797
		6	90	7.45	2.004	0.78	0.247	5.05	5.654

Table 5.2 The statistical analysis on the maximum peak force (F_{max}) texture parameter of potato crisps.

(mean value of control samples= 4.10 ± 1.346)

Sample (1)	F_{max} Mean value sample (1)	Sample (2)	Statistical significant sample testing results Sample (1) vs Sample (2)
CF-PNSD (3-4min)	4.68 ± 1.791^b	CF-PSSD	NS (P>0.05)
CF-PSSD (3-4min)	5.48 ± 2.179^a	VC-PSSD (5min, 110^{0}C, 150 mbars)	NS (P>0.05)
VC-NPND (120^{0}C, 150 mbars) 6min	6.02 ± 2.216^a	VC-PDND (120^{0}C, 150 mbars)	NS (P>0.05)
VC-PNSD (120^{0}C, 150 mbars)	6.62 ± 1.750^a	CF-PNND (3-4min)	SN (P<0.05)
VC-PSSD (120^{0}C, 150 mbars) 5min,	6.72 ± 2.401^a	CF-PSSD (3-4min)	NS (P>0.05)
VC-PSSD (5min, 110^{0}C, 150 mbars)	5.37 ± 1.308^a	VC-PSSD (120^{0}C, 150 mbars)	NS (P>0.05)
VC-PSSD (6min, 110^{0}C, 150 mbars)	7.45 ± 2.164^a	CF-PSSD (3-4min)	SN (P<0.05)

[a]Means with the upper letter "a" are significant different with control sample (P<0.05). [b]Means with the upper letter "b" are not significant different with control sample (P ≥0.05).

Table 5.3 The mean values of the two texture parameters (*SIT* and *SE*) of the potato crisps with different pre-treatment techniques under conventional and vacuum frying conditions.

Frying con -dition	Pre-treatment	Frying time (min)	*SIT* ($N.mm^{-1}$)		*SE* ($J.m^{-2}$)	
			Average	stdev	Average	stdev
Conven-tional frying	Control	4	3.27	1.211	53.73	14.049
		5	3.31	1.012	47.89	0.032
		6	4.98	3.086	27.59	13.199
	PNSD	3	6.83	2.578	34.40	14.823
		4	6.74	5.780	17.99	6.756
	PSSD	3	9.96	6.216	50.53	39.188
		4	8.45	5.083	51.46	32.451
Vacuum Frying (150 mbars)	NPNS (120°C)	6	4.97	1.671	41.05	41.941
	PNSD (120°C)	5	6.52	3.798	59.55	17.091
		6	6.50	1.258	36.35	12.397
	PSSD (120°C)	5	8.48	5.717	33.02	25.724
	PSSD (110°C)	6	10.70	7.353	25.42	8.315

The results obtained from measurement of the slope of initial tangent (*SIT*) are similar to the results of F_m (maximum deformation from deformation curves). There were significant differences ($P<0.05$) among the *SIT* of control samples and most of the other samples, which had pretreatment and were fried in both vacuum and conventional conditions. The NPND samples with VF were not significantly different to control samples (**Table 5.4**). In contrast with previous results (**Table 5.2)**, the PNSD samples with CF were not much different with control samples when considered on

Table 5.4 The statistical analysis on the slope of initial tangent (*SIT*) of the potato crisps.

(*SIT* mean value of control samples (4 to 6min) = 3.83 ± 2.047 $N.mm^{-1}$**)**

Sample (1)	*SIT* mean values of sample (1)	Sample (2)	Statistical significant sample testing results Sample (1) vs Sample (2)
CF-PDND (3-4min)	6.78 ± 4.356[a]	CF-PSSD	NS (P>0.05)
CF-PSSD (3-4min)	9.12 ± 5.54[a]	VF-PSSD (5min, 110°C, 150 mbars)	NS (P>0.05)
VF-NPND (120°C, 150 mbars) 6min	4.97±1.671[b]	VF-PDND (120°C, 150 mbars) 5-6min	NS (P>0.05)
VF-PDND (120°C, 150 mbars) 5-6min	6.51± 2.769[a]	VF-PSSD (120°C, 150 mbars) 5min,	NS (P>0.05)
VF-PSSD (120°C, 150 mbars) 5min,	8.48 ± 5.717[a]	VF-NPND (120°C, 150 mbars) 6min	NS (P>0.05)
VF-PSSD (110°C, 150 mbars) 5min	8.27 ± 5.855[a]	VF-PSSD (120°C, 150 mbars) 5min	NS (P>0.05)
VF-PSSD (110°C, 150 mbars) 6min	10.70 ± 7.353[a]	CF-PSSD (3-4min)	NS (P>0.05)

[a] The mean values with the upper letter "a" are significantly different from the control sample (P<0.05). **[b] The mean values with the upper letter "b" are not significantly different from the control sample (P ≥0.05).**

maximum force. Specially, as previous result the best *SIT* or crispiness was also given to PSSD vacuum frying potato crisps for 6 minutes of frying at 110^{o}C and under 150mbars (**Table 5.4**).

From the two crispiness evaluations for potato chips through *SIT* and F_{max} texture parameters, the results prove that the crispiness of fried potato chips can be improved by pre-drying and subsequently sugar solution dipping (PSSD) pretreatment under both conventional frying (CF) and vacuum frying (VF) conditions. The best crispiness was found with VF at 6 minutes, 110^{o}C and at 150mbars potato crisps (also see **Chapter 3**)

5.3.2.2 The surface energy

As mentioned in a previous section (**Section 5.2.1**), Bourne, Moyer and Hand (1966) recommended the area (W_{max}) under the force-distance curve as a measure of the work done during the test. The authors had mentioned that the smaller area under a curve, as from testing a crisp potato chip, which would mean it can be crunched up more easily between the teeth. Whereas, a larger area under a curve, as given from a limp chip, will be chewy and require much more effort of the jaw muscles for mastication (Bourne et al., 1966). A similar aspect, is the surface energy (SE), which corresponds to the work required for create a unit area of new surface (Blahovec et al., 1999) of the potato crisps was also calculated in this study by applying **equation (5.1)** $(= W_{max} / 2wt)$**.**

As seen in **Tables 5.1** and **5.3,** there were no significant differences (P≥0.05) found between the W_{max} values of the control samples and the other samples, which were fried under conventional or vacuum frying. This indicates that the potato crisps, which were PSSD or PDNS under conventional frying conditions or NPND, PDND, PSSD potato crisps obtained by vacuum frying, are as "easy to crunch between the teeth" as the control sample chips. In addition, the potato crisps with VC and PSSD at 6min, 110^{o}C and 150mbars probably require less energy for mastication compared with the control due to their surface energies being less than that of the control samples for this study.

5.3.2.3 The hardness

The hardness is considered as one of the texture qualities of the potato chips. The sensory panelists in the study of Segnini et al. (1999b) defined the hardness of potato chips as the force necessary to broken the chips. In general, a firm French fry with mealy internal texture was assumed to be acceptable (Nourian and Ramaswamy, 2003), whereas the soft, limp fries were rated as being poor (Voisey et al., 1963). The hardness in potato chips had a positive relation with the crispiness as **equation (5.12b)** given by Moskowitz and Kapsalis (1979) in the study of psychophysical relations in food texture:

$$\text{Hardness} = 3.16 + 0.25\ (\text{Crispiness}) + 0.76\ (\text{Toughness}) \qquad r^2 = 0.96 \qquad \mathbf{(5.12b)}$$

In this study, the hardness, stiffness and firmness (H, S_t, F) of fried potatoes were calculated, respectively using **equations (5.5), (5.6) and (5.7);** as proposed by Nourian and Ramaswamy (2003) in the study of the changes in texture of potatoes during frying.
Table 5.5 and **Figure 5.15** show the mean values of the hardness, stiffness and firmness (H, S_t, F) of potato crisps with different pre-treatment techniques under conventional and vacuum frying conditions. As seen in **Figure 5.15,** the samples that were pretreated with PDNS or PSSD and fried in vacuum or conventional conditions had the higher values in hardness, stiffness and firmness compared with control samples in both vacuum and conventional frying. Only vacuum fried samples without pretreatment (NPND) had firmness less than the control samples. This indicates that the pretreatment approaches such as PDND and PDSD can improve the texture quality of potato crisps in terms of the hardness, stiffness and firmness.

5.3.2.4 Modulus of elasticity

As mentioned above, the crispness of potatoes can also be represented by the modulus of elasticity (EM). De Waele and van Eijk (1996) and Blahovec et al. (1999) used EM as one of the parameters to evaluate the fried potato tissue crispness. From the point of crisp texture quality, higher values of EM and maximum tensile stress (MTS) were preferred (Blahovec et al., 1999). In addition to that, the specimens with a higher modulus of elasticity are less deformable, stiffer than specimens with a lower modulus of elasticity (Bourne, 1975).

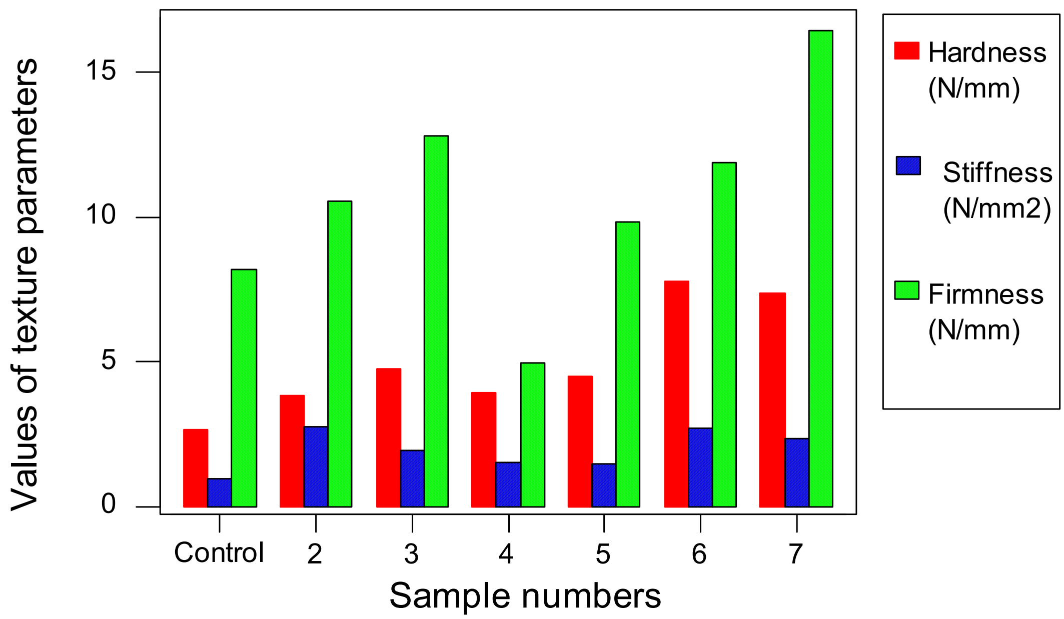

Figure 5.15 The mean values of the hardness, stiffness and firmness (*H, S_b, F*) of the potato crisp samples with different pre-treatment techniques under conventional and vacuum frying conditions. Sample number 2 = PDNS-CF; Sample number 3 = PSSD-CF; Sample number 4 = NPND-VC (120°C, 150mbars); Sample number 5 = PDNS-VC (120°C, 150mbars); Sample number 6 = PSSD-VC (120°C, 150mbars); Sample number 7 = PSSD -VC (110°C, 150mbars).

Table 5.5 The mean values of the three texture parameters hardness, stiffness and firmness (*H, S_t, F*) of potato crisps treated with different pre-treatment techniques under conventional and vacuum frying conditions.

Frying con-dition	Pre-treatment	Frying time (min)	*H*(N.mm^{-1})		S_t (N.mm^{-2})		*F*(N.mm^{-1}).	
			Ave	stdev	Ave	stdev	Ave	stdev
Conven-tional frying	Control samples	4	2.04	0.713	0.97	0.609	7.78	2.751
		5	2.72	0.541	0.82	0.395	8.63	0.182
		6	3.17	1.446	1.17	0.495	8.26	3.810
	PNSD	3	2.96	1.750	1.30	0.779	8.94	5.655
		4	4.68	3.833	1.60	0.930	12.13	6.142
	PSSD	3	4.94	3.046	2.06	0.911	12.27	5.123
		4	4.61	2.650	1.88	0.858	13.32	4.843
Vacuum frying (150 mbars)	NPNS (120^{o}C)	6	3.96	1.268	1.54	0.454	4.97	1.671
	PNSD (120^{o}C)	5	3.41	1.784	1.13	0.545	9.43	5.908
		6	5.61	1.716	1.85	0.576	10.20	4.384
	PSSD (120^{o}C)	5	7.78	3.170	2.72	1.039	11.87	6.535
	PSSD (110^{o}C)	6	7.36	3.913	2.38	0.824	16.45	6.925

In this study, the modulus of elasticity (N.mm^{-2}), Maximum relative deflection (MRD), Maximum tensile stress (N.mm^{-2}) of the potato crisps were calculated from the equations **5.3, 5.2, 5.4** respectively**.** The distance *l* between the supporting rods was 15 mm (**Figure 5.7**). **Table 5.6** shows the mean values of these three texture parameters (MRD, EM and

MTS) of the potato crisps at different pre-treatment techniques under conventional and vacuum frying conditions. As seen in **Table 5.6,** the potato slices (PSSD) in vacuum or conventional frying had the higher EM and MTS values compared with the control samples. Blahovec et al. (1999) agreed with the well known rule that higher crispness is observed for the crisps made from the tubers with a higher specific gravity. The results supported the theory given in this study as the PSSD increases the solid content in potato slices or the specific gravity of the potato slices. The results have further confirmed that the pre-drying and subsequently sugar solution dipping is the process that must have

Table 5.6 The mean values of the three texture parameters (*MRD, EM, MTS*) of the potato crisps with different pre-treatment techniques under conventional and vacuum frying conditions.

Frying con-dition	Pre-treatme-nt	Frying time (min)	*MRD*		*EM* ($N.mm^{-2}$)		*MTS*($N.mm^{-2}$)	
			Ave	stdev	Ave	stdev	Ave	stdev
Conven-tional frying	Control samples	4	0.10	0.038	29.06	10.756	1.32	0.293
		5	0.10	0.049	20.19	6.163	1.05	0.468
	PDNS	3	0.07	0.029	29.62	11.184	1.02	11.184
		4	0.06	0.033	24.94	21.402	0.84	0.365
	PSSD	3	0.07	0.035	49.08	30.639	1.58	0.519
		4	0.07	0.027	38.11	22.916	1.46	0.408
Vacuum frying (150 mbars)	NPNS (120^{0}C)	6	0.09	0.045	35.16	11.819	1.76	0.646
	PDNS (120^{o}C)	5	0.13	0.073	21.37	12.446	1.30	0.374
		6	0.06	0.014	23.84	4.862	1.18	0.215
	PSSD (120^{o}C)	5	0.05	0.011	32.68	22.019	1.34	0.480
	PSSD (110^{o}C)	6	0.05	0.016	35.94	24.710	1.34	0.387

increased the solid content, which not only reduces the oil uptake in potato during frying (**Chapter 2**), but also increases the texture quality obtained.

5.4. Conclusions

Pre-drying and subsequently sugar solution dipping (PSSD) is a promising method to improve the crispiness and the texture quality of potato crisps cooked under conventional or vacuum frying conditions. The results were collected by testing the crispiness of the potato crisps with three-point-support method through the texture parameters: Maximum Peak Force; Slope of Initial Tangent, Hardness, Stiffness, Firmness, Modulus of Elasticity and Maximum Tensile Stress. The vacuum frying appeared to have an improvement in the texture quality of the potato crisps compared with the conventionally pre-dried non-sugar solution dipped potato samples in terms of the crispiness and the elastic modulus from that without these treatments. There was no significant difference estimated in the energy to 'bite' potato crisps for the pre-treated potato crisps compared with the control samples. The best texture quality and the crispness were found in PSSD potato crisps after 6 minutes of frying at 110^{o}C and 150 mbars vacuum frying.

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6. ACRYLAMIDE FORMATION DURING CONVENTIONAL AND VACUUM FRYING PROCESS-EFFECTS OF PRE-TREATMENTS

6.1. Introduction

There have been a number of studies reporting on the formation of acrylamide in potato crisps conventionally fried. The high level of acrylamide formation when frying potato chips at high temperatures have been described (Tareke et al., 2002, Mottram et al., 2002; Stadler et al., 2002; Gertz and Klostermann, 2002). The reduction of acrylamide was particularly necessary as acrylamide was substantiated as a potential carcinogen in animal studies and was thought to have the potential that may affect human bodies when consumed in high amounts (Tareke et al., 2000). Low temperature vacuum frying was used in this study with the purpose of reducing the formation of acrylamide in fried potato crisps products. The effects of pretreatment techniques (PSSD and PNSD) combined with vacuum frying on the acrylamide formation of potato chips were also investigated since no detailed studies have ever been reported. There has been a few studies on the reduction of acrylamide in vacuum fried non-pretreated (NPND) potato chips reported (Granda et al., 2004 and Granda and Moreira, 2005), which has been published while the current study was being written up in this chapter, the acrylamide formations in potato crisps under both conventional and vacuum frying conditions NPND and pre-treated conditions such as PSSD and PNSD were also investigated.

6.2 Acrylamide

6.2.1 Acrylamide chemical, physical properties and environment effects

Acrylamide has a molecular formula of C_3H_5NO with various synonyms, such as Acrylic acid amide, Acrylic amide, Ethylenecarboxamide, Propenamide, Propenoic acid amide and Vinyl amide with the white crystalline solid (WHO, 1996). The chemical structure of acrylamide as presented in **Figure 6.1** and **Table 6.1** show the physicochemical properties of acrylamide (WHO, 1985).

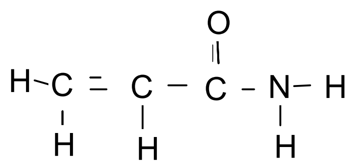

Figure 6.1 Molecular structure of acrylamide.

Table 6.1 Physical chemical properties of acrylamide

Property	Value
Physical state	White crystalline solid
Melting point	84B85 °C
Boiling point	125 °C at 3.33 kPa
Density	1.122 g/cm^3 at 30 °C
Water solubility	2150 g/l at 30 °C
Vapour pressure	0.009 kPa at 25 °C

In the chemical industry, acrylamide is used as a chemical intermediate or as a monomer in the production of polyacrylamide. Both of them, acrylamide and polyacrylamide are mainly used as flocculants in the treatment of municipal and industrial effluents. They are also used as grouting agents in the construction of drinking-water reservoirs and wells (WHO, 1985). Polyacrylamide is used in the refining of sugar and small amounts of acrylamide may remain in the final products (WHO, 1996). Due to its low vapour pressure and high water solubility acrylamide is not expected to be a common contaminant in air (WHO, 1996).

6.2.2 Effect of acrylamide on human

The affect of acrylamide on humans needs more caution. Average daily doses as low as 1mg/kg of body weight can sometimes produce some detrimental effects (WHO, 1996). In mutagenicity assays, acrylamide does not cause mutations in the bacterial test systems but does cause chromosome damage to the mammalian cells *in vitro* and *in vivo*. In a long-term carcinogenicity study in rats exposed via drinking-water, acrylamide induced tumours at various sites (Johnson et al., 1986). There is no direct evidence for acrylamide having a similar effect on humans, however, International Agency for Research on Cancer has placed acrylamide in Group 2B of probable carcinogenic (IARC, 1987). In further updated information dated on 08/26/1997, the evaluation of acrylamide as probably carcinogenic to humans placed it in Group 2A. Many other cases of human exposure to acrylamide have been reported, generally as a result of dermal or inhalation exposure of workers in grouting operations or factories manufacturing acrylamide-based flocculants. Typical clinical symptoms were skin irritation, generalized fatigue, foot weakness, and sensory changes, which cause disfunctions of either the central or the peripheral nervous systems (Auld and Bedwell, 1967; Garland and Patterson, 1967; Fullerton; 1969; Davenport, Farrell and Sumi, 1976).

Although acrylamide is considered as a harmful substance, this chemical degenerates in the environment (ie. Biodegradable). Its concentration decreased from 20 to 1 μg/litre in 24 h in the effluent from a sludge dewatering process (Arimitu, Ikebukuro and Seto, 1975). In water, generally, the maximum authorized dose of the polymer is 1 mg/litre. At a monomer content of 0.05%, this corresponds to a maximum theoretical concentration of

0.5 μg/litre monomer in water (National Sanitation Foundation, 1988). Acrylamide is soluble and as such is also degradable by microorganisms (Neely, Baranson and Blau, 1974).

6.3 Acrylamide formation during frying process

6.3.1 Pathways for the formation of acrylamide

Acrylamide is created by chemical Maillard reaction through the proposed pathway presented by Mottram et al. (2002). In this pathway, acrylamide was only created when asparagine(H_2N-CO-CH_2-$CHNH_2COOH$) or methionine (CH_3-S-$(CH_2)_2$-$CHNH_2COOH$) reacted with dicarbonyl compounds and Strecker degradation. In this study, 2,3-butanedione was used instead of glucose. In this path way, acrylamide can be created in two ways. The first way, from the Strecker aldehyde, which was formed from methionine is methional. The second way, the Strecker aldehyde was formed from acrolein, which was together with ammonia: subsequent oxidation of acrolein to acrylic acid followed by amidation could generate acrylamide (**Figure 6.2**).

In the investegation of Mottram et al. (2002), asparagine was the most appropriate amino acid in the acrylamide formation process through Maillard reaction. This Maillard reaction produced significant amount of acrylamide when the reaction occurred in buffer solution (221mg acrylamide per mol of amino acid at 185^{o}C). For dry reaction only 25mg mol $^{-1}$ acrylamide was formed, without buffer at the same temperature 185^{o}C. With other amino acids such as glutamine (H_2N-CO-$(CH_2)_2$-$CHNH_2COOH$) and aspartic acid (HOOC-CH_2-$CHNH_2COOH$), trace quantities of acrylamide were produced; and with methionine amino acid 5mg acrylamide per mol created in yield. On the other hand, with any of the other amino acids tested the acrylamide was not formed.

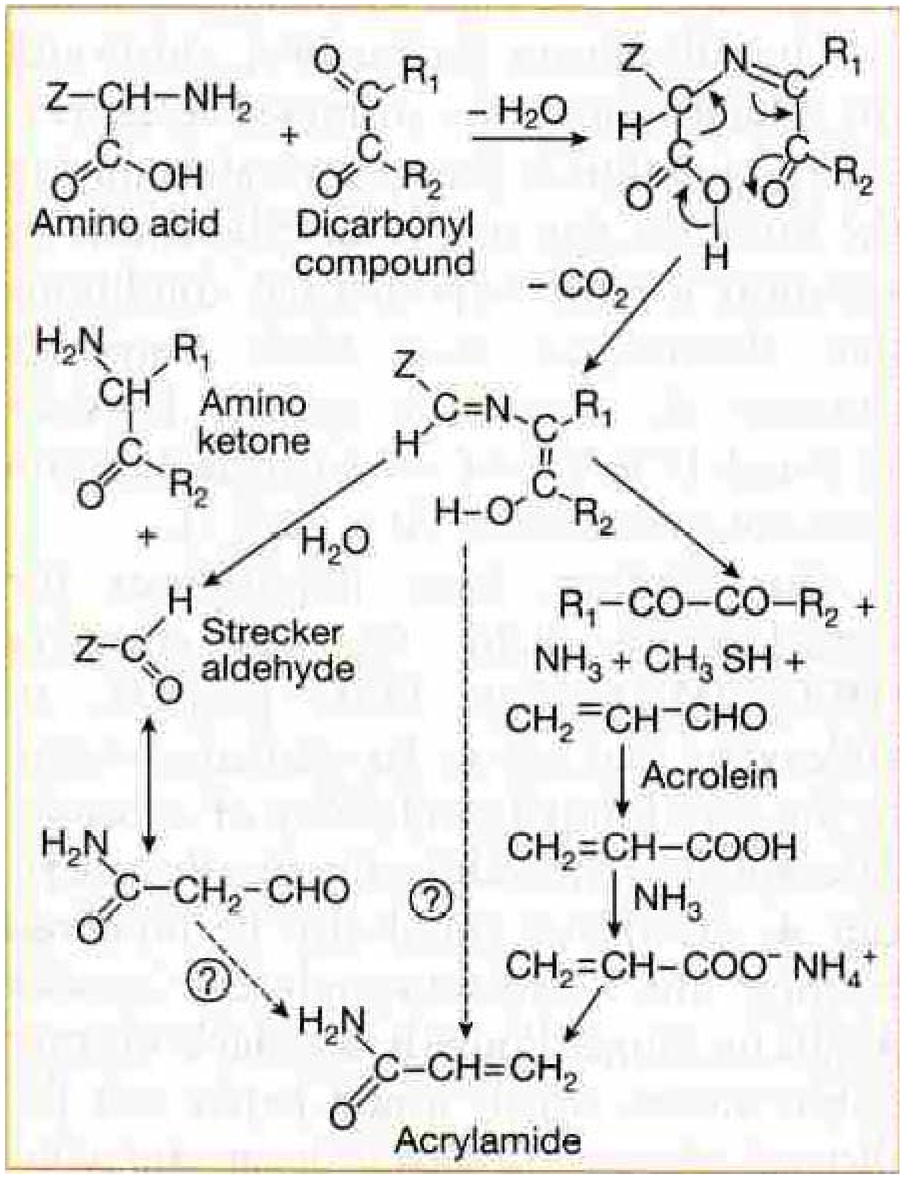

Figure 6.2 Previously proposed pathways for the formation of acrylamide after Strecker degradation of the amino acids (e.g. asparagines and methionine) in the presence of dicarbonyl products from the Maillard reaction (adopted from Mottram et al., 2002).

Similarly results, Stadler et al (2002) also found high concentrations of acrylamide formation with the presence of asparagine compared with glutamine and methionine

(**Figure 6.3**). The concentration of acrylamide was increased with time by reacting glucose with methionine rather than with asparagine and glutamine (**Figure 6. 3**).

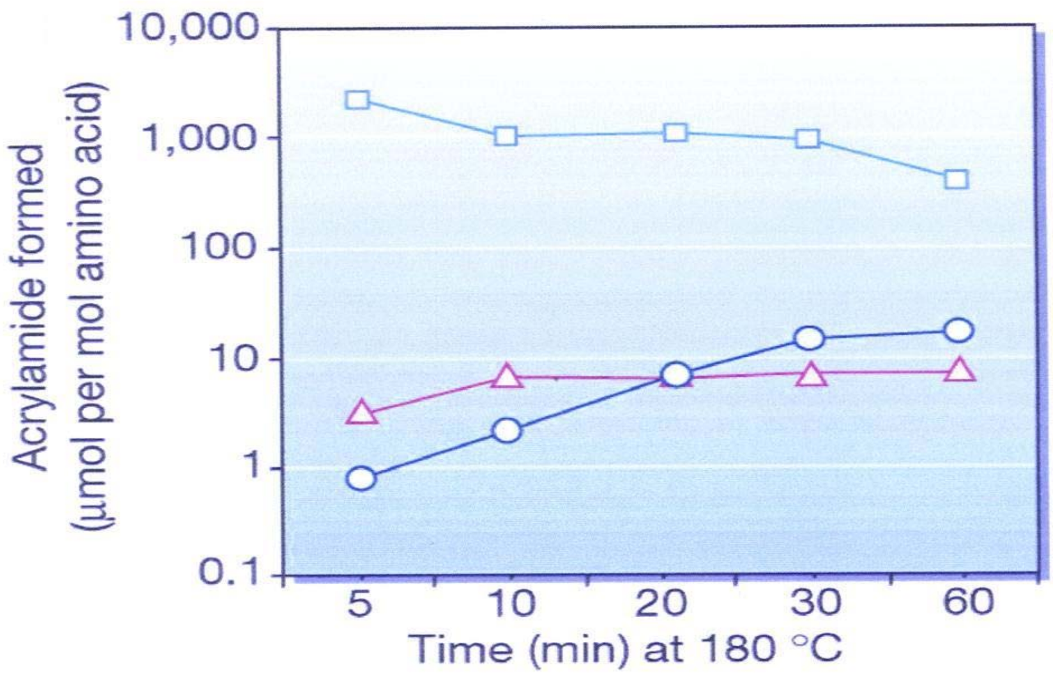

Figure 6.3 Logarithmic-scale plot of the formation of acrylamide over time in pyrolysates of glucose with glutamine (triangles), asparagines (squares), methionine(circles) (Adopted from Stadler et al., 2002).

6.3.2 Acrylamide in potato chips

Potato crisps contain high levels of acrylamide compared to other fried products as potatoes are rich in the particular amino acid (asparagines) (Belitz and Grosch, 1999). The content of this amino acid takes up 40% of the total amino acids in potatoes used in the potato chip industries (Martin and Ames, 2001). In normal potato tubers, the sucrose content displays a near 10fold greater compared to with glucose and fructose contents (Leszkowiat et al., 1990). This information was similar with the content sugar reported by Haase et al. (2003) investigated in the raw potatoes. **Table 6.2** (adopted from Martin and

Ames, 2001) shows the concentrations of sugars and amino acids in a potato cultivar used for chipping (Saturna) (United Biscuits, Personal Communication).

Table 6.2 Concentrations of sugars and amino acids in a potato cultivar used for chipping (Saturna) (United Biscuits, personal communication).

(Adopted from Martin and Ames, 2001)

Sugar	**Conc. (g/100 g)**	**Sugar**	**Conc. (g/100 g)**
Glucose	0.1	Fructose	0.08
Sucrose	1.07		
Amino acids	**Conc. (mg/100 g)**	**Amino acids**	**Conc. (mg/100 g)**
Ala	4.7	Lys	4.7
Arg	16.4	Met	4.7
Asn	93.9	Phe	4.7
Asp	4.7	Pro	4.7
Gln	28.2	Ser	4.7
Glu	9.4	Thr	18.8
Gly	0.0	Trp	0.0
His	7.0	Tyr	7.0
Ile	7.0	Val	9.4
Leu	4.7		

6.3.3 Factors influencing the formation of acrylamide

Temperature

There has been a number of studies on the formation of acrylamide related to temperature (Mottram et al.,2002; Tareke et al., 2002; Gertz and Klostermann, 2002). Most of them agreed that the concentration of acrylamide formation was dependent on the temperature. Mottram et al., 2002 investigated acrylamide formation from asparagines (0.1 mmol) and glucose (0.1 mmol) in 0.5 M phosphate buffer (100µl, pH 5.5) heated in a sealed glass tube for 20 min. The highest level of acrylamide formation was obtained at a temperature of 170^{0}C (**Figure 6.4**). It seems that no acrylamide was created at 120^{0}C with this study. Tareke et al (2002) studied the acrylamide formation in commercial French fries with an oven program with a total of 21 minutes heating time. A small increase (app. 30 µg/kg) in

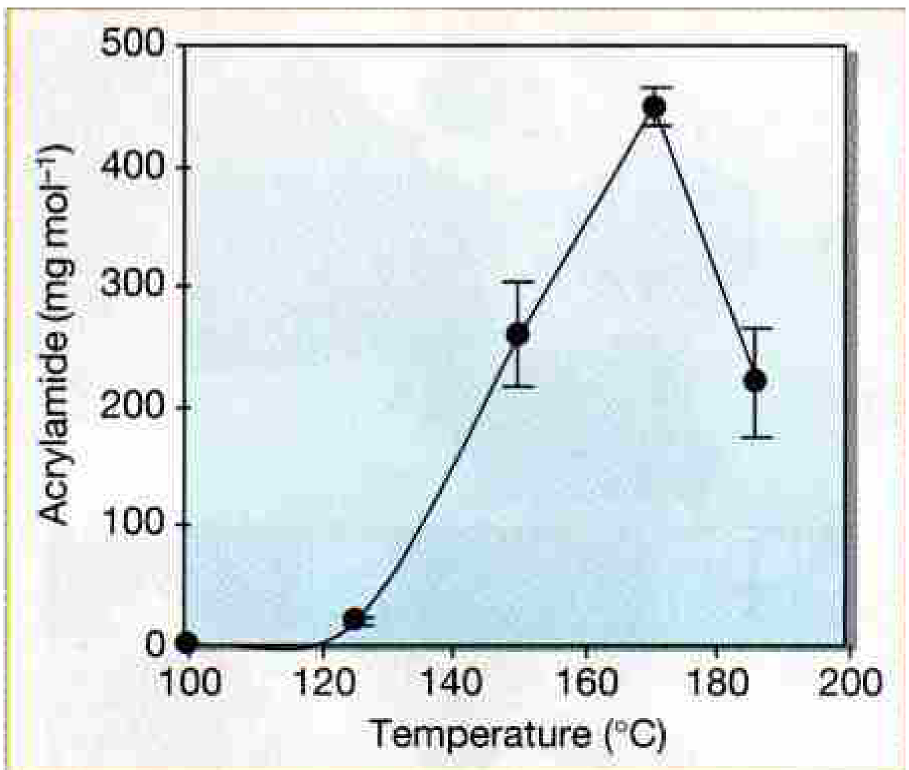

Figure 6.4 Temperature-dependent formation of acrylamide (mg per mol of aminoacid) from asparagine (0.1 mmol) and glucose (0.1 mmol) in 0.5 M phosphate buffer (100µl, pH 5.5) heated in a sealed glass tube for 20 min (adopted from Mottram et al., 2002).

the acrylamide level was measured at maximum temperature 120^{o}C with holding18.2 minutes. Whereas, heating for 19 minutes at 100^{o}C had no effect on the acrylamide content (**Figure 6.5** and **Table 6.3**). Indicating that the temperature needed for formation of acrylamide is higher than 100^{o}C. From this study, the level of acrylamide was found to increase (174 to 2273 µg/kg) with the oil temperature rise from 120^{o}C to 220^{o}C and the holding time from 18.2 to 14.2 minutes, respectively (Tareke et al., 2002).

In particular, the french fries investigated according to Gertz and Klostermann (2002) had acrylamide formation at a frying time of 2 minutes & 30 seconds and 3 minutes & 30 seconds, which is the normal frying time in restaurants (Gertz and Klostermann, 2002) at different temperatures from 160^{o}C to 185^{o}C. The results showed that the increase in acrylamide concentration was accelerated when temp is above 175^{o}C with an acrylamide level found at 1070 µg/kg at 180^{o}C and 1240 µg/kg at 185^{o}C compared with 287 µg/kg at 175^{o}C for 3 minutes and 30 seconds frying time. The acrylamide concentration also increased with the lengthening at frying time from 2 min & 30 seconds to 3 min & 30 seconds at these high temperatures (from 389 µg/kg, 674 µg/kg to 1070 µg/kg at 180^{o}C and 1240 µg/kg at 185^{o}C, respectively) (**Figure 6.6**).

Table 6.3 Acrylamide concentrations and weight loss in prepared and uncooked french fried potatoes heated in a programmed GC Oven (Total heating time = 21 min).

(Adapted from Tareke et al., 2002).

Max temp (^{o}C)	Acrylamide(µg/kg)	Time(min) at max temp	Weight loss (%)	Acrylamide, corrected values (µg/kg)
control	146	0	0	146
100	172, 174	19,0	14.9	146, 148
120	217	18.2	19.9	174
140	376	17.4	29.8	264
160	808	16.6	41.9	469
180	1965	15.8	49.0	1003
200	3479	15.0	54.3	1591
220	5051	14.2	55.0	2273

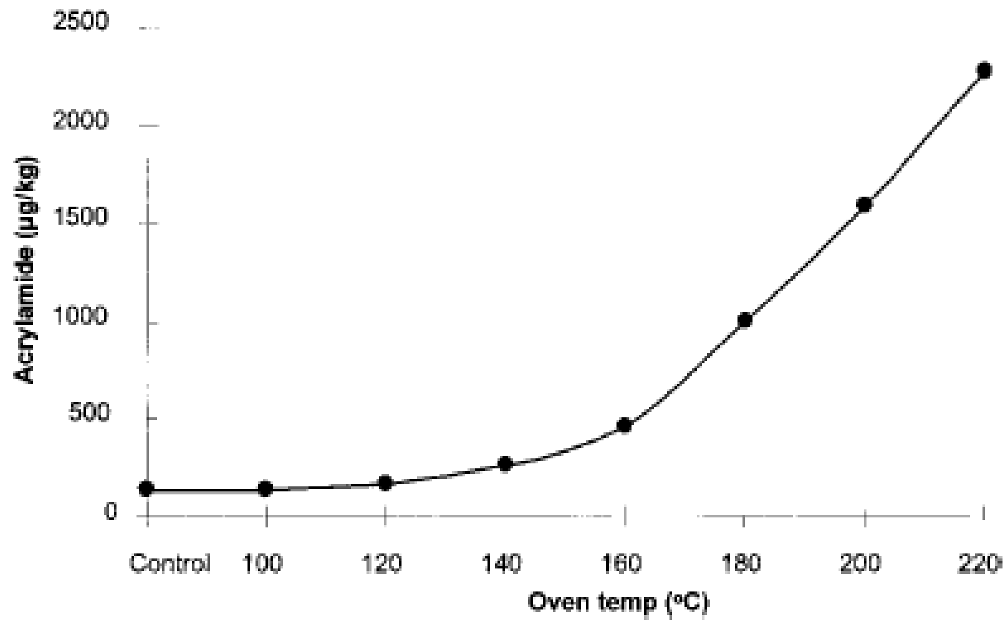

Figure 6.5 Acrylamide concentrations (micrograms per kilogram), corrected for weight loss, in French fried potatoes heated in a temperature-programmed oven (adopted from Tareke et al., 2002).

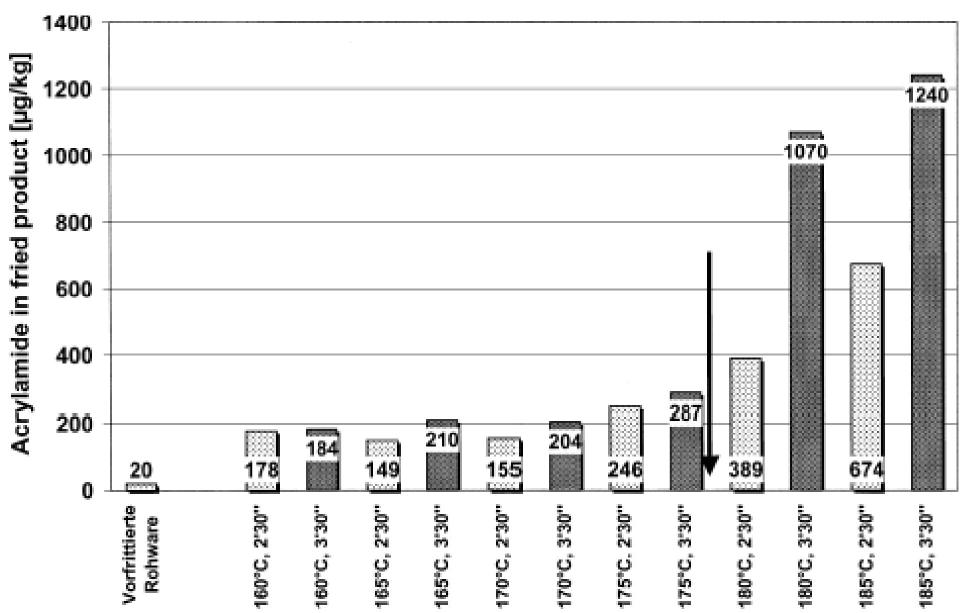

Figure 6.6 Change of acrylamide level in the French fries for different temperatures and heating times (frying oil: rapeseed oil) (Adopted from Gertz et al., 2002).

Moisture

Water also probably affected acrylamide formation. Stadler et al.(2002) found that the release of acrylamide was enhanced nearly threefold (960 ± 210 µmol mol^{-1}) when the water was added (0.05 ml) to the reaction of equimolar amount of glucose and asparagines before the thermolysis at 180^{o} C after incubation time of 30 minutes. Similar results obtained presented above in **Section 6.2.1** showed at the dry reaction a formation of only 25mg mol^{-1} acrylamide, whereas there was a significant 221mg acrylamide per mol of amino acid with buffer at the same temperature 185^{o}C (Mottram et al., 2002).

Sucrose

The effect of sucrose on the release of acrylamide is not clear, although Stadler et al. (2002) investigated the role of different carbohydrates in the formation of acrylamide. Te authors found that pyrolysing any of these amino acids (Asparagine (Asn), Glutamine (Glu), Methionine (Met), and Cystein (Cys)) with an equimolar amount of D-fructose, D-galactose, lactose or <u>**sucrose**</u> all led to a significant release of acrylamide. Full information of the acrylamide precursors of reducing sugars and amino acids obtained in the study by Stadler et al (2002) are presented in **Figure 6.7**. However, the full information of the acrylamide precursor of sucrose and amino acid were not given in this study. Acrylamide is probably only formed from sucrose when the hydrolysis of sucrose takes place, realeasing D-glucose and D-fructose.

More detailed information was given by Haase et al (2003) who compared the formation of acrylamide in potato crisps related to raw material of reducing sugar and non-reducing sugar. The total content of reducing sugars showed a good correlation with the acrylamide concentration in the fried products (r^2= 0.64). In detail, the concentration was pronounced for the monosaccharides (glucose: r^2= 0.60: fructose: r^2= 0.56), whereas the content of the disaccharide showed no correlation with the acrylamide concentration (sucrose r^2= 0.24) (**Figure 6.8**).

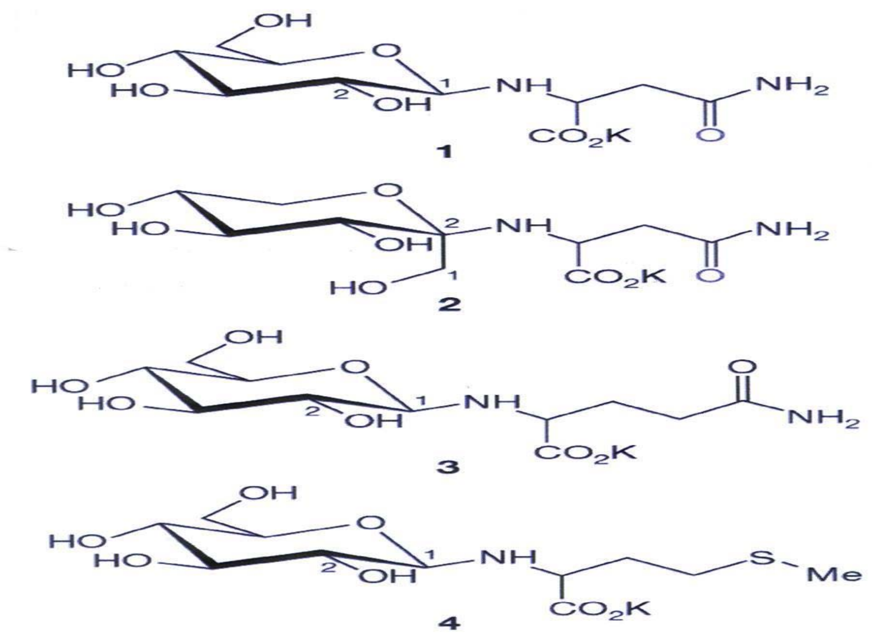

Figure 6.7 Chemical structures of the potassium salts, which could be acrylamide precursors in thermal decomposition reactions, of N-(D-glucos-1-yl)-l-asparagine (1), N-(D-fructos-2-yl)-l-asparagine (2), N-(D-glucos-1-yl)-l-glutamine (3) and N-(D-glucos-1-yl)-l-methionine (4) (Adopted from Stadler et al., 2002).

Frying oil and additives

The level of acrylamide in potato chips differs depending on the oil used. Some researchers found that potato slices fried in olive oil had 50 per cent higher acrylamide levels than those fried with corn oil (Canada's Investigative Consumer Program.htm). Similar results were presented by Gertz et al. (2002) by analyzing the level of acrylamide against different deep frying oils at different temperatures. The highest level of acrylamide (1271 µg/kg) was detected among the high oleic sunflower oil compared with the rapeseed oil, sunflower, palm olein double and palm olein oil at 180°C for 3’30’’ frying time. However, at the frying temperature of 170°C the highest acrylamide level (594 µg/kg) in French fries was evident with palm olein, which had the lowest acrylamide level at 180°C compared to others for the same frying time of 3'30''. **Figure 6.9** (adapted from Gertz et al., 2002) shows the level of acrylamide in French fried potato chips after frying for 3'30''in different oils at two different temperatures 170°C and 180°C.

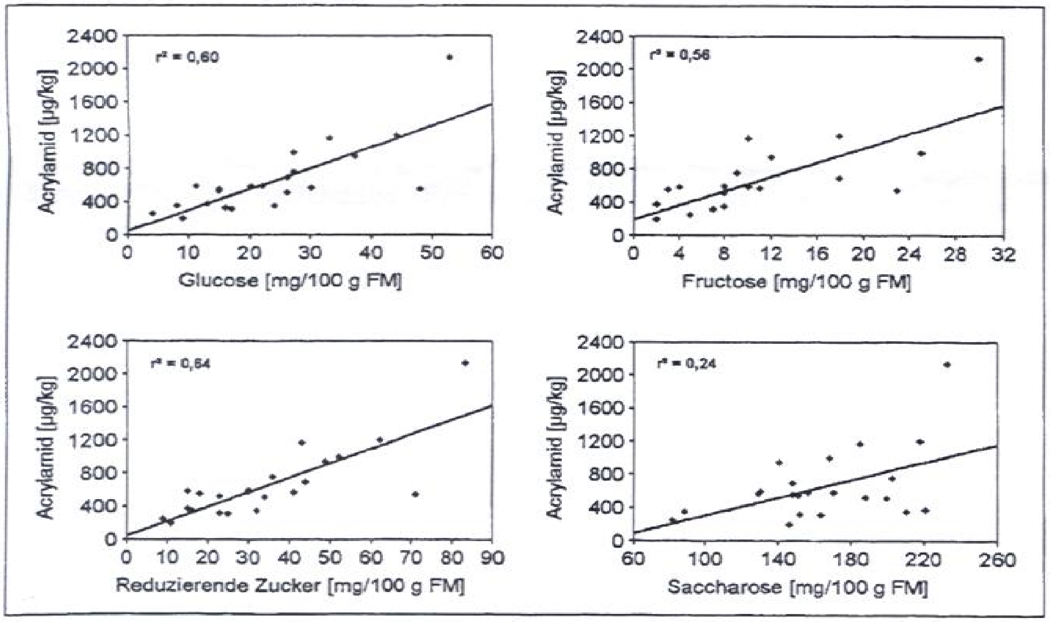

Figure 6.8 Regression of Acrylamide with Glucose, Fructose, total reducing sugar and saccharose (Adapted from Haase et al., 2003).

This means temperature plays an important role in the acrylamide formation process through the hydrolysis process of triacylglycerol and forming of acrolein from monoacylglycerol and forming of acrylic acid from reducing sugar. The full mechanism was presented by Gertz and Klostermann (2002) (**Figure 6.10).** Moreover, certain additives added to frying oil also affect the levels of acrylamide production. For example, at a conference in Germany on November 28th 2002, it was announced that specific additives to the frying oil, such as silicon for example, can have a major impact on the acrylamide content in the final product (Canada's Investigative Consumer

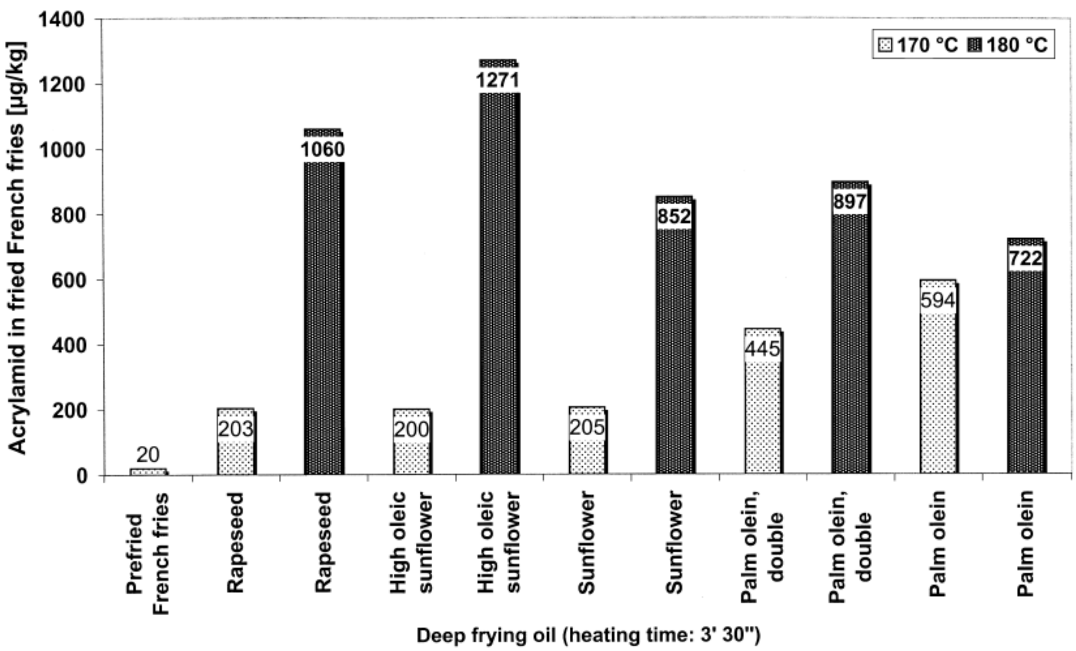

Figure 6.9 Change of acrylamide level in French fries after heating in various oils for 3mins and 33 seconds at 170°C and 180°C, respectively (Adopted from Gertz et al., 2002).

Program.htm). Gertz and Klostermann (2002) also studied the effects of additives in oil on acrylamide formation in French fried potato chips. The authors established that French fries prepared in restaurants where oils with a silicone addition demonstrated a higher level of acrylamide than the French fries in restaurants that used oils without silicone. Silicone, legally permitted in Europe as additive E900, is often used as anti-foaming agent that enhances the surface tension. There was a monomolecular layer formed at the surface of fried products when silicone was added to a deep frying fat. This layer may prevent/hinder or reduce the evaporation of water–steam, which removed acrolein or acrylamide. Therefore, the acrylamide concentration is increasing in such French fries (Gertz et al., 2002). The authors also found that a higher concentration of acrylamide was created in the potato chips when they were frying at higher temperature (180°C) compared to 170°C with the same amount of concentration of E900 added to the frying

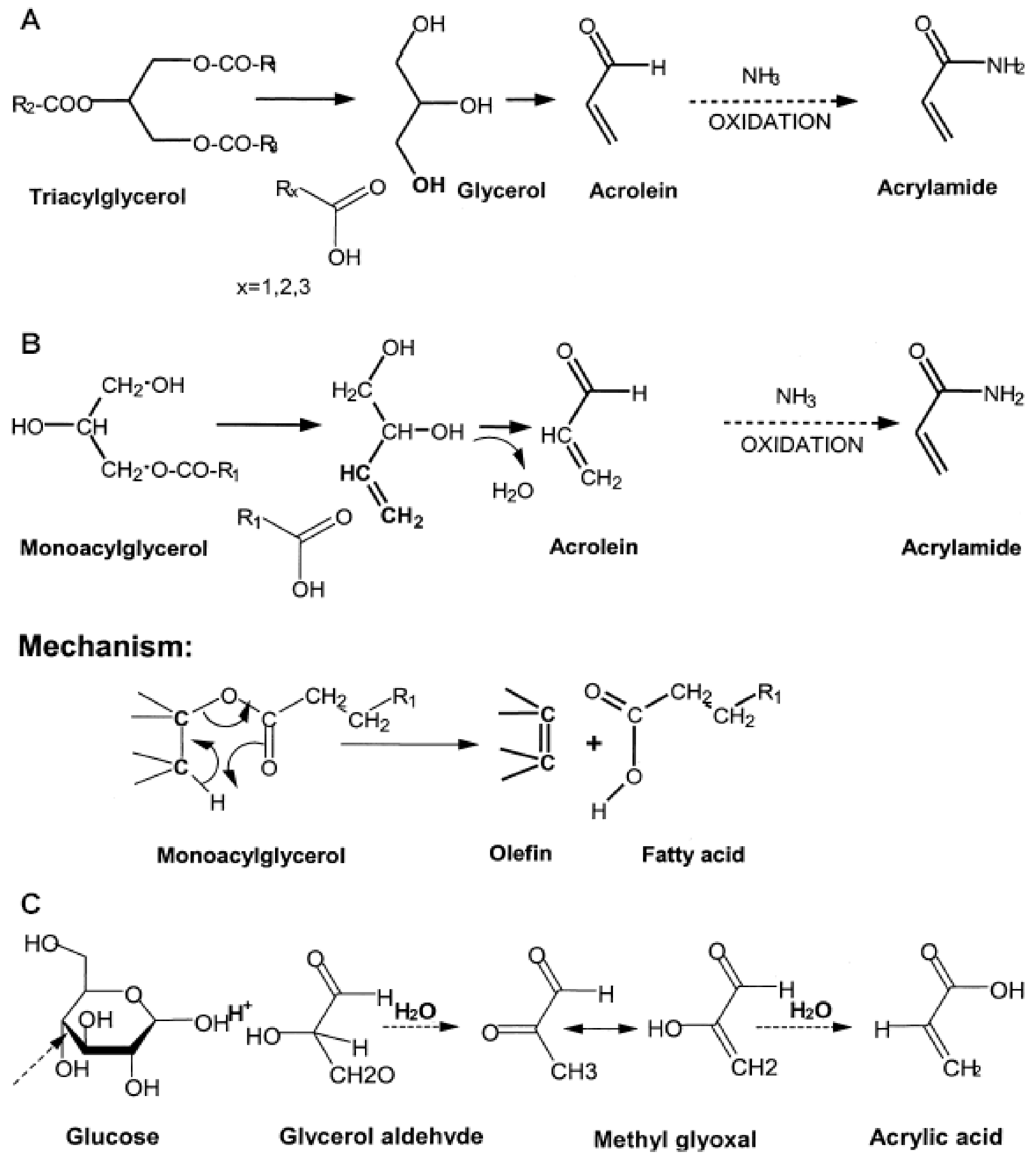

Figure 6.10 A. Forming of acrylamide by hydrolysis of triacylglycerol. B. Forming of acrolein by a cyclic mechanism from monoacylglycerol. C. Forming of acrylic acid from reducing sugar (Adopted from Gertz et al., 2002).

oil. The results were obtained from testing different oils in this research (Gertz et al., 2002).

In this current study, the frying canola oil used for acrylamide investigation does not contain the additives.

6.4 Materials and methods

6.4.1 Materials

The standard chemicals were purchased.

Acrylamide (GC assay ≥ 99.9%), Electran, BDH Laboratory Supplies , England. Hexane (95% purity), GC grade. Methanol (GLC assay ≥ 99.7%), specially purified for HPLC, Ajax Finechem, Australia.

6.4.2 Potato samples

Potato samples were prepared and fried as described in previous **Sections (2.2.2.1, 2.2.2.2, 3.2.2.3, 3.2.2.4)** and the experimental procedure is shown in **Figure 3.1.** Potatoes with the density of 1.1049 ± 0.0057 $g.ml^{-1}$ were chosen for the investigating acrylamide formation.

6.4.3 Acrylamide measurement

The method used (Gas Chromatography/ Mass Spectrometry) for acrylamide detection in this study is based on the method of Tateo and Bononi (2003) (Dipartimento di Produzione Vegetale, Università degli Studi di Milano, Italia).

Sample preparation

Each sample with 15 slices of potato chips (in order to obtain more than 5 g solid potato after oil extraction) was finely ground by coffee grinder and defatted in the Soxhlet extractor system as described in **Section 2.2.2.3.1.** The residual solvent was removed under vacuum. Twenty milliliters of methanol were added to 5 g of defatted sample in a sealed flask which was then stirred for 15 min followed by mixing for 2 min in an ultrasonic bath. The methanol phase was put into a sealed tube and centrifuged at 2,500 rpm for 5 min, then the recovered clear fraction was carefully poured in a volumetric glass 25 ml then diluted to volume (25ml) and fast filtered. One microlitre of the filtrate was injected into the GC/MS (splitless mode 1 min). For sample with low level acrylamide that could not be detected by the GC/MS in the above procedure, 10 ml of sample fluid was evaporated by using vacuum oven at ambient temperature to 2ml, (to increased by 5 time the acrylamide concentration) and then injected.

GC/MS analysis

A GC/MS QP5000 (Shimadzu) in acquisition SIM (Single Ion Mode) mode was used. The column was a EC^{TM}-WAX (30 m x 0.25 mm i.d., 0.25 μm film thickness; Alltech; Illinois, U.S.A.) and the temperature was set isothermal mode for 1 min at 60^{o}C, then it was increased at 10^{o}C/min to 240^{o}C. The acquisition mode was the SIM (Single Ion Mode) monitoring ion *m/z* 27, 55, and 71. The relative abundances in the acrylamide mass spectrum were, respectively, 27, 55, 71.

The calibration curve was established by measuring the SIM area of the *m/z* 71 peak (molecular ion). The external standard method was used: the calibration curves were made from standard solutions of acrylamide ranging from 27.875 to 2230 μg/L (ppb) and 128 to 10000 μg/L (these two calibration curves were established in this study).

Percentage reduction

The percentage reduction of acrylamide on treated sample compared with control sample was calculated by equation

$$\text{Reduction } \% = ((C_{control} - C_{treated}) / C_{control})*100 \qquad \textbf{(6.1)}$$

Where $C_{control}$ = Acrylamide content of control sample (μg/g solid)

$C_{treated}$ = Acrylamide content of treated sample (μg/g solid)

6.5 Results and discussion

6.5.1 Calibration curves

Two experiments were carried out to obtain the calibrations in this study. The first one had the standard solutions of acrylamide ranging from 27.875 to 2230 µg/L (ppb) The second standard curve had an acrylamide ranging from 128 to 10000 µg/L. Both of them were linear and had r^2 of 0.9909 and 0.9925 respectively in the range considerably. The relationship of area count and acrylamide concentration from two calibrations is similar. The final calibration curve is presented in **Figure 6.11. Figures 6.12** and **6.13** show a typical gas chromatogram of a potato sample analysed using GC-MS. Potato sample was prepared from the control sample (NPND) with 5 minutes frying time at 180°C.

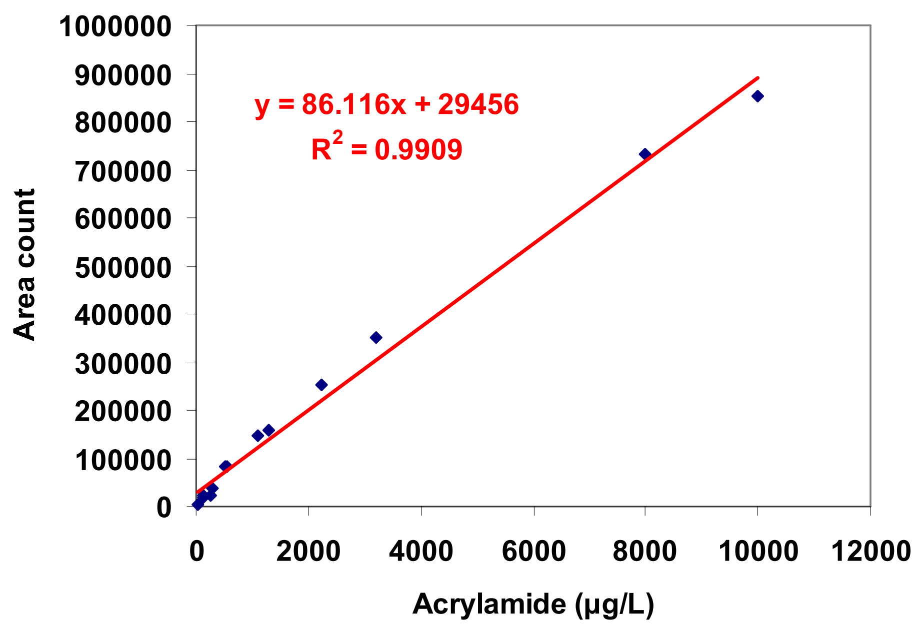

Figure 6.11 Calibration curve for acrylamide (GC/MS detection).

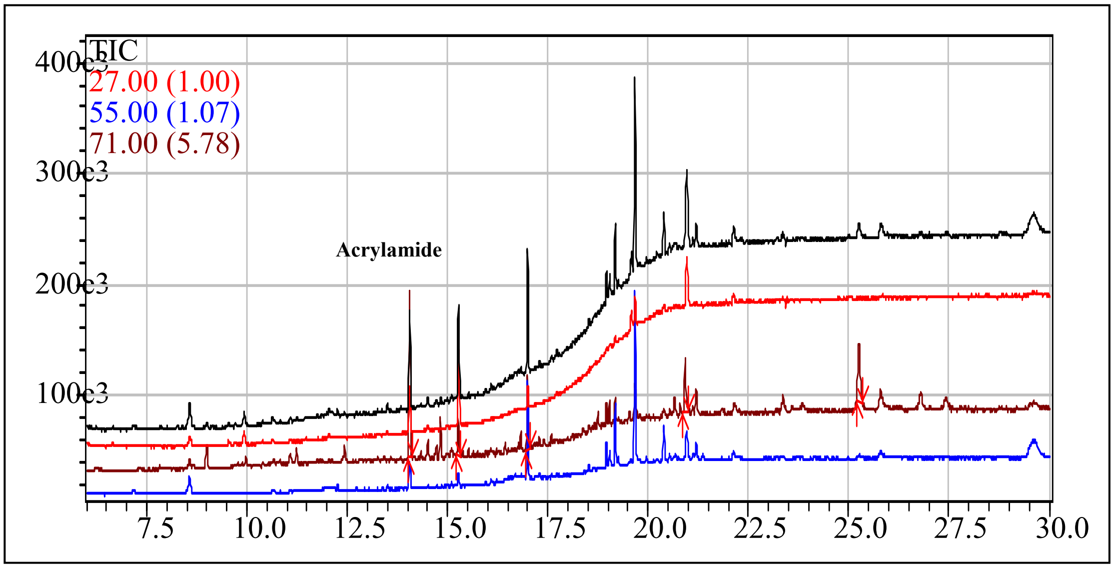

Figure 6.12 Gas chromatogram of a potato sample injection with GC-MS detection.

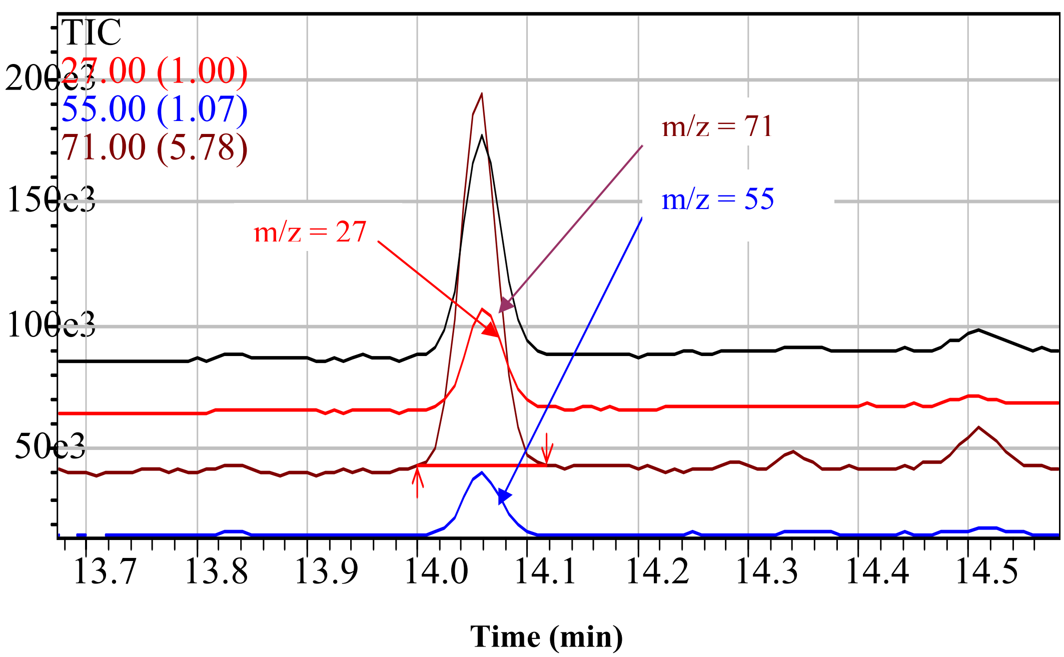

Figure 6.13 Chromatograph of acrylamide content analysis with GC/MS detection (SIM mode) of control sample potato crisps.

6.5.2 Effect of vacuum frying on the acrylamide formation of the PNSD treated potato crisps

Table 6.4 and **Figure 6.14** show the acrylamide content of NPND potato crisps conventionally fried at 180^{o}C (control samples) and acrylamide content of PNSD potato slices fried under vacuum frying at 120^{o}C, 150 mbars. The percentage reduction of acrylamide was also calculated by equation and presented in this table. There was a strong evidence that the acrylamide content (μg/gsolid) of potato crisps was significantly less under these conditions than the acrylamide content of control samples fried under conventional conditions 180^{o}C in the final stage of the frying process.

Table 6.4 Acrylamide contents of the PNSD potato crisps fried under vacuum at 120^{o}C, 150 mbars and that of the control samples.

Frying time (min)	Control samples		VF-PNSD (120^{0}C, 150 mbars))		Reduction % (on dry basis)
	Average (μg/g solid)	stdev	Average (μg/gsolid)	stdev	
0	0.00	0.000	0.00	0.00	0.00
1	1.44	0.000	1.09	0.026	24.23
2	2.03	0.307	5.25	0.059	not reduction
3	2.40	0.319	2.30	0.023	3.84
4	5.65	0.425	0.49	0.153	91.36
5	5.87	1.256	0.59	0.033	89.88
6	N/M*	N/M*	0.42	0.185	N/M*

N/M*: No measurements

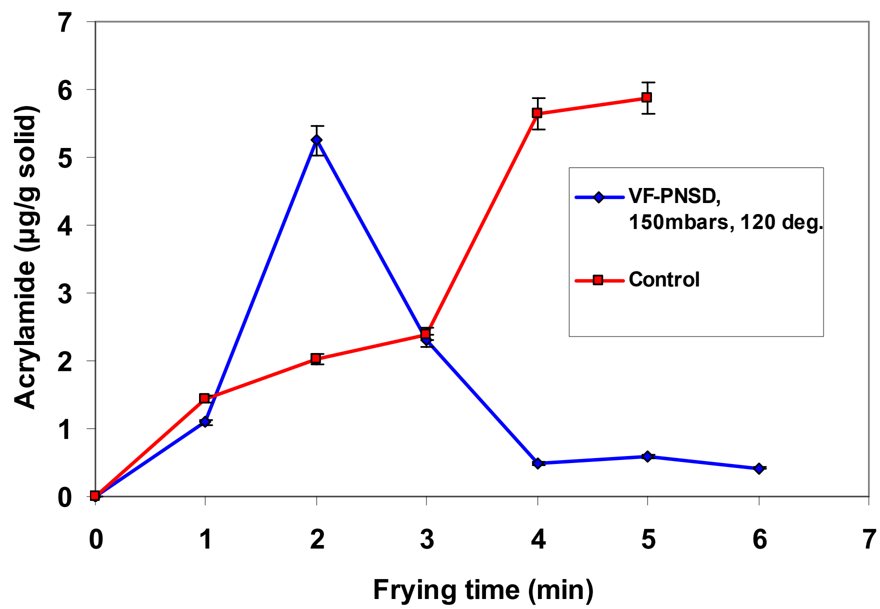

Figure 6.14 Acrylamide formation in vacuum frying (120^{o}C, 150 mbars) of PNSD potato crisps and conventionally fried (180^{o}C) control samples.

As described in **Section 5.3.2.1,** the control samples obtained at the last 4 to 5 (or 6) minutes of frying were considered as being representative of the final stages of frying. These are the timings when the potato slices obtain their crispiness. For PDNS the potato slices frying at 120^{o}C, 150 mbars the final stage was the last 6 minutes of frying time. At that stage, the acrylamide content of control samples was 5.87 ±1.256 µg/g solid whereas the content of acrylamide in vacuum frying samples was 0.42 ± 0.185 µg/g solid (**Table 6.4**). There was a 92.85 % (= ((5.87 - 0.42)/5.87)*100)) reduction on the acrylamide formation of PDNS potato crisps when the PDNS potato slices were fried at 120^{0}C, 150 mbars.

6.5.2 Effect of pre-drying on the acrylamide formation of the vacuum fried potato crisps

Table 6.5 and Figure 6.15 show the effects of pre-drying on the acrylamide formation in potato crisps under vacuum frying (120^{o}C, 150 mbars). There was a difference in the acrylamide content in potato crisps between pre-dried and non-pre-dried potato crisps. The lower acrylamide formation was observed in the pre-dried potato slices as compared to non-pre-dried. The percentage reduction on the acrylamide formation applying on the pre-dried samples is also presented on **Table 6.5**. The phenomenon of acrylamide formation in pre-dried potato chips is probably affected by the water content in potato crisps. The results agrees with Stadler et al. (2002) and Mottram et al., 2002 on the formation of acrylamide in buffer solution and in dry reaction as mentioned in **Section 6.3.2.2.**

The result obtained from the current study has not been reported previously.

Table 6.5 Acrylamide contents of the NPNS and PNSD potato crisps frying under vacuum conditions 150mbars and 120^{o}C.

Frying time (min)	VF-NPNS (120^{0}C, 150 mbars))		VF-PNSD (120^{0}C, 150 mbars))		% Reduction (on dry basis)
	Average (µg/g solid)	stdev	Average (µg/gsolid)	stdev	
4	2.05	0.497	1.39	0.170	31.90
5	1.87	0.155	0.70	0.056	62.45
6	1.17	0.364	0.37	0.010	68.61

Figure 6.16 demonstrates acrylamide content in potato crisps at conventional frying (control sample), PDNS and NPNS vacuum frying at 120^{o}C, 150 mbars. Vacuum frying at 120^{o}C, 150 mbars reduced acrylamide formation by 70 to 80% (= ((5.87 – 1.87)/5.87)*100)) to ((5.87 – 1.17)/5.87)*100); applying to non-pre-dried non-sugar dipped (NPNS) potato crisps and compared to control samples (**Table 6.4** and **6.5**). The results in this study were obtained in the same period as that by Granda et al. (2004) and Granda and Moreira (2005). The levels of acrylamide detected are in general agreements with their findings.

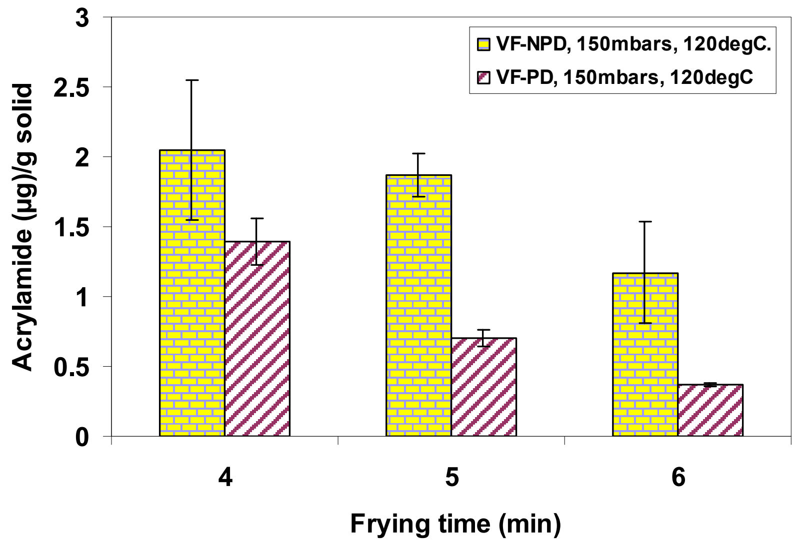

Figure 6.15 Effect of pre-drying on the formation of acrylamide in the potato crisps under vacuum frying (120^{o}C, 150 mbars).

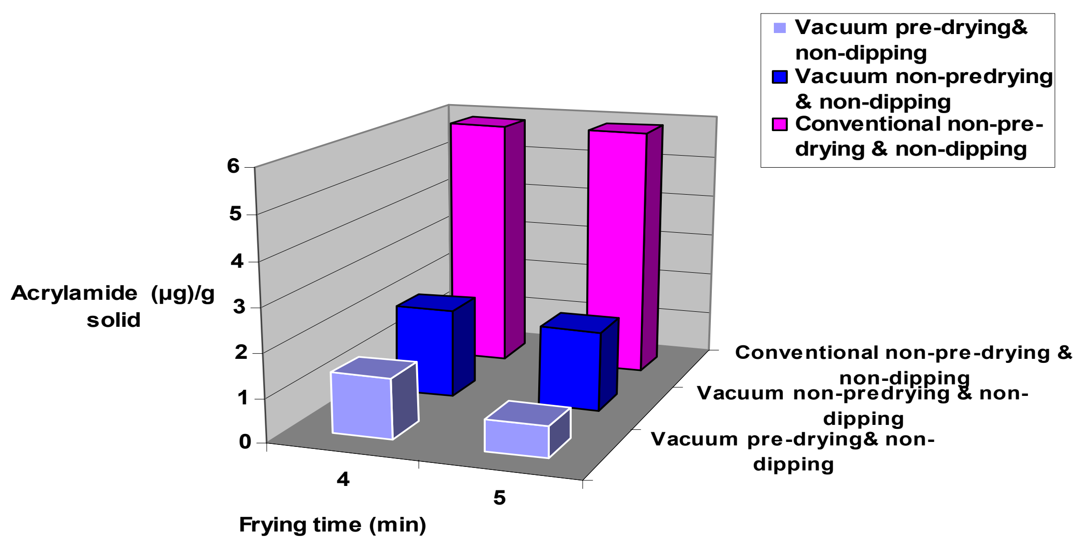

Figure 6.16 Acrylamide content in potato crisps using different treatment and frying methods.

Potato crisps pre-dried and non-sugar dipped (PNSD) vacuum fried at 110°C, 150 mbars were also measured for their acrylamide contents, but no acrylamide was found in those samples. However, high level of acrylamide were found in pre-dried and sugar dipped potato crisps vacuum fried at 110°C, 150 mbars. The results were in contrast to a number of studies on the levels of acrylamide by the effects of temperature and sugar (saccharose) on the acrylamide formation in laboratry as well as in fried potato chips (Tareke et al., 2002; Mottram et al., 2002; Stadler et al., 2002; Gertz and Klostermann, 2002 and Haase et al., 2002). The formation of acrylamide at high temperature has been verified by these researchers and it seemed that no acrylamide was created at 120°C as shown by Mottram et al. (2002). On the other hand, Tareke et al. (2002) also found low acrylamide formation at 100°C and 110°C when French fried potatoes were heated in a temperature-programmed oven. Haase et al. (2002) have showed that no correlation on the saccharose contents on the acrylamide formation in potato crisps.

6.6 Conclusion

Vacuum frying is an excellent technique to reduce the acrylamide formation in fried potato crisps. There has been 80% acrylamide reduction in the NPNS potato crisps, which were vacuum fried at 120°C, 150 mbars. Pre-dried and vacuum-fried potato crisps had less acrylamide formation compared to the untreated crisps. There has been a 92% acrylamide reduction in the pre-dried potato crisps, which were vacuum fried at 120°C, 150 mbars and no acrylamide was detected when the crisps were pre-dried and non-sugar dipped (PNSD) and vacuum fried at 110°C, 150 mbars.

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7. SUMMARY OF THE MAIN CONCLUSIONS

Vacuum frying and pre-treatment of potato crisps have been shown to be effective processes in the oil content reduction of fried potato crisps. Pre-drying and subsequent sugar solution dipping are considered as an advantageous pre-treatment procedure to considerably reduce the amount of oil uptake during frying and to improve the crunchiness of the potato crisps. Crisps that had been pre-treated and conventionally fried at 180^{o}C had 30 % reduction (on wet basis) on the oil content compared with untreated samples. There was more reduction obtained in the oil content of potato crisps when crisps had been pre-treated and vacuum-fried at 110^{o}C, 150 mbars. They had 58 % (on dry basis) or 42.22 % (on wet basis) less oil than the samples that were not treated but fried under the conventional condition at 180^{o}C.

Vacuum frying at low temperature is an advantageous technique to improve the colour of pre-dried and sugar dipped potato chips.

Vacuum frying is an excellent technique to reduce the acrylamide formation in fried potato crisps. The crisps which were pre-dried and then vacuum fried had less acrylamide formation compared to untreated crisps. Acrylamide was undetectable when the crisps were pre-dried and vacuum fried at 110^{o}C, 150mbars. Under those conditions, potato crisps contained less than 50% (on dry basis) or 39.68% (on wet basis) of oil compare to the control samples. Their colour and crispiness have been found to improve considerably.

8. RECOMMENDATIONS FOR FUTURE WORK

- Acrylamide formation of fried potato crisps at low temperatures with the additional sugar needs to be investigated further (one indication from this study though not written in detail is that sugar addition may increase acrylamide formation).
- Sugar hydrolysis of potato during frying may need to be investigated.
- Kinetics of colour change and acrylamide formation of potato crisps with pre-drying and sugar solution dipping and then vacuum frying, should be established.
- Heat transfer and mass transfer characteristics of the potato crisps frying under vacuum conditions should be studied in detail.

9. PUBLICATION

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Reducing oil content of fried potato crisps considerably using a 'sweet' pre-treatment technique

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