Review

Pioneer Works on Rheology of Foodstuffs in Japan

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Food is essential to life. The traditional and distinctive types of foods have been maintained and provided over many centuries in every country in the world. During recent years, processing technology has been developed for manufacturing a wide range of foods, and meanwhile many investigations on the rheology of foodstuffs have been made by scientists in the various academic disciplines. This article reviews the original works on rheology and texture of foodstuffs published by Japanese authors, and integrates advances made in areas of food science and technology in Japan. The contents are divided into four sections; some interpretations of food texture, rheological characteristics of traditional Japanese foods, progress in methods of rheology in allied fields, and international correlations in research activities on the rheology of foodstuffs.

Key Words: Disperse system / Hydrocolloid / Kinesthesia / Psychorheology / Texture profile

1. INTRODUCTION

About fifteen centuries ago, Japan brought a country under a single authority and took the first step towards forming an original nation under the influence of the old Asian civilization originated mainly in ancient India, China and Korea. In the course of social growth, Buddhism and the national archaic sentiment on Nature (not Shizen but Onozukara or Jinen in the archaic Japanese expression) affected the various ways of everyday life including the diet. The Japanese people finally kept meat and dairy products away from their dishes, since an Imperial ordinance of prohibition order had issued against the habit of meat eating in seventh century by the Emperor Tenmu (?-686). Consequently, this resulted the development of traditional Japanese dishes, which were mainly composed of a variety of cereals, vegetables, fishes and poultry.

In the middle of the nineteenth century, Japan emerged from a long feudal isolation and made an effort to form a modern nation patterned after Western countries. This is the so-called Meiji Restoration. The nation has since undergone abruptly many changes in their life styles and has passed through a variety of great experiences including improvements in nutrition and dietary life because of a measure calculated to enrich and strengthen a country. The various food-processing industries have continued its growth, and the consumption of meat and dairy products is now increasingly high.

Food research in this country is being conducted either for a mutual benefit on a common basis by the public institutes and universities, or privately by the food companies. The research activity on food science should be concerned with the various academic disciplines including rheology, as dietary life widely and yet deeply maintains social activities in the world.

We can assess the mechanical behaviour of foodstuffs in two ways. Just as foods have colour, smell and taste, so they exhibit mechanical behaviour in which they react in certain ways when we deform them. They may be hard or soft, tender or tough (roughly meant as Yawarakai or Katai in Japanese, respectively), chewy or brittle, smooth or stringy. They may flow easily or with difficulty. We can touch the food, squeeze it, bite it or chew it and say what we think of it. This is the sensory approach. On the other hand, it is certainly possible to assess objectively the mechanical behaviour of foods, i.e., the physical approach. This is independent of the individuals, uses instruments and should be called rheological. The interaction between the sensory and rheological approaches has been referred to as psychorheology.

This article reviews some historical backgrounds and pioneer works on rheological approaches to the mechanical property of a variety of foodstuffs in Japan. The leading story in this review will be developed in a period from roughly about 1960’s to 1980’s.
2. WHAT FOOD TEXTURE IS

It is not easy to translate an English term “texture” into Japanese because of a wide spectrum of connotations, e.g. a word “textile” is the same origin with texture derived from Latin. As far as the food texture is concerned, Ms. Szczesniak \textit{et al.} \textsuperscript{6} confirmed that the texture is very significant among food attributes in the consumer awareness based on the word-association test given to one hundred people with selected 74 food products in order to determine their degree of texture consciousness and terms used to describe kinesthesia (\textit{i.e.}, mouth feel) of foods. Szczesniak \textsuperscript{7} then made an attempt at proposing a texture profile of foods (cited in Ref. 4 in Japanese) in which textural attribute could be subdivided into three categories as “mechanical”, “geometrical” and the other “analytical” characteristics.

Her proposal for texture profile of foods had been widely accepted in the field of food science, while Sherman \textsuperscript{8} examined her texture profile precisely and suggested various modifications so as to place them on a more basic rheological foundation. It is remarked that Szczesniak in US and Sherman in UK, an opponent in argument on the food texture with each other, had cooperated in a task for bringing out of an international journal concerned with rheology, psychrheology, physical and sensory testing of foods (\textit{i.e., Journal of Texture Studies}) under the supervision of Scott Blair in 1969. Their efforts to issue this quarterly journal have been succeeded to Bourne, Cornell Univ.

Yoshikawa \textit{et al.} \textsuperscript{9} pointed out that the English sensory terms for expressing the texture characteristics of foodstuffs can only be understood by the English speaking people, because the delicate nuances of human sensations are so unique in each language that many of them are not possible to be translated satisfactorily into each other. Yoshikawa \textit{et al.} \textsuperscript{9, 10} therefore set out to prepare a texture profile using Japanese sensory terms. They asked a group of respondents to select pertinent words from the Japanese texture terms and to indicate their relative importance for each of the specified 97 food items. Because of certain peculiarities of the Japanese language, however, they faced to a difficulty of grouping these words into categories reflecting the various textural characteristics of foods, since there are many onomatopoeic words of synonyms in the Japanese language for expressing the same or similar sensations. This had been described in details in English papers. \textsuperscript{11-13}

Recently, Ms. Hayakawa \textsuperscript{14} has published an interesting collection of literary essays introducing many of words in Japanese concerned with a variety of delicacies in human sensations in the dietary life in Japan.

The author would like to cite an opinion to the food texture stated by Soně\textsuperscript{15} in 1966 in his book, as the followings: “Texture is one of the technical terms which may be used for describing the physical qualities of foodstuffs. The physical qualities expressed objectively and subjectively should be represented by pure quantities or by physical meanings. Thus, first, the sensory responses to stimulation must be defined using physics and psychology. Second, it is necessary to apply objective measurements in order to clarify the physical qualities. A systematized approach for study of the first case is the so-called psychorheology or psychophysics, and the second case belongs to rheology”.

3. TRADITIONAL MATERIALS BEING TESTED

Since the food materials themselves are so diverse, it is not surprising that the types of foods studied present a rather confusing pattern, which may be understood by reference to the genesis and history of the Japanese social background \textsuperscript{1} described hereinbefore.

Japanese people had originated many seafood products because of the geographical condition. A typical one is a gel-state food “Kamaboko”, which is prepared from raw fish meat by mixing with a small amount of salt, grinding into a mash, and heating in a fixed size and shape. The gel state in Kamaboko is brought by heating mashed fish meat. Mashed one gradually starts to coagulate even at room temperature, and this phenomenon is denoted as “Suwar”. Shimizu H, \textit{et al.} \textsuperscript{36} studied the stress relaxation of flying-fish meat mashed with 3% salt, and had shown that the tensile force of the sample increases with increasing time at a definite temperature, while the relaxation velocity becomes progressively lower. The reviewer would like to note that Shimizu and his school had made a lot of works on the rheological properties of Kamaboko, and they had tried to explain physical meanings of the sensory terms used by manufacturers describing the quality of mashed fish meats and products of Kamaboko.\textsuperscript{17} All the results obtained were gathered in the collection of research materials entitled “Publications of Shimizu and Associates on Food Chemistry of Marine Products, 1929-1949; 1951-1953; 1954-1955; and 1956-1960” published by the Laboratory of Technol. Chem. Dept. of Fisheries, Kyoto Univ.

A series of studies on the binding quality of fish meat gels based on the measurement of rheological properties were also made by Satoh \textit{et al.} \textsuperscript{18-20}, and they extended studies to the
binding quality of various meat products.

One of the most important staple foods in Asia including Japan may be rice at present. Japanese people especially prefer to eat the soft and sticky cooked rice, which is prepared from the so-called japonica-type short grain. Katoh 23) suggested that the textural property of cooked rice plays a very significant role in the sensory assessment. Chikubu et al. 22) measured the viscoelasticity of gelatinized rice starch using oscillatory rheometer, and they clarified that both dynamic viscosity and elasticity were much influenced by the quality of rice starch under definite condition of gelatinization. Yasumatu et al. 23, 24) attempted to make clear some factors affecting the cooking quality of rice in view of correlating texture of cooked rice with rice compositions in a series of studies.

The noodle “Udon” is one of the traditional staple foods in Japan. It is essentially boiled dough strings prepared from a mixture of wheat flour and salted water. Shimizu T, et al. 25) investigated the physical properties of typical Udon provided from domestic Japanese wheat flour. The results obtained indicated that Udon exhibits instantaneous elasticity of the order of $10^6$ Pa, viscous flow about $10^9$ Pa·s, and some retarded elasticity under constant stress. The elastic modulus decreased with increasing temperature, suggesting that both entropy and internal energy changes occur when Udon is deformed. They also found that the elastic modulus, breaking energy, and stress relaxation increase while a period of boiling time increases.

The traditional confection “Yôkan” is ordinarily prepared from red bean (i.e., Azuki) starch, sugar and agar-agar. A concentrated suspension of the starch in sugar solution is heated, and then prepared gel state with agar-agar. Nakagawa 26) had advised for testing the texture of Yôkan applying a modified penetrometer, and suggested that the sensory term “body” or “consistency” of Yôkan is much influenced by the amount of sugar together with the condition of mixing procedure of the suspension during heating before gelatinization.

In addition to the above, we have a variety of traditional foods, which are certainly familiar in dietary life in Japan. A kind of pudding “Uiro” prepared from rice flour is one of the Japanese confectionary foods; it is essentially a rice starch gel containing sugar and flavours. It is also well known that “Konnyaku” and “Tokoroten” are hydrogels of polysaccharides; the former is basically thermo-irreversible konjac-mannan gel and the latter is mainly composed of aqueous agar-agar solution exhibited thermo-reversible gel. The so-called “Tôfu” is the coagulum of soybean protein, so that Western people will be able to have an imagination on Tôfu as soybean curd. “Kogori-tôfu (i.e., Kôya-tôfu)” is provided by freeze-drying fresh Tôfu, and shows a sponge-like porous appearance.

Ms. Nakahama 27) played a lot of pioneer works on rheology of gel-like foods in the field of cookery science together with her coworkers. She 28) made a lot of examinations on the creep behaviour and jelly strength of starch gels. The results obtained can be summarized, as follows: (1) The creep behaviour of starch gels could be represented by a mechanical model with six elements. (2) The mechanical parameters of the model and jelly strength were much influenced by the origin of starches. (3) The mechanical parameters and jelly strength increased with increasing amount of oligo-saccharides. (4) An addition of inorganic salts was effective of increasing elastic moduli. Nakahama et al. 29) made an attempt at predicting correlation between the amount of ingredients and rheological properties of starch gels using a simple lattice design for multi-component systems. The texture of cooked Kogori-tôfu was also studied by Nakahama et al. 30), and it was suggested that the sensory assessment of texture of the cooked sample is influenced by the condition of storage of the original Kogori-tôfu.

The late Ms. Katsuta 31), Nara Women’s Univ, left many works on rheology and texture of foods, e.g. psychorheological approach on the elastic modulus of a traditional local production “Sasa-Dango” in Niigata district. The author has felt a great regret at the loss of her research activity using modern techniques in the field of cookery science.

### 4. PROGRESS IN METHODS IN ALLIED FIELDS

There were original works on the theoretical and instrumental aspects for measuring and understanding characteristics of rheology and texture of a variety of foodstuffs.

Oka et al. 32) developed a theory on the behaviour of a Bingham body when parallel plates plastometer was applied. This theory was successfully utilized by the practice for expressing the creep behaviour of plastic fats (e.g. margarine) and butter. 33–35) The cone penetrometer was used to measure the textural properties of various semi-solid foods so as to derive the apparent viscosity and yield value from relationship between the cone penetrating force and the depth of the cone in a constant speed penetrometer. 36) Nakahama 37) constructed a compression type plastometer for evaluating mechanical properties of various gel-like food materials such as starch
gels, boiled egg-white, pudding, Yōkan, Tōfu, cooked rice, etc. Okabe \textsuperscript{38–40} attempted to construct various types of instruments for evaluating textural properties of solid foods. These instruments can be classified into three general types; a compression type plastometer, a simplified texturometer, and a tensile testing machine. The instruments could be used to obtain the creep curve, the mastication pattern, and stress relaxation of various solid foods, respectively. Okabe \textsuperscript{41} also tried to analyze the mastication patterns for their physical meanings, and classified them into four types as elasticity, retarded elasticity, plastic flow, and brittle fracture. Shimizu T, \textit{et al.} \textsuperscript{42, 43} observed dynamic viscoelasticity of wheat flour dough in a range of very low frequency using a double cylinder rheometer designed by Nakagawa \textit{et al.}\textsuperscript{44} Kon-no \textit{et al.}\textsuperscript{45} reported on the trial manufacture of an apparatus for measuring dynamic viscoelasticity of gel-like foods in an audio frequency. Matsumoto \textsuperscript{46} designed an apparatus for evaluating static relaxation modulus of soft food materials such as wheat flour dough within a series of normal strains. Using this apparatus, he found that the mixture of hydro-gluten protein isolated from wheat grains behaves as a linear viscoelastic body.

The rheological properties of butter and related materials were widely studied by Sonè.\textsuperscript{15, 35} He and his coworkers\textsuperscript{33, 34} measured the effects of working on the mechanical properties of butter, and found that the plastic viscosity and rigidity decrease rapidly with the amount of working procedure while pronounced recovery of these values can be observed after setting for more than 8 days. Sonè\textsuperscript{35} therefore considered the effect of working procedure on the destruction of the network structure of fat crystals formed in butter as well as on the size reduction of each fat crystal. The recovery of apparent viscosity and yield value due to setting was considered to be associated with re-crystallization of fat molecules, so that Sonè tried to examine the dilatometry of butter specimens over a setting period of two weeks at a constant temperature. He evaluated the degree of crystallization of fats from the specific volume of butter specimens, and found successfully a relationship between the amount of crystallized fats in butter and the magnitude of apparent viscosity or yield value of butter. He found that the Avrami theory\textsuperscript{47} for crystallization kinetics of metals gave an analogous with changes in rheological properties of butter and fats.

Nishinari and his coworkers\textsuperscript{49} proposed a zipper model approach in respect to the thermo-reversible gel-sol transition occurring in some of the hydrocolloids. According to the zipper model approach, a gel is assumed to consist of zippers, and each zipper consists of $N$ parallel links playing secondary weak bonds, \textit{e.g.} hydrogen bond. They simulated an opening process of molecular zippers from both ends when dissolution occurs in hydrated gels. The zipper model approach will be possible to explain, for example, the effect of sucrose on DSC curve of aqueous agar-agar gels.\textsuperscript{50}

### 5. INTERNATIONAL CORRELATIONS

It may be well known that Scott Blair originated a series of studies on the psychorheology from his interest in an ability about sensory assessment of craftsmen in bread and cheese manufactures just before the World War II. Kambe\textsuperscript{51, 52} introduced details about thought and historical background of the psychorheology according to many of articles published by Scott Blair and his colleagues.

About that time (1956), Nikuni, Isemura and their coworkers\textsuperscript{53} translated an English book into Japanese entitled as “Foodstuffs, Their Plasticity, Fluidity and Consistency” edited by Scott Blair. This translation work was seemingly expected a role in stimulus to the research activity concerning to the field of food science in Japan, but the reviewer did not obtain any information on the real state of affairs at that time.

On the other hand, the author translated a Japanese book\textsuperscript{15} entitled as “Consistency of Foodstuffs” written by Sonè into English, and published in Holland. This translation work was fortunately introduced by Scott Blair\textsuperscript{54} in a book review with his well-meaning comment. The author also translated an English book\textsuperscript{21} into Japanese entitled “An Introduction to Food Rheology” written by a friend of him, Muller, Univ of Leeds. The author struggled to complete a translation work with Muller’s literary sentence, while Kambe\textsuperscript{55} had kindly prepared a book review on this translation work.

Nishinari organized an International Conference on Hydrocolloids at Tsukuba in 1992, and then he has continued to play a principal role in organizing committee of the Conference, which has been held in all parts of the world in alternate years. Nishinari has also made an effort to edit the proceedings of an International Conference on Hydrocolloids, and the proceedings of the 1st and 4th Conferences\textsuperscript{56, 57} have stimulated Japanese people working for not only food science but the other areas of science and technology. Foodstuffs are regarded as so complicated dispersions that the colloid and
interface science plays a significant part in the field of food science. Nishinari et al. 50) have recently translated an English book entitled as "An Introduction to Food Colloids" written by Dickinson, Univ of Leeds, into Japanese. This translation will be sure to give a wide spectrum of academic disciplines for understanding precise conditions of a variety of foodstuffs.

6. CONCLUDED REMARKS

Rheology, which has been skillfully introduced into polymer science and technology from the middle of the last Century 59), should also be of direct relevance to the research activity in food science and technology.

In addition, achievements in colloid and interface science should contribute to understand the substance and state of foodstuffs, which are one of the typical dispersions consisting of a variety of biological components. The rheology of disperse foodstuffs, which are one of the typical dispersions consisting of polymer science and technology from the middle of the last Century 59), should also be of direct relevance to the research activity in food science and technology.

In addition, achievements in colloid and interface science should contribute to understand the substance and state of foodstuffs, which are one of the typical dispersions consisting of a variety of biological components. The rheology of disperse system 60) therefore plays a significant part together with biorheology 61) in the field of food science. Dickinson 58) has described in his book, as follows: "What seems to make us happy when we first come into this world is a regular supply of a warm white colloids called milk. As we grow up, we acquire a taste for other food colloids like butter, cheese, mayonnaise, ice cream, and so on. Colloidal particles are the little things that give these foods their characteristic properties. It gives pleasure to the mind to learn why milk is a stable colloid, and how it can be transformed into cheese and yogurt. In terms of the food we like to eat, the little things mean a lot."

The author would like to dedicate this short review to the late Dr GW Scott Blair and to Dr P Sherman (Prof emeritus, Univ of London), who had given a favour to him an atmosphere of rheology when he was working for the Unilever Research Lab, Welwyn, UK from 1966 to 1970.

REFERENCES