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Received: 2017. March – Accepted: 2017. July

Food safety and energetics analysis of the heat treatment of milk

Keywords: properties of cow's milk, heat treatment, pasteurization, peroxidase enzyme inactivity, food safety, plate pasteurizer, heat output, COP, energetics

1. Summary

The food safety and energy efficiency of the heat treatment of cow's milk was investigated by our research group. Of the known heat treatment processes, the results of our investigation are presented in the case of a cow's milk treated at 75 °C and held for 5 minutes. Proper treatment of cow's milk is probably the most pivotal issue in food production, but from the point of view of the manufacturing plant, food safety and the amount of energy used for the production are important as well. Our measurements were carried out using the PG 015 pasteurizer of the Department of Food Hygiene of the University of Veterinary Medicine. The electricity input and the amount of heat used during the technology were measured. The efficiency of food production was defined as the ratio of the utilized energy to the energy invested. To verify the adequacy of the heat treatment, peroxidase enzyme inactivity tests were performed untreated milk, and for treated milk, without and with holding it at the given temperature for the proper length of time.

Based on our measurement results it can be stated that a heat recovery zone built into the technology keeps the COP (coefficient of performance) value above one. By optimizing the length of the heating and the heat treatment, by adjusting the desired technological temperature precisely, and by the application of food safety limit values and analyses, the efficiency of a larger system can be improved significantly as well.

2. Quality and food safety characteristics of milk

Milk production is an important quantitative and qualitative factor in human nutrition; milk production is responsible approximately 25% of food production. The term milk usually refers to cow's milk. Milks of other mammals are usually designated by word combinations that indicate their origins (e.g., buffalo milk, goat's milk).

By drinking one cup of milk a day, we can contribute significantly to the recommended daily intake of nutrients. Regular consumption of milk and dairy products is recommended for a healthy and balanced diet.

The properties of the animal species and the individual animals, the composition of the feed and the feeding method, weather conditions, seasons and the lactation period all have a major influence on the chemical composition of milk.

The biological function of milk is to provide nutrients and immunological protection to newborns. For most animal species, milk is the only food consumed for weeks, or even months. Therefore, it should contain all the nutrients necessary for growth and development: amino acids, vitamins, minerals, energy (***Table 1***).

So milk and its products contain many important nutrients. Milk consumption is a fast and easy way to supply nutrients to the body with a relatively low calorie intake.

Milk mainly consists of water, and a small amount, approximately 12.5% dry matter. The dry matter is composed of milk fat, proteins, lactose, minerals and

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vitamins. The amounts of the individual components of milk may vary within a wide range **[1]**, **[2]**, **[6]**, **[11].**

Milk, cheeses and yogurts contain the beneficial nutrients listed in ***Table 1*** in varying amounts.

From a colloid chemistry point of view, milk is a complicated polydisperse system, consisting of organic and inorganic ingredients. It is partly an aqueous solution (minerals, lactose), partly a colloidal solution (proteins), and partly an emulsion (fat).

Milk is a „fat in water" emulsion; butter is a „water in fat" emulsion. Colloidal solutions are characterized by the dispersion of small, electrically charged particles, and by their affinity to water molecules. In milk, whey proteins are found in the colloidal solution, while casein proteins are found in the colloidal suspension **[12]**, **[13].** The most important ingredients of milk are listed in ***Table 2***.

Water is the solvent of certain ingredients of milk (lactose, certain vitamins, minerals, salts). Water is also the dispersion medium of water insoluble materials (milk fat, proteins, enzymes, colloidal minerals). More than 83% of the weight of milk is water. Because of the high water content, milk spoils very easily. Shelf life is also influenced by the amounts of free and bound water.

For cow's milk, fat content can vary widely (2.8-6.5%). The major part (>99%) of the fat content of milk consists of the fatty acid esters of glycerol, i.e., triglycerides. To a much smaller extent, mono- and diglycerides are also present. Milk contains other lipids also, such as phospholipids, glycolipids, lipoproteins, serins, carotenoids, as well as fat-soluble vitamins, free amino acids and flavorings.

Cream is obtained by skimming milk. When cream is fermented using lactic acid bacteria, sour cream is obtained. The remaining part after skimming is called skimmed milk or low-fat milk. The name of completely non-fat milk is plasma.

The fat content of milk is finely distributed in the form of fat globules, as an emulsion. There is a fat droplet, consisting of glycerides, inside the fat globules, surrounded by a phospholipid (lecithin) layer. The entire structure is covered on the outside by a protective protein coating, which is negatively charged outward, so the fat globules repel each other in sweet milk (pH = 6.7). During churning, the protective coating is disrupted, liquid fat is released and clumps together.

Milk fat consists of approximately 200 fatty acids, at least 90% of which are non-volatile saturated and unsaturated compounds: palmitic acid (C16:0), stearic acid (C18:0), myristic acid (C14:0), oleic acid (C18:1), etc.

Consequently, the amount of volatile saturated and unsaturated fatty acids is approximately 10%, responsible for the characteristic aroma of milk fat: butyric acid (C4:0), caproic acid (C6:0), caprylic acid (C8:0), capric acid (C10:0).

Milk fat contains all physiologically important essential fatty acids, including linoleic acid and linolenic acid. Next to breast milk, the composition of cow's milk is closest to the ideal composition in terms of nutrition physiology.

Milk fat is also a major source of energy, 1 g of milk fat provides 38 kJ of energy. The quality and quantity of milk fat are influenced by the type of the dairy cow, the course of lactation and the feeding.

Milk fat is an important source of vitamins: it contains vitamins A, D, E and K, among others.

3. Milk proteins

The amount of proteins in cow's milk can vary between 2.8 and 4.5%. 95% of the nitrogen-containing compounds of milk are made up of proteins. The remaining 5% consists of amino acids and other N-containing compounds.

Cow's milk contains almost all of the essential amino acids necessary for human health. The essential amino acid requirement of an adult can be met by the consumption of 0.5 liters of milk per day, with the exception of phenylalanine and methionine.

Milk proteins can be divided into two main groups: caseins and whey proteins. In addition to these proteins, small amounts of other proteins are also present, for example, the membrane proteins of the fat globules and enzymes. In the milk of ruminants (cows, sheep, goats), caseins are predominant (casein milks). In the case of other domestic animals and humans, the amount of albumins is greater (albumin milks).

Caseins (phosphorus-containing proteins) occur only in milk, bound to calcium.

Caseins coagulate due to rennet. They also coagulate as a result of alcohol, if the pH of milk is <6.3. That is why the alcohol test can be used to check the freshness of milk.

During the coagulation of milk, whey proteins remain in solution, i.e., in the whey, and can be divided into the albumin and globulin fractions. In the case of mastitis, the amount of albumins and globulins increases significantly. During heat treatment, these proteins can burn onto heat transfer surfaces, decreasing the efficiency of pasteurization.

Lactoferrin is an iron binding glycoprotein, removing iron (Fe^{3+}) from microorganisms, therefore, it has a bacteriostatic effect (especially on Gram-negative bacteria).

Transferrin is also an iron binding glycoprotein, entering milk from blood plasma (plasma protein).

Phosphatases catalyze the hydrolysis of phosphoric acid esters. Phosphatase is a heat-sensitive enzyme, inactivating at 72 °C in 15 seconds, therefore, the measurement of the phosphatase content can be used to check the pasteurization of milk. Bacterial phosphatases are heat-resistant; alkaline phosphatase is mainly produced by *Penicillium* species, while acidic phosphatases are produced by *Staphylococcus*, *Achromobacter* and *Penicillium* species.

Amylase catalyzes the hydrolysis of starch into sugars. It is heat-sensitive, inactivates at 56 °C in 30 minutes. Its activity also decreases while standing, and so the quantitative determination of amylase can be used to check the freshness of milk. Bacterial amylase is mainly produced by spore-forming bacteria, such as *Bacillus* species and yeasts.

Proteases are protein-digesting enzymes, which can only be detected after prolonged storage at a warm temperature (37-42 °C). They are partially inactivated during pasteurization. Lactic acid bacteria produce proteolytic enzymes that are used in cheese production (*Clostridium, Achromobacter* species), but are also responsible for the spoilage of pasteurized milk.

Xanthine oxidase decolorizes methylene blue in the presence of formaldehyde (Schärdinger reaction). It is present in large amounts in cow's milk, but only traces can be found in breast milk, therefore, the analysis of the xanthine oxidase enzyme can be used for the rapid differentiation of the two milk types.

Catalase decomposes hydrogen peroxide to water and free oxygen. Its activity increases in mastitic milk because of the high catalase content of the white blood cells in the milk, therefore, catalase analysis can be used as an indicator of mastitic milk **[9]**.

4. Lactose

Lactose is a disaccharide, consisting of a glucose and a galactose molecule. It is less sweet and dissolves in water slowly. It is used in the pharmaceutical industry and in formula manufacturing. In the human body, it is degraded by the lactase enzyme, the lack of which causes lactose intolerance. The lactose content of cow's milk is 4.7-4.8%, the amount being relatively consistent across different species. In the case of mastitis, the lactose content of the milk decreases. Crystalline lactose caramelizes at 170-180 °C. In aqueous solution, caramelization starts at 80 °C. The characteristic flavor of boiled milk is due to this process. Lactose is converted into lactic acid by the enzymes of lactic acid bacteria. The salts of lactic acid, i.e., lactates, are degraded to propionic acid and acetic acid, or lactic acid and butyric acid by different bacteria. These processes can be utilized in the production of sour milk products, by the addition of the appropriate pure culture.

5. Minerals

Different macro- and microelements are found in milk in the forms of organic and inorganic salts (***Tables 3 and 4***).

6. Vitamins (and provitamins)

Milk contains all the vitamins needed for humans, however, it cannot be considered a complete source of vitamins, because the amounts of certain vitamins do not cover the needs (e.g., vitamin C), and they can also decompose during heat treatment or by light.

7. Physical properties of milk

The color of milk is white or yellowish white. Its white color comes from the proteins and fat globules of the colloidal solution. The yellowish color comes mainly from carotene. Watered milk is of bluish white color.

Milk is almost odorless, if milking has been performed hygienically and it was cooled rapidly. The frequent characteristic odor of udder-warm milk comes from the air of the cowshed or from possible contaminants of milk, because volatile substances are absorbed strongly by milk fat.

Milk is slightly sweet, full, free from foreign flavor. It is sweet because of the lactose, and full because of the lipids. Skimmed milk has an „empty" flavor. Homogenization, decreasing the size and increasing the number of the fat globules enhances the full flavor, because more fat globules come into contact with the taste buds of the tongue.

The flavor and color of milk are strongly influenced by feeding, but they are also affected by the course of lactation, contamination, and the state of health of the dairy cow.

8. Food safety aspects of pasteurization

Milk can also contain microorganisms which enter the milk during milking or transportation. By the inactivation most of these microorganisms, milk will not endanger the health of the consumer, and will be suitable for processing. The most efficient way of sterilization is heat treatment.

Pasteurization is the sudden, short-term warming of liquids to 60-90 °C, followed by rapid cooling, in order to destroy pathogenic bacteria and to reduce the number of other microorganisms as much as possible, in a logarithmic way. The procedure was developed by the French chemist Louis Pasteur (and Claude Bernard), who recognized and demonstrated that microorganisms can cause fermentation and diseases, and that foods spoil because of airborne organisms. The method was mainly used to increase the shelf-life of wine, vinegar and beer, first in 1862.

At the same time, several months earlier, successful experiments had been also performed by the chemist Móric Preysz, who presented his research results under the title "Preventing the secondary fermentation of Tokaji wine"on October 16, 1862, at the assembly of the Association of Hegyalja Wine Producers **[4]**.

Pasteurization therefore is a heat treatment below 100 °C, performed in order to reduce the number of microorganisms to such a low level, which no longer poses a health risk and, at the same time, extends the shelf-life of the product.

In the dairy industry, different forms of pasteurization are used. Heat treatment procedures are shown in ***Table 5*** **[5], [6].**

During pasteurization, in addition to as complete destruction of germs as possible, the goal should be not to change the original nature and properties of milk considerably. The heat treatment procedure is carried out depending on the dairy product to be prepared. Pasteurization does not necessarily cause complete germ destruction; the efficiency of standard procedures – the rate of germ destruction – is 99.0-99.9%. UHT (Ultra High Temperature) pasteurization and sterilization result in „commercial sterility", with an efficiency of almost 100%. Potentially surviving microbes cannot propagate to such an extent within the shelf-life of the product which would induce any alteration in milk.

Heat treatment is primarily justified by human health aspects (destruction of microorganisms) and regulations, but the procedure is also aimed at safer manufacturing and, in certain cases, the shaping of the character and the sensory properties of the product.

According to EU regulations, the heat treatment of milk is the: „heating of factory milk used in the production of raw milk and milk-based products, resulting in a negative phosphatase reaction". For the production of dairy products, only milk that has been treated at least at 71.7 °C for 15 seconds, or which has undergone an equivalent heat treatment, can be used **[14], [15], [16]**.

To test the efficiency of heat treatment, it is common practice to perform the inactivity test of the peroxidase enzyme.

Among pathogenic microbes, the most heat-tolerant (thermotolerant) is Mycobacterium tubercolosis (TBC). Therefore, the temperature and length of pasteurization has to be above the thermal death curve of the TBC pathogen. The temperature-time curve of the inactivity of the phosphatase enzymes of milk is above the death curve of TBC bacteria, therefore, if the phosphatase enzymes have been inactivated, then, supposedly, TBC pathogens have been destroyed as well.

The peroxidase enzyme degrades as a function of treatment temperature and time, so it is suitable for checking the proper heat treatment of the samples. The analysis can be carried out using the Storch test. The basis for the determination is that, in inadequately heat-treated milk, hydrogen peroxide is decomposed by the peroxidase enzyme, and the atomic oxygen thus liberated oxidizes N,N-diethyl-1,4-phenylenediamine hydrochloride to a gray colored compound. During the experiment, the Storch test was performed on 3 parallel samples for each heat treatment method. During the test, 50 μl of 1–3 m/m% H_2O_2 solution was added to 5 ml of heat-treated milk sample, then the sample was homogenized. Subsequently, 100 μl 2 m/m% paraphenlyenediamine solution was added to the sample dropwise, and then the sample was again homogenized. The color reaction was visible to the naked eye within a few seconds **[3]**.

Figure 1 shows the results of peroxidase enzyme tests of cow's milk samples taken before, during and after the heat treatment process. In the picture on the left, the result of the reaction of untreated raw cow's milk is shown, while in the middle, the result of milk treated at 75 °C, but for only a short time. In the picture on the right, the result of the peroxidase enzyme inactivity test of cow's milk treated at the appropriate temperature for the appropriate time is shown **[3]**. A target value of T=88 °C was set on the pasteurizer. The actual treatment temperature was 75 °C.

9. Energetics aspects of milk processing

The heat treatment of milk is an easily automated process for both small, medium and large companies. In the vast majority of cases, milk as a raw material is available to processors in sufficient quantity and quality. The already mentioned pasteurization as a technological process can be regulated easily in practice and can be managed well. Generally, each milk processing plant has its own well-established „recipe" in terms of machine settings, using which the number of microorganisms can be lowered to the appropriate level.

In accordance with 21st century requirements, in order to obtain energy performance certificates, plants and large companies are more and more forced to improve energy efficiency (Energy management systems MSZ EN ISO 50001:2012 standard) **[17]**.

Thus, even in the case of an existing technology, it is desirable to strive to find optimum energetics.

In the case of the heating and holding operations, research has already been carried out to investigate the effects of microwave heat treatment **[7]**.

Possibilities for novel technological solutions were also investigated regarding the application of heat pumps in the food industry **[8]**.

At the same time, energetics and thermal conditions are not always clear even in the case of equipment frequently used in the food industry, operating with traditional plate heat exchangers.

Figure 3 shows a photograph of the PG 015 experimental equipment of Agrometál-Food-Tech Kft. in the Food Technology Laboratory of the Department of Food Hygiene of the University of Veterinary Medicine.

In the case of the PG 015 plate pasteurization equipment, having a nominal flow rate of q=150 liter/hour under operating conditions, the temperature (T) of the milk was measured during heat treatment at various technological points. The pathway of milk is indicated by arrows in ***Figure 4*** **[10]**.

The instantaneous thermal input (Q) can be calculated from the difference between the measured temperature values. For example, from the temperature difference between T_0 and T_1, the value of Q_{01} can be calculated:

$$Q_{01} = c \cdot \dot{m} \cdot (T_0 - T_1)\ [kJ/s]=[kW],$$ where:

c – is the specific heat of milk 4.1813 [kJ/kg °C];*

$\dot{m}$ – is the mass flow of milk [kg/s];

T_0 – is the temperature before holding [°C];

T_1 – is the temperature after holding [°C].

Figure 5 shows the evolution of the major technological parameters as a function of time. In the heating stage, left of the dashed line, the desired temperature value was T_k=75 °C. After t=300 s, the value of T_1 can be read from the figure. To the right of the dashed line, the heat treatment stage can be seen. The current (I) drawn by the equipment from the grid was measured in all cases. For the heat treatment stage, a flow rate of q=150 l/h was set.

Based on the measured temperature data and the flow rate, the thermal input and the heat energy generated can be calculated.

During the measurements, the technology was divided into four distinct stages:

- Q_{02} – the stage of heat energy required to warm up milk (based on T_0-T_2) [kWh];
- Q_{01} – the stage of heat energy lost during holding (based on T_0-T_1) [kWh];
- Q_{13} – the stage of heat energy required for cooling (based on T_1-T_3) [kWh];
- Q_{37} – the stage of heat energy required for the cooling of the tank (based on T_3-T_7) [kWh].

The indicator for energy efficiency quantification is the coefficient of performance (COP), which is the ratio of the heat energy and the electric energy drawn from the grid.

Based on the instantaneous current values drawn from the electrical grid, the instantaneous value of the electrical power can be calculated. Knowing the instantaneous values and the operating time, the actual amount of electricity used can be calculated. As was described above, the instantaneous heat input and the thermal energy generated can be determined from the measured technological parameters. Based on these, the coefficient of performance can be determined easily.

Figure 6 shows that the coefficient of performance was determined both for the heating and the holding stage. It can also be seen from the figure that, taking into consideration one heating and one holding stage, the „overall" coefficient of performance of the experimental system was determined as well.

In practice, in accordance with the technological parameters, the system is heated up at the beginning of the shift, and then several holding stages are added to the production, depending on the final products to be manufactured in the plant.

With our experimental settings, we would like to draw attention to the fact that significant amounts of energy can be saved by a well-designed plant technology, by adequate scheduling of daily production, and by decreasing the number of unnecessary heating stages.

One of the first steps of the increasingly fashionable energy audits is the mapping out of the efficiency of energy systems. Based on existing data, the goal is to improve the efficiency of operation.

Energy optimization is usually aimed at reducing expenditure, however, in the food industry, safety and quality are of primary importance.

Based on these, it is not enough to search for an energy optimum, meaning minimum energy consumption, it is advisable to support the effectiveness of our milk pasteurization technology using microbiological analyses, such as the above-mentioned peroxidase enzyme inactivity test.

10. Conclusions

As a result of the food safety and energetics analysis of the heat treatment of cow's milk it can be said that the heat treatment of the product is influenced by numerous factors. If the physical, chemical and microbiological characteristics of milk are known, as well as the energy efficiency of the available heat treatment process, then our production process can be optimized in accordance with food safety regulations. During the optimization, by taking into consideration the results of the accepted peroxidase enzyme inactivity tests, the efficiency of our system can be improved, making our production cost-effective.

Currently, we are working on food analytical measurement methods enabling further technological optimization, aimed at following the physical parameters of milk (e.g., conductivity, pH, redox potential), built into the technology. Characteristics measured during the technological process provide an opportunity to improve the quality of the final product.

Regarding the relationship between one of the physical parameters of milk, its conductivity, and the efficiency of the heat treatment, there is currently no sufficient number of test results available. However, we are able to differentiate between raw milk and differently heat-treated milk, based on conductivity. Verification of the procedure is still under way.

11. Acknowledgement

Our research and measurements are carried out at Szert István University, at the University of Veterinary Medicine and with the help of the instruments and staff of Agrometál-Food-Tech Kft.

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