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Electrical engineering in milk pasteurization: ohmic heating, pulsed electric fields, instrumentation, and process control

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ABSTRACT

Milk pasteurization is a critical operation for reducing pathogenic microorganisms while retaining acceptable nutritional and sensory quality. Conventional low-temperature long-time and high-temperature short-time processes rely on controlled heating, accurate temperature measurement, and verified holding times. Electrical engineering contributes directly through power conversion, resistive or dielectric heating, high-voltage pulse generation, instrumentation, automation, and process safety. This review examines milk pasteurization technologies reported up to 2017, emphasizing conventional electrically controlled thermal systems, ohmic heating, and pulsed electric field processing. The operating principles and engineering requirements of each approach are considered alongside microbial inactivation, product quality, and scale-up constraints. Ohmic heating converts electrical energy into heat within conductive milk, whereas pulsed electric fields apply short high-voltage pulses to disrupt microbial cell membranes, often in combination with mild heating. Published studies demonstrate promising microbial reductions and quality retention, but outcomes depend strongly on electric-field strength, pulse parameters, temperature, flow distribution, and milk composition. Remaining challenges include nonuniform treatment, electrode fouling or corrosion, high-voltage equipment cost, sensor reliability, and validation of microbial safety. The review concludes that integrated electrical, thermal, and control-system design is essential for reliable, energy-conscious, and scalable milk pasteurization.

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1. INTRODUCTION

Milk pasteurization is an essential food-processing operation designed to reduce pathogenic microorganisms and improve product safety. Conventional pasteurization uses carefully controlled combinations of temperature and processing time to achieve the required microbial inactivation while limiting undesirable changes in milk composition. The effectiveness of this operation depends on heating uniformity, accurate temperature measurement, sufficient holding time, and reliable cooling after treatment. In industrial facilities, these requirements make pasteurization not only a food-processing problem but also an important application of electrical engineering, instrumentation, and automation.

The main engineering challenge is maintaining consistent thermal and electrical treatment despite variations in milk composition, flow rate, equipment condition, and operating temperature. Conventional systems generally use electrically powered pumps, heaters, temperature sensors, controllers, and actuated valves to maintain the required process conditions. Emerging technologies introduce additional electrical requirements, including controlled alternating-current supplies for ohmic heating and high-voltage pulse generators for PEF processing. These developments create opportunities for more direct energy delivery, but they also introduce challenges involving electrical safety, treatment uniformity, equipment reliability, and process validation [1], [2].

This review examines the relationship between electrical engineering and milk pasteurization through literature published no later than 2017. It focuses on conventional electrically controlled thermal systems, ohmic heating, and pulsed electric field processing. The discussion connects their operating principles with power-conversion requirements, sensing, automation, microbial inactivation, and milk quality. The objective is to identify the engineering factors that determine whether an electrically assisted pasteurization system can provide safe, repeatable, and economically practical operation.

2. CONVENTIONAL MILK PASTEURIZATION AND ELECTRICAL CONTROL

Conventional pasteurization remains the principal reference process for evaluating alternative milk-treatment technologies. Low-temperature long-time processing uses relatively moderate heating over an extended period, whereas high-temperature short-time processing uses higher temperatures and shorter holding periods. Industrial HTST systems commonly employ plate heat exchangers, holding tubes, pumps, temperature sensors, and automatic flow-diversion arrangements. These components must operate together to prevent inadequately treated milk from entering the product outlet.

Electrical engineering contributes to conventional pasteurization through heating equipment, instrumentation, and automated control. Temperature sensors, including resistance temperature detectors and thermocouples, provide feedback to electronic controllers that regulate heaters and associated actuators. Programmable logic controllers can coordinate pumps, valves, alarms, and temperature-control sequences according to defined operating conditions. A dependable system must also detect sensor faults, loss of heating capacity, abnormal flow, and power interruptions before these conditions compromise product safety.

Temperature measurement is particularly important because the holding time is meaningful only when the required temperature is actually maintained throughout the relevant process. Poor sensor placement, calibration errors, delayed measurements, or nonuniform flow can result in incorrect estimates of thermal exposure. Control systems should therefore incorporate calibrated sensors, suitable sampling intervals, alarm thresholds, and protective interlocks. These requirements demonstrate that conventional pasteurization already depends substantially on electrical instrumentation and control engineering [1], [2].

3. OHMIC HEATING: DIRECT ELECTRICAL HEATING OF MILK

3.1. Operating principle and electrical configuration

Ohmic heating is an electrically driven thermal process in which alternating electric current passes directly through a conductive food material. Milk acts as an electrical resistance, converting electrical energy into heat within the product rather than relying exclusively on heat transfer from an external surface. The process therefore offers the possibility of rapid volumetric heating, with heating performance strongly influenced by electrical conductivity and applied electric-field strength. Kaur and Singh reviewed the underlying principles and applications of ohmic heating, identifying electrical conductivity as a key parameter in equipment design [3].

An ohmic heating system typically consists of electrodes, a food-processing chamber, an alternating-current power supply, voltage-control equipment, temperature sensors, and a data-acquisition unit. The electrodes transfer electrical energy into the milk, while the power supply determines the applied voltage and operating frequency. Electrode geometry and spacing influence the electric-field distribution and therefore affect heating uniformity. The electrical properties of milk must also be characterized because composition, temperature, and ionic content influence conductivity and energy absorption [3], [4].

3.2. Potential benefits and technical limitations

Ohmic heating can reduce the time required to raise product temperature because electrical energy is generated within the food itself. This characteristic may reduce temperature gradients and improve heating uniformity compared with some indirect heating arrangements. Sivaraman *et al.* [5] reviewed the application of ohmic heating in dairy processing and discussed its relevance to microbial inactivation, product quality, electroporation, and fouling. Nevertheless, these advantages depend on equipment design and operating conditions rather than being guaranteed by the heating principle alone.

Electrode performance is a major consideration in practical ohmic heating systems. Direct contact between electrodes and milk can lead to electrochemical reactions, electrode corrosion, or migration of metallic components into the product. Fouling and deposits may also change the effective electrical and thermal behavior of the processing chamber during extended operation. Consequently, electrode material selection, electrical waveform, frequency, cleaning procedures, and food-contact compatibility must be considered during system development [4], [5].

3.3. Implications for process control

The control of an ohmic heater requires coordinated regulation of electrical input and product temperature. Electrical conductivity may change as milk heats, which can alter current flow and power dissipation during processing. A controller that relies only on a fixed voltage command may therefore fail to maintain the intended heating profile under changing product conditions. Closed-loop regulation using temperature and electrical measurements can provide a more dependable basis for controlling the process [3], [5].

4. PULSED ELECTRIC FIELD PROCESSING

4.1. Principle of microbial inactivation

Pulsed electric field processing uses short-duration, high-voltage electrical pulses to expose microorganisms to intense electric fields. The applied field can induce electroporation, which creates pores in microbial cell membranes and may lead to irreversible loss of membrane integrity. Unlike conventional thermal pasteurization, PEF can produce microbial inactivation with relatively limited bulk temperature increase when operated under appropriate conditions. Early engineering reviews identified PEF as a promising technology but emphasized that reliable treatment delivery and industrial-scale equipment design were major obstacles [6]–[8].

A PEF processing system typically contains a high-voltage power supply, pulse-forming circuit, switching device, treatment chamber, electrodes, cooling equipment, and process-monitoring instruments. The power electronics must generate pulses with controlled amplitude, duration, frequency, and waveform. The treatment chamber must expose the flowing milk to a sufficiently uniform electric field while avoiding excessive electrical stress and unwanted discharge. These requirements make PEF a particularly important intersection of high-voltage engineering, electronics, food microbiology, and process design [6], [7].

4.2. PEF applications in milk processing

Research has investigated PEF as an alternative or complementary treatment for reducing microbial populations in milk. Ang *et al.* [9] evaluated microbial quality, physicochemical characteristics, and selected nutrients in milk processed using PEF under different treatment and storage conditions. Their findings demonstrated that treatment conditions influence microbial outcomes and that product quality must be considered alongside microbial reduction. Lau *et al.* [10] also compared PEF-based processing with conventional thermal pasteurization and microfiltration, highlighting the importance of evaluating both microbial inactivation and refrigerated shelf life.

Further research has examined the response of specific microorganisms to PEF treatment. Wu *et al.* [11] investigated the inactivation of *Bacillus cereus* spores in milk and found that spores were relatively resistant to PEF alone, while treatment conditions involving higher temperatures influenced inactivation. Mosavi *et al.* [12] reported that PEF effectiveness against bacteria in whole milk increased with treatment temperature and electric-field intensity. These findings indicate that PEF performance depends on the interaction between electrical parameters, thermal conditions, microbial characteristics, and milk composition.

4.3. Product quality and process optimization

The quality of PEF-treated milk is another important consideration when evaluating the technology. Palanisamy and Thirunavukarasu *et al.* [13] compared volatile compounds in PEF-treated milk and conventionally pasteurized milk, demonstrating that processing conditions can influence the volatile profile. Shadowski [14] subsequently examined bacterial reduction and enzyme inactivation in bovine whole milk treated with PEF and preheating. These studies illustrate that microbial safety, enzyme activity, flavor, and nutritional properties should be evaluated together rather than treating bacterial reduction as the only performance criterion.

PEF optimization requires careful selection of electric-field strength, pulse width, pulse number, frequency, inlet temperature, and flow rate. Saura *et al.* [15] investigated continuous milk pasteurization using PEF and demonstrated the importance of operating conditions, preheating, and post-treatment holding arrangements. Nallaperuma *et al.* [16] also studied the suitability of experimental design methods for predicting microbial inactivation under different PEF conditions. These investigations show that process optimization should combine electrical measurements, thermal monitoring, microbial testing, and statistical evaluation.

5. COMPARISON OF ELECTRICAL PASTEURIZATION TECHNOLOGIES

The three principal approaches differ in how electrical energy contributes to microbial inactivation and product heating. Conventional pasteurization uses electrical energy mainly to operate heaters, pumps,

sensors, and control systems, while the milk receives heat through an external thermal medium. Ohmic heating passes current directly through the milk to generate heat internally, whereas PEF applies short high-voltage pulses to disrupt microbial cell membranes. Each approach therefore requires a different combination of power electronics, sensing, process control, and safety measures [18]-[21].

Conventional thermal pasteurization has the strongest position as an established industrial process with well-understood operating principles. Ohmic heating offers potentially rapid volumetric heating, but electrode compatibility, conductivity variation, and long-term operating stability require careful attention. PEF provides a promising route to microbial inactivation with limited bulk heating, although its effectiveness can vary according to microorganisms and process conditions. Neither electrically assisted approach should be assumed to replace validated conventional pasteurization without sufficient microbiological evidence and regulatory approval [5], [6], [9], [12].

6. ELECTRICAL ENGINEERING CHALLENGES AND FUTURE DEVELOPMENT

The development of reliable electrical pasteurization equipment requires attention to energy conversion, process measurement, and operational safety. Ohmic systems need stable power delivery and electrode designs that minimize corrosion, fouling, and nonuniform current distribution. PEF systems require high-voltage components capable of generating repeatable pulses under continuous processing conditions. Both technologies also require accurate temperature measurement and monitoring of product flow to ensure that the intended treatment is consistently delivered [5]–[8].

Automation offers an important route to improving process repeatability and reducing dependence on manual operation. A modern system can combine temperature sensors, current and voltage measurements, flow sensors, programmable controllers, data logging, and alarm functions. These components can support automatic adjustment of heating power, detection of abnormal operation, and traceability of processing conditions. Future systems should also incorporate fault detection, sensor calibration management, electrical protection, and secure recording of critical process data.

Industrial implementation remains constrained by equipment cost, scale-up, process validation, and maintenance requirements. PEF equipment can require expensive high-voltage power supplies and switching devices, while ohmic systems must address electrode durability and product-contact safety. Treatment uniformity is especially important because an apparently correct average temperature or voltage does not necessarily establish that every portion of milk has received an adequate treatment [18]-[25]. Further development should therefore prioritize validated continuous-flow designs, integrated electrical and thermal monitoring, and long-duration testing under realistic production conditions [6]–[8], [15].

7. CONCLUSION

Electrical engineering plays a central role in milk pasteurization through heating systems, power electronics, sensors, instrumentation, and automatic process control. Conventional thermal pasteurization remains an established approach, but ohmic heating and PEF offer alternative methods for delivering electrical energy to milk during processing. Ohmic heating converts electrical energy into heat within the product, whereas PEF uses high-voltage pulses to induce microbial membrane damage. Research published up to 2017 demonstrates promising applications, although performance depends on equipment design, electrical parameters, temperature, microbial resistance, and product composition.

The main challenge is ensuring that electrical treatment produces consistent microbial safety without compromising milk quality or operational reliability. Future systems should integrate accurate sensing, adaptive power control, validated treatment chambers, and comprehensive process monitoring. Industrial adoption will also depend on equipment cost, electrode durability, high-voltage safety, and compliance with food-processing regulations. Ultimately, successful electrical pasteurization requires the coordinated design of electrical, thermal, mechanical, microbiological, and control subsystems.

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