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Combining computer aided food engineering and electro-heating applications as contribution to food processing sustainability

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Can the combination of computer aided food engineering and electro-heating applications contribute to food processing sustainability? To what United Nations Sustainable Development Goal (SDG) this combination could contribute? Those are the questions addressed in this perspective. SDG7 is aimed to ensure the access to affordable, reliable, and sustainable and modern energy for all. According to World Bank, ensuring access to modern food cooking solutions is a key component to achieving for SDG7, and -since cooking is mainly based on heating processing- also the access to modern food heating solutions must be considered as a key component to achieving for SDG7. Electro-heating applications (EHA) in food processing include all processes using the interaction of a food material or product with an electromagnetic field, as in microwave, radio-frequency, and moderate electric fields processing. These technologies involve the use of electrical and -more recently- electronic circuits and require professional figures in their design. As result, the installation cost of these technologies is way higher than installation cost for heating processes using fossil sources, as fuel for fire boilers, as an example. Furthermore, at industrial level, these technologies may require *ad-hoc* design. Consequently, the food processing industry is quite slow in embracing such technologies along the productive lines. Computer aided food engineering (CAFE) has been recognized as valuable approach to shifts the paradigm from trial-and-error-based design to model-based design, using digital tools for the virtual representation of a food product or process, predicting the behavior of it. The combination of CAFE and EHA is the only way to help the food industry to embrace sustainability in most operations in which the heat transfer is involved. This paper presents a viewpoint on the challenges and opportunity to combine CAFE and EHAs as contribution to food processing sustainability.

KEYWORDS

computer aided food engineering, moderate electric fields, microwaves, radio-frequency, food processing sustainability

1. Introduction

According to the UN General Secretariat, the Sustainable Development Goals represent an opportunity to adopt resilient and inclusive low-carbon development pathways that must be used to help conserve natural resources, transform food systems, create better job opportunities, and move toward a green economy transition, more inclusive and just (United Nations, 2022). United Nations Sustainable Development Goal 7 (SDG7) is aimed to ensure the access to affordable, reliable, and sustainable and modern energy for all. There is no doubt that the electrical energy is the only form of energy that can be capillary distributed, without problems of emissions at least on the site where the energy is used. Furthermore, electrical energy can be produced by renewable sources. The share of renewable sources in total final energy consumption amounted to 17.7% globally in 2019 (IEA, IRENA, UNSD, World Bank, WHO, 2022). The shift toward an energy transition involves also developing Countries, where the installed renewable energy-generating capacity is growing fast (Ourworldindata.org, 2023). The run toward an independence from fossil fuel will probably accelerate the access to clean electrical energy, even if the COVID-19 pandemic has slowed the rate of new accesses.

Ensuring access to modern food cooking solutions is a key component to achieving for SDG7 (SDG 7.1.2), and -since cooking is mainly based on heating processing- also the access to modern food heating solutions must be considered as a key component to achieving for SDG7 (World Bank, 2020).

Electro-heating applications (EHA) in food processing include all processes using the interaction of a food material or product with an electromagnetic field, as in microwave, radio-frequency, and moderate electric fields processing. These technologies involve the use of electrical and -more recently- electronic circuits and require professional figures in their design. As result, the installation cost of these technologies is way higher than installation cost for heating processes using fossil sources, as fuel for fire boilers, as an example. Furthermore, at industrial level, these technologies may require *ad-hoc* design. Consequently, the food processing industry is quite slow in embracing such technologies along the productive lines.

Computer aided food engineering (CAFE) has been recognized as valuable approach to shifts the paradigm from trial-and-error-based design to model-based design, using digital tools for the virtual representation of a food product or process, predicting the behavior of it (Datta et al., 2022).

This paper presents a viewpoint on how the combination of CAFE and EHAs can contribute toward food processing sustainability.

2. Electro-heating applications in food processing: efficiency first

Most EHAs interact with the food material in a volumetric way. This means that—in most the circumstances—the limiting resistance to heat transfer (can be conduction in solid-like products or convection in liquid like ones) is overcame by the direct dissipation (inside the food product) of the electromagnetic energy into heat. This interaction makes the food heating very fast, if compared to convection or (even better) to conduction in foods. These techniques are claimed to provide an even temperature distribution, but this is not always true, since in many cases there may be the need to mitigate the heating in certain portions of the food to avoid over-heating and—consequently—over processing of the food product (Pace et al., 2011).

Microwave heating is part of the household appliances of an increasing number of consumers. Microwave technology was first adopted in food preparation for the fast heating provided. Industrially, microwaves are used in several processes, going from MW-assisted drying, MW-assisted vacuum drying, MW pasteurization/sterilization (Guzik et al., 2022). Microwave processing efficiency (defined as energy taken by the food product with respect to the energy taken from the electrical grid) has been reported going up to 90% in some cases (Tian et al., 2023), considering this process as contributing to sustainability in material processing (Singh et al., 2023). The issue of this technology remains about the precision in energy delivering. Microwave technology, also at industrial level, is still dominated using magnetrons at 2.45 GHz. In the last 10 years, the research has shifted toward the use of so-called solid-state technology, using antennas to generate and propagate the electromagnetic field at the due frequency (Brown, 2022). A magnetron-based MW system is an open loop system, while a solid-state MW system is a closed loop. Systems based on solid-state technology include one or more antennas that monitor the absorption of electromagnetic energy in the cavity and, through a feedback loop, provide real-time adjustments to the emission of RF energy. In this way, standing waves in the cavity are eliminate, allowing for more precise energy application. This new technology is based on extensive research and development tasks, during both the design and optimization steps. While magnetron-based MW systems were often designed on rules of thumb and trial-and-error procedures, the design of solid-state MW systems also requires competences in electronics and in smart control systems (Hopper, 2020). The knowledge of dielectric properties of food products and food ingredients is of paramount importance when designing such systems, as these properties can vary according with the food composition (Lyng et al., 2014).

Radio-frequency assisted heating works at frequencies in the range of MHz: particularly, for industrial, scientific, and medical (ISM) uses the frequencies allowed by the US Federal Communication Commission: 13.56, 27.12, and 40.68 MHz. MW and RF processing are both classified as dielectric heating methods. At lower frequencies (RF) ion depolarization tends to be the dominant heating mechanism while at higher frequencies (MW) ion depolarization and dipole spin can both be dominant loss mechanisms, depending on humidity and content of salt within a product (Tang et al., 2005). RF heating has been applied in different processes, as disinfestation of grains and in-shell fruits, roasting, meat and fish defrosting, post-baking processing (Hou et al., 2014; Zhang et al., 2022). Installed RF systems for the food industry are usually designed based on rules of thumb and trial-and-error procedures. Also, the set-up of food processing operations in such systems is usually based on trial-and-error procedures.

In MEF processing of foods, a food is exposed to an electric field at a level ranging from about 1 to 1,000 V/cm, at a frequency lower than 10^4 Hz. Unlike MW and RF processing which result mainly in thermal effects, moderate electric field (MEF) can have a purely thermal or non-thermal based on the electric field strength applied (Sastry, 2008). The use of moderate electric field (MEF) heating as an emerging cooking/microbial inactivation technology has gained considerable attention in more recent times. As alternative heating/cooking method, MEF has been proven to be very efficient in cooking of meat and meat products (Zell et al., 2010; Icier et al., 2014). In any case, the use of moderate electric heating for commercial uptake has been relatively low to date (Bedane et al., 2021), except for ohmic heating installations for pasteurizing fruit juices and particulate solid-liquid systems. Design of MEF systems is often based on calculations on both electrical circuit characteristics and energy balance.

3. Computer aided food engineering: the new era

Modern computers and software have boosted the use of computer aided design in food engineering, for systems and for processes. As recently discussed by Datta et al. (2022), CAFE includes all the computational based techniques that can be applied to design, re-design, control, optimize and–generally–to analyze a system and /or a process.

In the years, the scientific literature showed a growing interest in this subject, with major works done about MW heating and on RF at process and at product level (Chen et al., 2016; Gulati et al., 2016; Huang et al., 2018; Altin et al., 2022). Industrially, modern solid-state MW systems were developed also using a CAFE approach for the design (Hopper et al., 2018, 2019).

CAFE is also utilized for system/process optimization. Among the optimization problems of industrial food processes, heat treatment has been studied in more detail, with the aim of determining the minimum treatment required to ensure food safety while preserving organoleptic and nutritional values.

Recently, CAFE-based optimization has been implemented in many food processing operations, including drying and frying, but also in the design of electro-assisted systems. For example, constrained optimization has been applied in the design of cavity geometry in a microwave pasteurization process, radio-frequency thawing, or for the choice of ancillary systems (still about RF, Huang et al., 2018). These successive approaches demonstrated the importance of combining optimization algorithms with specified geometric constraints and objective functions.

The availability of improved physics-based mathematical models has played a vital role in improving the optimization of model-based food processing. As in related industries, optimization with data-driven models is likely to be considered in the food industry. The availability of huge datasets has led to such data-driven optimization and this approach should facilitate the development of decision platforms in CAFE (Datta et al., 2022).

4. Discussion

Electro-heating applications are gaining momentum in food industry. According to Atuonwu and Tassou (2021), EHA technologies can promote low-carbon food processing. For these systems to be sustainable, a lot of parameters are required for comparison with the conventional systems. It is a difficult task to benchmark the performance indicators and then compare the data to the existing system/process. Still, there is no technique which can directly provide the sustainability index for any manufacturing process by direct comparison to conventional system. In any case, the following three parameters could be a common starting point for researchers involved in determining the sustainability of processes and systems in the food industry:

- parameters determining the process/system performance (i.e., energy efficiency);
- parameters affecting the environment, at soil, water and air level;
- parameters affecting safety and health.

Efficient usage of energy and lack of direct emissions make these technologies the perfect candidates for the green transition of the food industry. However, still there are many challenges which are faced by the researchers during the processing of foods by these methods. Some of the challenges are listed below:

- challenging real time analysis;
- complex multiphysics applications;
- lack of comparable data;
- these systems are based on electronics, with consequently high associated cost;
- these systems require contactless temperature measurement, to avoid interactions with the electromagnetic field.

In all the above-mentioned points, CAFE can give a fundamental contribution, in the design and optimization of systems and processes and also in gaining knowledge and reducing the time of operations. The complexity of such systems will be mitigated by a better knowledge of the phenomena taking part in a particular process in a particular system.

5. Conclusion

With reference to the questions put at the begin of this paper, undoubtedly the combination of CAFE and EHA is the only way to help the food industry to embrace sustainability in most operations in which the heat transfer is involved, so specifically helping the decarbonization of the food industry, contributing to UN SGD7 (affordable and clean energy) but also to SDG12 (responsible consumption and production), and SDG13 (take urgent action to combat climate change and its impacts).

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

FM contributed to the whole article conceptualization, preparation, and submission of the manuscript.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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