International Journal of Thermal Sciences 111 (2017) 175–187

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Simulation and control of continuous glass melting by microwave heating in a single-mode cavity with energy efficiency optimization

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ARTICLE INFO

Article history:
Received 22 October 2015
Received in revised form
27 July 2016
Accepted 17 August 2016

Keywords:
High temperature microwave heating
Continuous glass melting
Microwave numerical modeling
Automatic impedance matching
Input power optimization

ABSTRACT

Calculations of continuous glass melting in a single-mode 2.45 GHz microwave oven are reported. The aim of this work is to optimize the microwave heating of the glass raw material to have a controlled and highly efficient oven. The two-way coupling process between electromagnetic and thermal fields is solved using COMSOL software in a 3D transient simulation that includes phase change and surface-to-surface thermal radiation. A methodology was developed and coded to automatically control the microwave energy supply and to maximize the material's microwave absorption during the 3D transient simulation. The developed methodology to achieve high Key Performance Indicators (KPI) was applied to the continuous melting of a glass raw material powder, the results show promising energy consumption reduction and improved task efficiency.

1. Introduction

Conventional glass furnaces consist of a combustion space and a tank for the molten glass circulation to be homogenized until it leaves the furnace. Glass production is an energy intensive process in which many tons per hour of raw materials enter the tank and are melted by a large amount of heat released by the flames in the furnace in the form of radiation and convection. Existing glass melting furnaces have been optimized in the last decades [1]. Computational modeling has contributed to achieve the reduction of fuel consumption, emissions and also enhance the glass quality [2,3]. Consequently further breakthroughs or improvements in energy saving, pollutants reduction and product quality require a new melting paradigm.

Microwave heating has been successfully applied in many low-temperature applications: to process products with a high water content [4,5], being the food processing the most successful [6,7]. In the last two decades microwave systems have been extended towards high-temperature heating and today it is an emerging technology for the processing of a variety of materials in ceramics, composites and metals [8,9]. Several studies [10–13] reported enhancements of the microwave heating over conventional processing techniques due to its volumetric heating characteristic. Microwave heating for melting applications has been limited for small samples [14,15] and to the authors knowledge the continuous large-scale melting of materials with microwave energy has not been previously reported.

Microwave energy for glass melting processing may bring considerable benefits by reducing energy consumption and environmental pollution. The design objective is to have a microwave melting cavity with higher efficiency than a conventional glass oven. However major challenges need to be overcome in order to develop microwave glass melting technology.

There are many factors that affect microwave heating: dielectric properties, penetration depth, operating frequency, operating mode, placement inside the oven, insulation materials, load geometry and oven geometry. Consequently material characteristics such as microwave transparency or opacity create extreme difficulties compared with an absorber material such as water. The susceptibility of a material to dielectric polarization, and hence its propensity to absorb and dissipate microwave radiation, is dependent on its dielectric properties as given by the complex permittivity. Nowadays materials with a small microwave penetration depth are grain sized by crushing and milling in order to become microwave absorbers. These powders can be characterized by experimental equipment [16] and by computational methods based in a homogenization approach [17]. Materials with a high

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http://dx.doi.org/10.1016/j.ijthermalsci.2016.08.015

ability to dissipate microwaves, susceptors, may be added to intensify the heating, in which, the susceptor's temperature raises to levels where it may then heat the material particles.

One of the resolved modeling challenges of the high temperature microwave heating is the two-way coupling of the electromagnetic physics with the heat transfer one, which details are explained in Alpert et al. [18]. For the heating to achieve maximum efficiency there is a need to change the cavity geometry so that the electromagnetic field adjusts in a way that it is more intense where the material is more able to transform the microwave energy in heat. For most materials, the microwave absorption properties, namely the loss factor, are higher where the material is hotter. So, when the thermal field changes either because of some kind of local heating or cooling, the system will no longer be in its maximum efficiency point at the system's resonance.

In an industrial environment the processed materials only have a high loss factor at very high temperatures consequently the cavity geometry should be continuously adjusted by a control algorithm to maximize the microwave absorption otherwise the system will converge to a low efficiency heating, usually below 50%. This constitutes the main problem to be solved and requires unsteady 3D multiphysics predictions coupled together with an optimization methodology to reach steady state solutions with a microwave efficiency higher than 90% for the majority of the cases. For low temperatures microwave e.g. food processing this methodology is not required due to the low variation of dielectric properties during the process.

Interest in using numerical modeling of the microwave heating physics has been increasing in the recent years. For example, in the work of Salema et al. [4], COMSOL software is used to simulate the microwave heating of biomass steady samples, where the bed height and specific heat capacity variations affected the temperature distribution and heating behavior, with this model the detection of hot and cold spots could be achieved and it was validated with experimental data. Jacob et al. [19] uses Fluent to simulate the migration effects of Al_2O_3 nanoparticles in base water during microwave heating, the obtained numerical results are extensively compared with experimental measurements.

Numerical models are also been used as a design tool of microwave systems. Yousefi et al. [20] studies the microwave heating of continuous flowing water, where the effects of varying the inlet velocity and the diameter of the container tube are studied, evidences of a critical diameter where the absorbed heat is maximum are presented in this work. The microwave cavity geometry is the same as the one used by Zu et al. [21], which is one of the first cavity design works to use a numerical modeling tool for different parametric studies. Cherbanski and Rudniak [22] studies the microwave induced convection of distilled water in a monomode cavity, in this work it was concluded that shift of 5 *MHz* in the waveguide frequency can results in a decrease of 20% of the microwave efficiency, showing the importance of maintain the resonance of the system during the numerical simulation.

By another hand, it is well known that the strong dependence on material dielectric properties on temperature may originate the problem known as thermal runaways. Kriegsmann [23] first presented an asymptotic analysis and control on microwave to avoid thermal runaways. Since then several temperature feed back system name been proposed see e.g. Refs. [24–26]. However the detection of the temperature time gradient in microwave heating is complex and difficult in real applications. The present paper presents a simulation methodology that enables the prediction of complex unsteady fields of coupled electromagnetic and heat transfer physics in a detailed 3D microwave cavity with geometric fidelity.

The new computational methodology proposed in this work aims to optimize the microwave oven efficiency by “tuning” of the microwave cavity during the operation of the continuous microwave oven in order to maintain the resonance of the microwave system while avoiding the high temperature gradients caused by the thermal runaways.

Next section describes the computational procedure to obtain converged solutions for microwave melting of glass. This is followed by the results for different operation modes which lead to the optimization of the continuous microwave heating process to maximize efficiency. In this section the analysis of results for different operating conditions and the parametric studies of the mass load and temperature before input can also be found. The paper closes with summarizing conclusions.

2. Model

2.1. Mathematical and physical model

In order to describe the microwave heating of glass processing both the electromagnetic and temperature fields need to be solved. In general all microwave heating models use electromagnetic waves solved in a frequency domain coupled with transient heat transfer physics, a justification to this approach is presented by Jerby et al. [27]. So, for each time step of the heat transfer equation the electromagnetic field inside the cavity must be obtained. Helmholtz equation in the frequency domain is used to obtain the electromagnetic (EM) field using time harmonic sources:

$$\nabla \times \mu_r^{-1}\left(\nabla \times \overrightarrow{\boldsymbol{E}}\right) - k_0^2 \varepsilon_r{}' \overrightarrow{\boldsymbol{E}} + k_0^2 j\left(\varepsilon_r{}'' + \frac{\sigma}{\omega\varepsilon_0}\right)\overrightarrow{\boldsymbol{E}} = 0 \tag{1}$$

where the wave number in free space is defined as

$$k_0 = \omega\sqrt{\varepsilon_0\mu_0}, \tag{2}$$

μ_r is the relative permeability, $\overrightarrow{\boldsymbol{E}}$ is the complex electric field, $\varepsilon_r{}'$ is the relative dielectric constant, j is the imaginary number, $\varepsilon_r{}''$ is the relative loss factor, σ is the electric conductivity, ω is the wave angular frequency, ε_0 is the permittivity in vacuum and μ_0 is the permeability in vacuum.

The heat transfer in microwave heating is governed by the energy equation resulting in the transient heat equation that allows to obtain the thermal field solution. The energy equation is defined by:

$$\frac{\mathrm{d}\rho E}{\mathrm{d}t} + \nabla.(\rho \boldsymbol{u} E - k\nabla T + q_r) = Q_{em} \tag{3}$$

where ρ is the density, $\boldsymbol{u}$ is the velocity, k is the thermal conductivity, T is the temperature, q_r is the radiative heat flux and Q_{em} is the heat source due to the electromagnetic energy absorbed by the material.

The internal energy, E, can be translated into a temperature dependent variable, but for that we have to resort to the following relation:

$$E = H - \frac{p}{\rho} \tag{4}$$

and the definition of the sensible enthalpy,

$$H = H_{ref} + \int_{T_{ref}}^{T} c_p \mathrm{d}T + \int_{p_{ref}}^{p} \frac{1}{\rho}\left(1 + \frac{T}{\rho}\left(\frac{\partial\rho}{\partial T}\right)\Big|_p\right)\mathrm{d}p \tag{5}$$

where p is pressure, T_{ref} is the reference temperature used in the