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Thermal Characterization of Microwave Assisted Foaming of Expandable Polystyrene

Caracterización térmica de poliestireno expandible manufacturado con microondas

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Abstract

Microwave range had been widely used for heating processes. In this work theoretical and experimental results on manufacturing of expandable polystyrene using specific frequencies of 2.45 GHz are presented. Simulations of temperature distribution were performed using the software *Comsol Multiphysics*®. In order to increase the material absorption to microwaves, several solvents as ethanol, a mixture of ethanol/water and hydrogen peroxide were tested. Temperature distribution inside material was measured with an infrared laser sensor. Microwave heating allows *Expanded Polystyrene Styrofoam* (EPS) molding in 180 seconds, reaching a considerable manufacturing time reduction compared with traditional processes where drying time may take up to one day.

Keywords:

- microwave
- manufacture and polystyrene

Resumen

El rango de microondas se ha utilizado ampliamente para procesos de calentamiento. En este trabajo se presentan estudios teóricos y prácticos de la manufactura de poliestireno expandible mediante calentamiento por microondas a 2.45 GHz. Se realizaron simulaciones de incremento de temperatura y su distribución en el material utilizando el software Comsol Multiphysics®. Con la finalidad de incrementar la absorción del material a microondas, se realizaron experimentos con diferentes solventes tales como etanol, agua oxigenada y agua purificada. Se midió la distribución de temperatura dentro del material mediante un sensor de láser infrarrojo. El calentamiento por microondas del material permite el espumado del poliestireno expandible (EPS) en 180 segundos, alcanzando una reducción considerable del tiempo de fabricación en comparación con procesos tradicionales en los cuales el tiempo de secado puede durar hasta un día.

Descriptores:

- *microondas*
- *manufactura y poliestireno*

Introduction

Polystyrene foam is a polymer produced from styrene monomer known as *styrofoam*; their use in food and electronics packaging, airplane and automotive parts, sporting equipment, among others, it has become a trend last years due to its different advantages as light weight (reduced bulk density), easy to form, low thermal conductivity, and low cost of production (Warsiki *et al*., 2012; Tsivintzelis *et al*., 2007). Commercial interest in polymeric foams has been increased due to new emerging applications and the ability to foam a variety of polymeric materials or composites. Despite their success, the continuous growth in research of foamed polymers into new markets depends on the ability to enhance control over its mechanical structure and performance (Emami *et al*., 2014).

Conventional polymer foaming process usually consist of polymer matrix saturation with a fluid (solvent) and its volatilization by increasing temperature, which induce phase separation, resulting in formation (nucleation) and growth of pores inside the polymer matrix (Tsivintzelis and Panayiotou, 2013). Polystyrene foaming has been extensively studied, for example, recently Nistor *et al*. (2013) prepared micro-cellular PS foams and studied the influence of toluene residua on the foam structure, using CO_2 as high-pressure inductor. They observed that foam heat insulation properties improve with increasing porosity, and that toluene residua increased the porosity by increasing the cell sizes and lowering the thickness of the compact skin at the film surface. Gutiérrez *et al*. (2014), foamed polystyrene using limonene solutions as solvent and CO_2 as foaming agent. They studied the effect of pressure, temperature, concentration of the solution, contact time and vent time over the diameter of cells, its standard deviation and the cells density, observing that the most suitable conditions to foam polystyrene from limonene solutions were 90 bar, 30°C, 0.1 g of Polystyrene/ml limonene, 240 min contacting and 30 min venting. Thus, foaming process strongly depends on solvent type and how temperature is raised. Usually, natural gas or fossil fuels are used in this process. However, constant increase in their prices and the pollution factor leads to finding new and clean (non-toxic) manufacturing techniques. Electromagnetic waves ranging from radiofrequency to microwaves could be an efficient alternative option for processes involving heating increase in polymers (Mallakpour and Rafiee, 2011). Sen *et al*. (2011), used microwave irradiation as the source of energy for expansion process and 2-propanol as expansion agent, however, they did not studied the thermal effects which have a direct impact in the quality of the product.

This work present thermal characterization profile of EPS manufacturing using microwaves as the source of heating throughout polystyrene foaming, and using ethanol, a mixture of ethanol/water and hydrogen peroxide as expansion agents. Advantages of this method includes fast heating, low-cost process, and independence of fossil fuels.

Methods and procedures

In order to characterize thermal profile, experimental and numerical simulations using *Comsol Multiphysics®* were performed.

Experimental foaming process

Samples of 130 ml commercial expandable polystyrene with a density of 20 kg/m^3 and thermal conductivity of 0.35 W/m·K were utilized. To increase the radiation absorption, experiments in conjunction with three sol-

vents: ethanol, a mixture 25:75 wt./wt. of water/ ethanol and hydrogen peroxide were performed. Purity of ethanol utilized was 96%. Solvents were applied directly to pre-expanded EPS beads with a syringe. After that, samples were heated for 180 seconds into a commercial microwave oven with maximal power P = 950 W and frequency f = 2.45 GHz as shown in Figure 1a. In order to determinate thermal distribution, measurements of foamed material were performed using an infrared laser measurer fabricated by Extech Instruments model 42510A. Temperature measurements were taken at the center, top, bottom and lateral side (Figure 1b).

Mathematical modeling and simulation

Since EPS is transparent to microwave wavelength, a heat transfer mechanism is required. Polar molecules as water present favorable conditions to be heated when they are irradiated by microwave. Eq. (1) and (2) describe the process of microwave heating (Warren *et al*., 2012).

$$\rho_d C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q_{abs} \quad (1)$$

$$q_{abs} = \omega \varepsilon''_{eff} |E|^2 \quad (2)$$

From eq. (1)

ρ_d = material density
C_p = specific heat at a given temperature
k = thermal conductivity
q_{abs} = absorbed volumetric power density

From eq. (2)

w = angular frequency
$\varepsilon''_{eff} = (s/\omega\varepsilon_0)$ = imaginary part of the complex permittivity from the material which is also known as loss tangent (tgδ)
σ = material conductivity
ε_0 = free space permittivity
E = electric field

Steam produced above boiling point allows thermal energy transfer to the materials such as polystyrene to achieve thermal expansion required for its manufacturing process. The property that determines the absorption of electric field produced by microwave and its conversion to heat is the complex dielectric constant. This parameter is composed by the dielectric constant of the material that represents the capacity to store electric charge, and the loss tangent (tgδ), which is the absorption level of radiation that is transformed to heat. Table 1 shows microwave absorption of some solvents (Shadpour, 2011). It is observed that water provides a medium absorption level. Hence, uses of solvents of high loss tangent are expected to be more efficient for EPS manufacturing with microwave.

In order to estimate the response time and 3D thermal distribution simulations were performed in the software *COMSOL Multiphysics 4.3*. Parameters utilized are shown in Table 2.

From Table 2, the value of electric conductivity is cero since EPS is a dielectric material. Relative permittivity is a complex number where the real part represents the dielectric constant of material and the complex

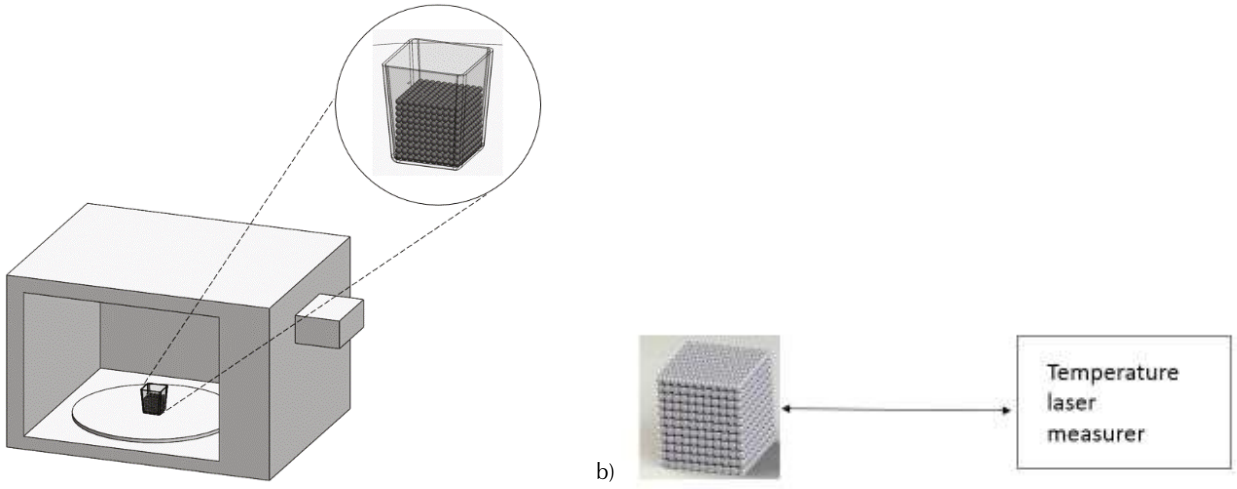

Figure 1. Experimental scheme: a) material microwave manufacturing, b) temperature measurements

Table 1. Classification of solvents for microwave absorption

High (tgδ>0.5)	Medium (0.1<tgδ<0.5)	Low (tgδ<0.1)
Ethanol	Acetic acid	Chloroform
Dimethyl sulfoxide	1,2-dichlorobenzene	Ethyl acetate
Methanol	N-methyl-2-pyrrolidone	Toluene
Hydrogen peroxide	Water	Hexane

Table 2. EPS properties considered in the simulation

Property	Value	Unit
Electric conductivity	0	S/m
Relative permittivity	2.7-0.000141*j	dimensionless
Relative permeability	1	dimensionless
Thermal conductivity	0.029	W/(m*K)
Density	20	Kg/m^3
Heat capacity at constant pressure	1210	J/(kg*K)

number means material absorption or loss tangent which is in the range of $5x10^{-7}$ to $5x10^{-3}$ (Jerzy *et al.*, 1998). Relative permeability of 1 means that the material is not affected by magnetic fields. Thermal conductivity is the quantity of heat transmitted through a unit thickness in a direction normal to a surface of unit area, due to a unit temperature gradient. According to Askeland (2001) its value for foam polystyrene is 0.029. Density is the material mass per unit volume, its from 10 to 50 kg/m^3 (EPS, 2003). Finally, heat capacity is the amount of heat needed to raise the temperature of the system by one degree. For expanded polystyrene its value is 1210 J/(kg*K) (Incropera and DeWitt, 1999).

Results and discussion

Experimental results of EPS fabrication using solvents

In order to study the repeatability of manufacturing process, each experiment was made six times. Obtained results of EPS mixed with ethanol, below 120 seconds of microwave heating presented expansion as required in the manufacturing process. However, moisture was also present which is undesirable. At 150 seconds, humidity was eliminated, but the material presented easy detachment of polystyrene pearls. At 180 seconds of microwave radiation, only small detachment on the top of material was observed (Figure 2a). Tests were also performed for a mixture of water/ethanol with a volume ratio of 4:3. In the range of 120 to 180 seconds humidity and material detachment was observed (Figure 2b).

Better results were achieved when hydrogen peroxide was used as solvent. In this case, at 180 seconds, expanded EPS did not present detachment, nor humidity (Figure 3).

Due favorable results achieved with hydrogen peroxide, quantitative studies were performed in this particular case. Experimental thermal distributions of EPS at top, bottom, center and lateral side after microwave heating with hydrogen peroxide are shown in Figure 4. Results showed an accuracy of ±6 °C at top, bottom and lateral sides. However, accuracy at center was ±23 °C.

a)  b) 

Figure 2. Experimental results of EPS with different solvents, a) ethanol and b) mixture of ethanol /water

a)  b)  c) 

Figure 3. Sample of EPS manufactured by microwave radiation and hydrogen peroxide as solvent, a) top, b) lateral and c) bottom-lateral

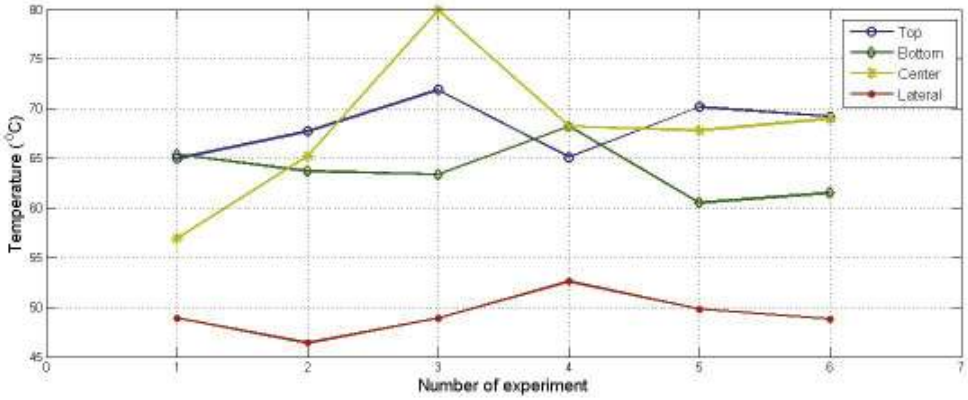

Figure 4. Experimental results on thermal distribution for 130 ml of EPS with hydrogen peroxide exposed to 180 seconds of microwave radiation

Numerical simulation results

Result of numerical simulation performed in COMSOL Multiphysics solving eqs. (1) and (2) is shown in Figure 5. Input parameters utilized were: f = 2.45 GHz, t = 180 s and $\varepsilon = 2.7\text{-}141 \times 10^{-6}$ j. As it can be seen from Figure 5, simulated thermal distribution varies in a range of 21°C. Theoretically, this is mostly originated by the electric field distribution of microwaves. Simulations behavior on top sections of lateral sides showed agreement with experimental results in the range of 45 to 52°C.

Thermal distribution shown in Figure 6 corresponds to a final time of simulation at 180 seconds. The evolution of temperature with respect to time is depicted in Figure 6. Initial condition of temperature was 25°C. As it can be seen from Figure 6, increase of temperature is exponential below 80 s. From 80 to 180 seconds temperature behavior is linear with a slope of 0.14.

Discussion of results

Experimental results showed that the use of ethanol as solvent for heating EPS with microwaves in spite of a fast increase in temperature, it produces moisture or easy detachment of pearls in EPS which could represent an issue in industrial processes. The same problem was observed for mixture of ethanol and water. Moisture problem can be solved increasing time exposure to microwaves from 180 to 300 seconds. However, this represent an increase of 60% of kWh which also represents an increase in cost production. In the other hand, the use of hydrogen peroxide showed elimination of moisture and lack of detachment of EPS. Numerical simulations showed a temperature range on the system (EPS and solvents) from 45 to 65°C, whereas experimental results showed an overall range from 46 to 80°C. This variation may be associated with the conditions of measurements at the center of the material. In this case temperatures were taken by destructive tests. On the other hand, measurements in lateral sides, top, and bottom are more uniform as can be seen in Figure 4.

Conclusions

Fabrication of EPS with microwaves at 2.45 GHz and three different solvents, *i.e.* ethanol, hydrogen peroxide and a mixture of water/ethanol were demonstrated. The better result was achieved with hydrogen peroxide. Elimination of moisture and solid EPS fabrication was observed for 180 seconds of manufacturing process. Si-

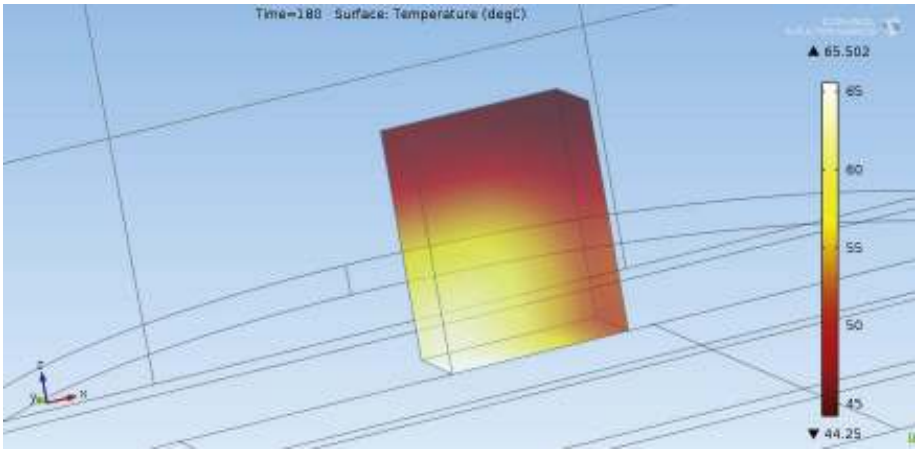

Figure 5. Simulation of thermal distribution in EPS with hydrogen peroxide irradiated by microwave

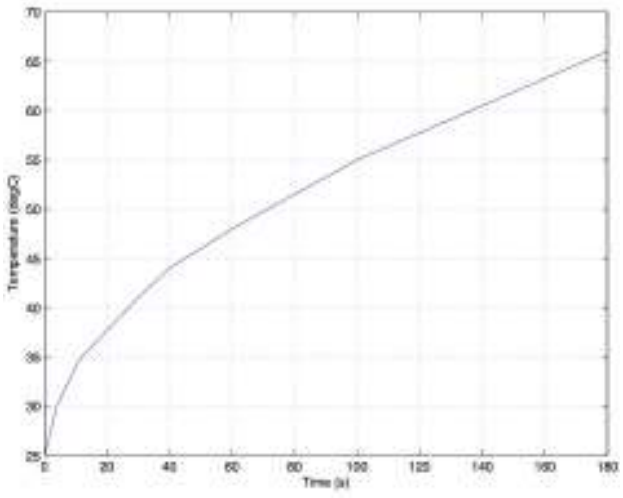

Figure 6. Theoretical temperature increase as a function of time EPS with hydrogen peroxide

mulation and experimental results showed non-uniform thermal distribution, which depends of microwave wavelength, and the electrical field distribution. Future studies could include the implementation of longer wavelengths to attenuate temperature variations. This work could potentially benefit polystyrene manufacturing industry, specifically in energy and time saving.

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