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Design and performance evaluation of an ohmic heating unit for thermal processing of highly viscous liquids

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ARTICLE INFO

Article history:
Received 2 October 2007
Accepted 5 February 2008

Keywords:
Ohmic heating
Fluid jet
Radar sensor
Thermal treatment

ABSTRACT

The overall objective of this study is to design, build and test a prototype automated ohmic heating cell by using a fluid jet to serve as a basis for modification and scale-up for industrial use. The new technology consists of applying an alternative electrical current to a falling jet between two electrodes. The length of the jet is the primary critical process factor in ohmic heating using a fluid jet. A radar level sensor was validated at different operating conditions. Two air valves, that depressurize or pressurize the ohmic cell, ensure the control of the jet length for precision and reliability. The thermal performances and the technical feasibility of this innovated automated ohmic heater were approved. Tests with carboxymethylcellulose (CMC) solutions (2%, w/w) demonstrated that this technology can be efficient for thermal processing of highly viscous liquids.

1. Introduction

Ohmic heating is a conduction heating technique for liquids and pumpable particles. It consists of equipment for passing an alternative current through the fluid between electrodes. Aqueous solutions, in particular, are almost always sufficiently conductive to permit a high power density to be dissipated, because dissolved salts provide ions as charge carries. Ohmic heating is a very effective way for energy conversion into heat in the workload. The efficiency of conversion is over 95%. Large amount of power are readily dissipated (>300 kW) in continuous flow systems of high mass flow throughput.

Towards the end of the 19th century and during the first half of the 20th century, various processes for the thermal treatment of liquids by direct resistance heating were developed (Jones, 1897; Beattie, 1914; Anglim, 1923; Prescott, 1927; Fettermann, 1928; Getchell, 1935; Ball, 1937). However, its commercial application for continuous sterilization and packaging did not succeed because of corrosion of electrodes and electrolysis of the heating medium. In addition, there was a lack of accurate and robust process control equipment in order to keep the temperature within the necessary ranges (Kucherenko, 1968; Armatore et al., 1998; Tzediakis et al., 1999).

During the past decade, new improved electrode materials and equipments design have become available. The developments of new ohmic sterilizers have reduced the cost by a factor of 10 between 1993 and 2003. The most recent achievements in ohmic heating are the development of the APV (1993) and Emmepiemme (2002) processes for the sterilization of particulate foods (Sastry and Palaniappan, 1992a,b,c; Fryer and De Alwis, 1998; Legrand et al., 2007).

Recently there has been a great deal of research on the application of this technique to food processing for a variety of purposes (Qihua et al., 1993; Roberts et al., 1998; Huang et al., 1997; Marcotte et al., 1998; Marcotte, 1999; Piette et al.,

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doi:10.1016/j.cherd.2008.02.005

Nomenclature

C_p	specific heat capacity (J kg °C^{-1})
d	nozzle diameter (m)
d_t	tube diameter (m)
D	duty cycle
e_t	glass tube thickness (m)
f	frequency of alternating voltage (Hz)
g	standard gravity (m s^{-2})
h_c	cone height (m)
H	fluid level (m)
I	current (A)
k	temperature factor (°C^{-1})
K	consistency factor (Pa s^n)
L	distance between electrodes (m)
L_t	length of the glass tube (m)
$\dot{m}$	mass flowrate (kg s^{-1})
n	flow behaviour index
P_0	Pomerantsev number
$P_{supplied}$	power supplied to the ohmic cell (W)
$P_{thermal}$	power generated in the fluid (W)
R	radius of the nozzle (m)
t_d	delay time between pulses (μs)
t_p	width of the voltage pulse (μs)
t_s	period of the signal (μs)
T_i	inlet temperature (°C)
T_o	outlet temperature (°C)
v	volume of the fluid (m^3)
V	voltage (V)
x	axial position (m)

Greek letters

α	cone angle (°)
λ	thermal conductivity of the fluid (W m^{-1} °C^{-1})
ρ	mass density (kg m^{-3})
σ	specific electrical conductivity (S m^{-1})
σ_0	specific electrical conductivity at reference temperature (S m^{-1})

Subscripts

0	reference value for electrical conductivity
c	cone
d	delay
i	inlet
o	outlet
p	pulse
s	signal
t	tube

2004; Ayadi et al., 2004; Chaminda et al., 2005; Praporscic et al., 2006; Soojin et al., 2007; Soojin and Sastry, 2007). It has been recognized that the ohmic heating system may have technical advantages over other heat exchangers if the liquid is very viscous, thermally sensitive, or prone to fouling of heated surfaces in the equipment (Heppell and Michael, 2000). In today's market, there is a tubular ohmic heater working at flowrates going up to 5 T/h. More than 28 installations were marketed in Europe (France, Spain, Italy, and Greece).

Although the technique appears both simple and advantageous, several difficulties are encountered in its application. The fouling encountered in the vicinity of walls and electrodes and the frequent cleaning of installed units are nowadays a significant issue still not solved yet for the processing of highly viscous products.

New continuous ohmic heating apparatus using a fluid jet is proposed in this paper. It consists of the application of an alternative electrical current directly to the falling jet between the two electrodes. The design is based on the elimination of the product–wall interface in the heating zone. In this heating zone the essential temperature rise occurs because the current density in the holding zone, composed of the receptacle, is negligible compared to that in the jet. The overall objective of this work is to design, build and test this prototype automated ohmic heating unit by fluid jet to serve as a basis for modification and scale-up for industrial use.

2. Methods and materials

A scheme of experimental setup is presented in Fig. 1. It consisted of three different sections: (1) a preheating zone with a Joule effect heater (Actini, Evian, France), (2) a heating zone with the ohmic heater cell by fluid jet (Emmepiemme, Picanza, Italy), and (3) a cooling zone. It included the following elements in series: a storage tank (150 l), a volumetric feed pump (PCM Moineau type, Vanves, France), a double-tube heat exchanger as cooler (Actini, Evian, France), and a back pressure valve at the installation outlet.

The flowrate was measured using an electromagnetic flowmeter (EMC, type Promag 30, Auckland, New Zealand) with a precision of within 1% of the full range. The bulk temperatures were measured by use of platinum resistance probes (Pt 100 Ω to 0 °C with a ±0.1 °C accuracy) placed at the inlet and outlet of each zone. Relative pressure was measured with manometers (JUMO, type 4AP30, Fulda, Germany) at the inlet and outlet of experimental setup with a precision of 0.1%.

The used power supply (Emmpiemme, Piacenza, Italy) delivers bipolar potential pulses, refer to Fig. 2. Electrolysis is prevented by the use of high frequency alternating voltage. The frequency f is up to 30 kHz with switching voltage up to 3800 V. Both positive and negative pulses of the bipolar pulse output had the same pulse width t_p (μs), and were equally spaced by adjusting the delay time t_d (μs), according to the following formulae

$$t_s = t_p + t_d \quad (1)$$

$$D\frac{t_p}{t_s} = \frac{t_p}{t_p + t_d} \quad (2)$$

where t_s is the period of the signal (μs), D is the duty cycle, and therefore the power supplied to the ohmic cell has the following form (Soojin et al., 2007; Ghnimi et al., 2007a,b)

$$P_{supplied} = V_p I_p D \quad (3)$$

where V_p is the peak voltage (V) and I_p is the peak current (A) delivered by the power supply. In our case, the maximum power supplied is equal to 50 kW.

The tension delivered by the power supply was measured by a high voltage probe with large bandwidth to ensure that transients and fast signals edges will be captured (Tektronix P6015A, 75 MHz, attenuation 1000X, Oregon, USA). The current was measured using a current probe (Pearson, 20 MHz, California, USA) with specified rise time (less than the rise time of the viewed current pulse) which ensures the intact seizure of the transients and the faces of signals of fast rise. Fig. 2 shows the