Energy Efficiency of a Novel Ohmic Heating Technology by Fluid Jet

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ABSTRACT

Ohmic heating is a food processing operation in which heat is internally generated within foods by the passage of alternating electric current. The electrical power supplied to the Ohmic cell is critically dependant on the electrical conductivities of the foods being processed. A lot of information about this project is available. There is no information about the effect of power supply pulse parameters on the energy efficiency of the Ohmic heating process.

This paper reports experiments on the effect of duty cycle changes in power supply energy efficiency. The voltage and current measurements at high frequency were performed.

The results suggest that duty cycle (D) reduce energy efficiency of the Ohmic heating process, which varied from 65 % to 90 %. The energy efficiency of the power supply up to 90 % was obtained when the duty cycle exceed 0.8. A predictive model of the energetic efficiency of the power supply according to the duty cycle is given. Based on thermal balance, the energy efficiency of the Ohmic cell is close to 96 % and independent of pulse parameters, flow rate or fluid level inside the receptacle.

Introduction

Ohmic heating is an innovative electro-heating method embraced by the food industry for processing of a broad range of food products. The passage of an electric current through a food heats by the Joule effect, the food behaves as a resistor in an electrical circuit. The advantages of continuous Ohmic heating are a rapid heating with improved treatment homogeneity and high energy efficiency.

The developments of new Ohmic sterilizers have reduced the cost by a factor of 10 between 1993 and 2003. The most successful designs are the Ohmic sterilizer APV® (Fryer and De Alwis 1989) and EMMEPIEMME® (Legrand et al. 2007), suitable for thermal treatment of heterogeneous foods like fruits, meat mixtures and tomato particles.

Although the technique appears both simple and advantageous, several difficulties are encountered in its application. It's already known that Ohmic heaters powered by low-frequency (50 to 60 Hz) alternating currents induced a corrosion of stainless steel electrodes and apparent electrolysis of the heating medium. These electrochemical phenomena can be effectively suppressed by using high frequency alternating currents (Armatore et al. 1998, Wu et al. 1998, Samarayanake et al. 2006).

However, the use of high frequency generators especially for industrial Ohmic heating may be limited by cost considerations. Therefore, viable process control methods that go up the energy efficiency are of great interest. The power supply developed by EMMEPIEMME® is basically a rapid switching device that enables the application of current and voltage as high frequency short duration pulses. The effects of the pulse parameters on energy efficiency during

Ohmic heating have not yet been studied. The aim of this study was to test the effect of duty cycle on the energy efficiency of the Ohmic heating technology by fluid jet, which would be useful in future thermal applications in food industry.

Materiel and methods

Ohmic Heating System Investigated

High frequency power supply system. The EMMEPIEMME® power supply delivers bipolar potential pulses, as shown in Figure 1. Electrolysis is prevented by the use of high frequency alternating voltage. It had a frequency 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 (33 µs) and were equally spaced by adjusting the delay time t_d according to the following relationships.

$$T = t_p + t_d$$

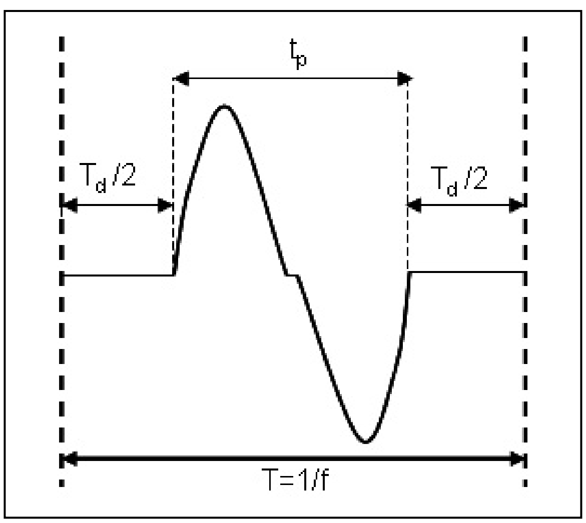
$$D = \frac{t_p}{T} = \frac{t_p}{t_p + t_d}$$

Pulse waveform derived from the power supply was independently manipulated by adjusting the delay time (off-time between adjacent pulses) and therefore the power supplied to the Ohmic cell (P_{input}) was:

$$P_{input} = V_p I_p D$$

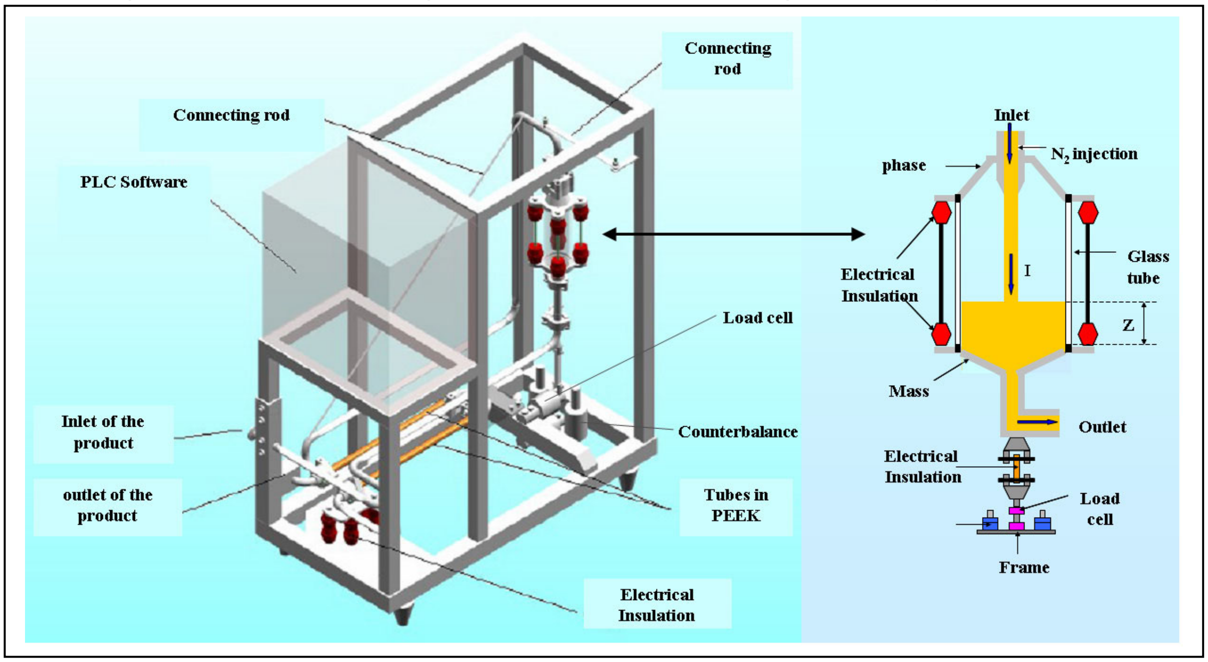
Where V_p and I_p were respectively the peak voltage and peak current delivered by the power supply. In our case, the maximum power supplied is equal to 50 kW.

Figure 1. Schematic Diagram of the Centering of Bipolar Pulses



Ohmic heating cell by fluid jet. This continuous Ohmic heating cell consists in applying an alternative electrical current directly in a fluid jet, falling between two stainless steel electrodes. The flow domain consists of a cylindrical glass tube connected to the electrodes; which are tightly held in position using rubber rings and four iron bars with nuts and bolts. The inlet, a round jet of small cross-section through which liquid leaves from the nozzle tip, is connected to the phase. The outlet, a conical receptacle through which the liquid is taken out, is connected to the mass (Figure 2).

Figure 2. Schematic Diagram of the Ohmic Heating Process by Fluid Jet



Fluid level control. The length of the jet is controlled and maintained constant by working two air valves that depressurize or pressurizing the Ohmic cell with air or nitrogen and adjusting the liquid level with a counter-pressure valve.

Data Acquisition system. The data acquisition system was Eurotherm Chessel 4250G. It was used for logging temperature distribution, flow rate, pressure drop, applied voltage and current with time. The data were automatically archived as ASCII in a PCMCIA card.

Voltage, current and power measurements. Accurate tension and current measurements at high frequencies becomes more critical for today's complex devices and systems. In our case the tension delivered by the power supply (400-3800V), was measured by a high voltage probe (Tektronix P6015A). The high bandwidth (up to 75 MHz) of the tension probe ensures that transients and fast signal edges will be captured intact. The tension probe's attenuation (1000X) keeps the waveform amplitude well within the graticule limits. The main characteristics of electrical network such us the total power (P_{total}) given to the power supply was measured by a triple-phase analyser (Qualistar CA 8334).

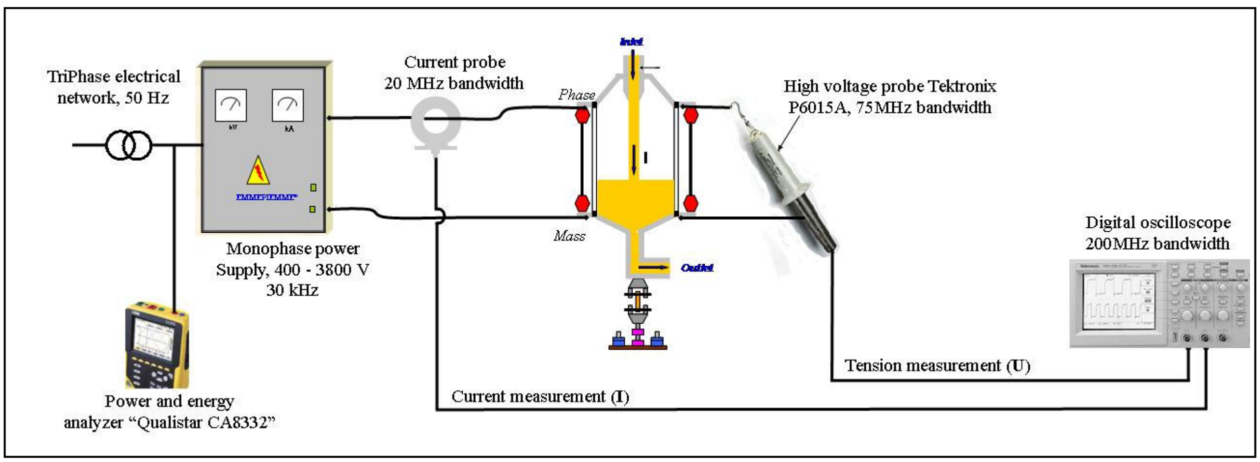
For the measurement of the current through the fluid jet, the sensor must have a specified useable rise time less than the rise-time of the viewed current pulse. We used a Pearson® current probe with large band-width (up to 20 MHz) which ensures the intact seizure of the transients and the faces of signals of fast rise (Figure 3).

Experimental Procedure

The experimental device integrates an agitation tank, a volumetric feed pump (PCM Moineau type), two tubular heat exchangers (one Joule effect heater for pre-heating and one double-tube heat exchanger for cooling) and an Ohmic cell by fluid jet for heating. The flow rate was measured using an electromagnetic flowmeter with a precision of within 1 % of the full range. The bulk temperatures were measured by use of platinum resistance probes (Pt100 Ω to 0°C with a ±0.1°C accuracy) placed at the inlet and outlet of each zone. These probes were calibrated using a constant temperature water bath and a precision thermometer.

Aqueous Carboxymethylcellulose (CMC) solutions of 2 % (w/w) concentration were used in the experimental tests. Three flow rates and six fluid levels in the receptacle were used for each power supplied. Experiments were conducted at constant pulse width (33 µs), while varying delay time with all flow rates and fluid levels inside the Ohmic cell.

Figure 3. Schematic Diagram of the Electrical Measurements



Results and Discussions

Validation of Voltage and Current Measurements

The energy efficiency of the power supply system requires precise measurements of the effective energy delivered at the Ohmic cell. The main problem is the efficiency of current measurements. Above 50 MHz, the conventional passive probes severally distort the waveform. It can significantly affect the response of the measuring equipment.

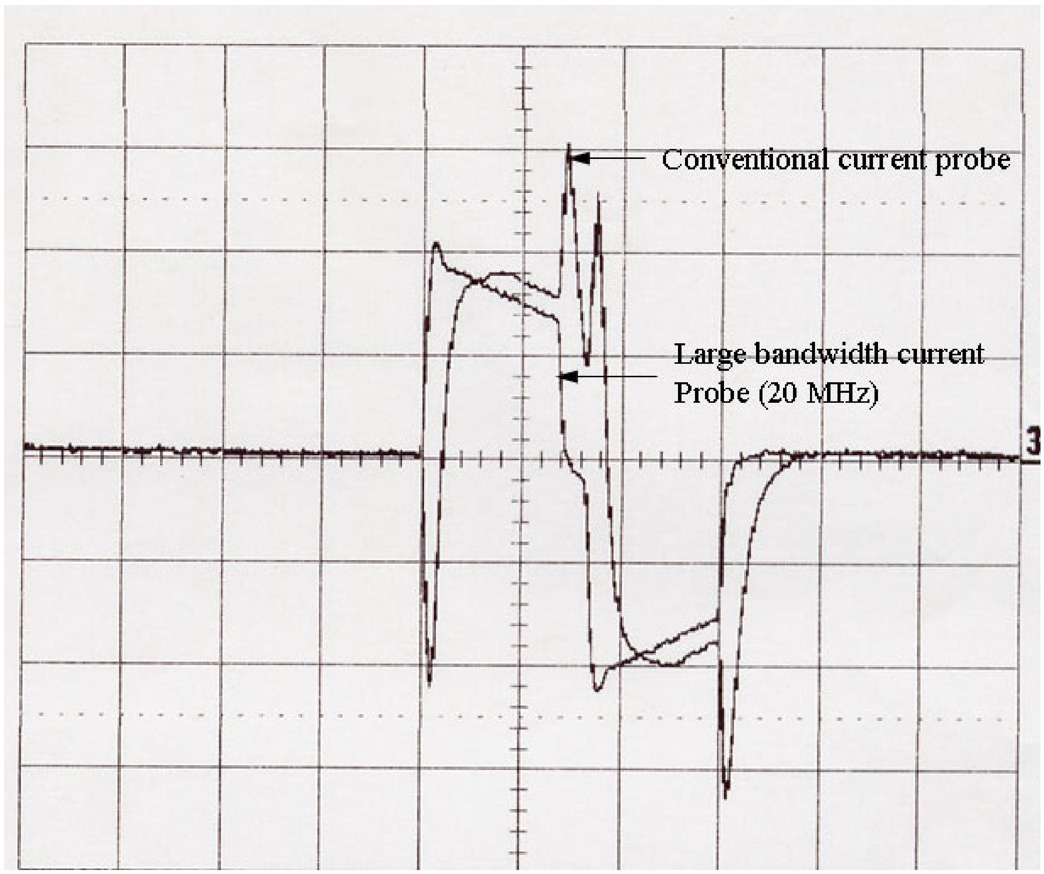
Thus, when the signal contains frequency components above 50 MHz, an alternative measurement technique is required to ensure accurate results. The typical oscilloscope pulse waveforms of current observed with a conventional probe were compared to those taken with the Pearson® probe. As shown in Figure 4, the Pearson® probe represents an extremely effective tool to accurately measure a high frequency current.

The total input power in the Ohmic heating experiments was calculated using its RMS (Root-Mean-Square) current and RMS voltage measured by the two large bandwidth probes:

$P_{input} = V_{rms} I_{rms}$

Figure 5 shows RMS current versus RMS applied voltage plots for the Pearson® probe. These measurements validate the use of current and tension probes and also demonstrates that, any current-dependent electrode voltage polarization resistance is negligible.

Figure 4. Pulse Waveforms of Current Obtained from Conventional and Large Bandwidth Probes



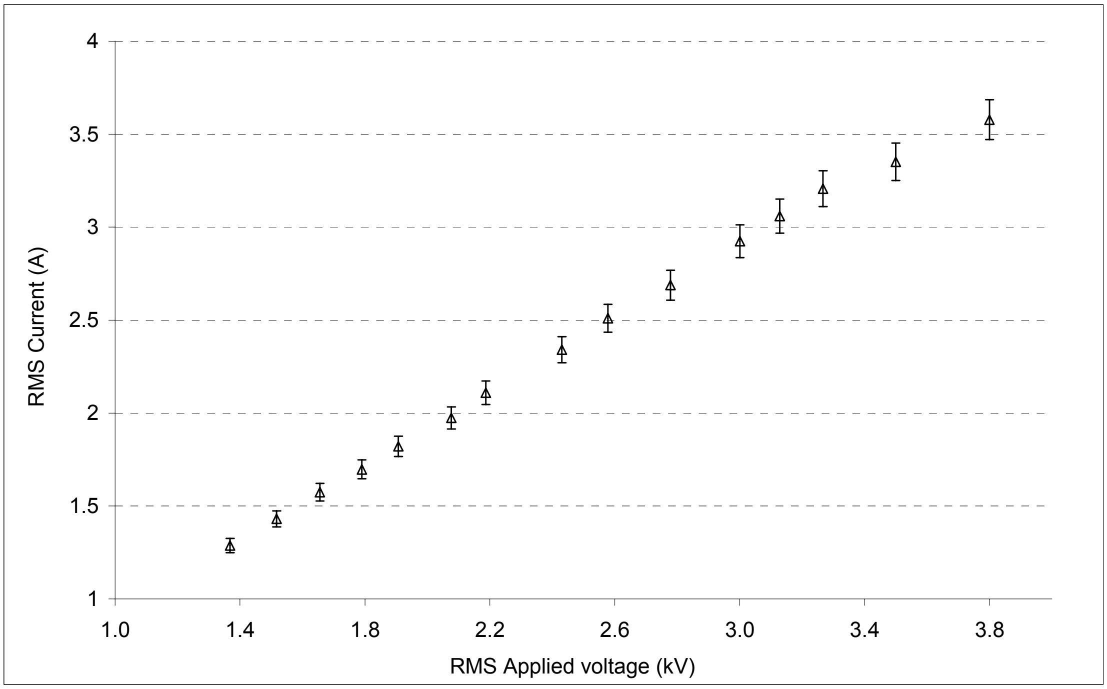
Energy Efficiency Aspects

The thermal power dissipated inside the liquid is proportional to the difference between outlet and inlet temperatures (°C), the mass flowrate ($kg.s^{-1}$) and the specific heat capacity.

$P_{thermal} = QC_p(T_o - T_i)$

Where $P_{thermal}$ was the thermal power dissipated inside liquid (W); Q the mass flowrate ($kg.s^{-1}$); C_p the specific heat capacity ($J.kg^{-1}.\ °C^{-1}$); T_0 the outlet temperature (°C) and T_i the inlet temperature (°C).

Figure 5. Plot of Current vs. Applied Voltage for 2% (w/w) CMC in the Ohmic Cell, Fluid Level inside the Ohmic Cell 70mm, Flowrate = 200 L/h.



The outlet temperature profiles were influenced by the fluid level inside the Ohmic cell, the flow rate, the electric conductivity and the voltage gradient. For the Carboxymethylcellulose solution used in this present study, regression of the voltage and current measurements indicates that the conductivity σ (S.m-1) is a linear function of the temperature.

$$\sigma(\mathrm{S.m^{-1}}) = 0.142 + 0.0078T,\ (R^2 = 0.998)$$

This relation is valid for temperatures from 18 to 100°C. All other physical properties (i.e. density, specific heat and thermal conductivity) are very close to those of water. The effect of flowrate and fluid level on the temperature rise (T_o-T_i), inside the Ohmic cell, is shown in Figure 6. These experimental measured temperatures, voltage and current provided a reference to compare the actual input power used to heat the liquid to the real thermal power received. Accordingly, we defined a coefficient of performance for the power supply, the Ohmic cell and the global system according to the following relationship.

$$\eta\ (Ohmic\ cell) = \frac{P_{thermal}}{P_{input}}(100);\ \eta\ (power\ supply) = \frac{P_{input}}{P_{total}}(100);\ \eta\ (global) = \frac{P_{thermal}}{P_{total}}(100)$$

Effect of delay time on the energy efficiency of the power supply. The power supplied to Ohmic cell (P_{power_supply}) was varied by adjusting the delay time between two adjacent pulses. The pulse width was maintained constant and equal to 33 µs. The main purpose of these experiments was to quantify the influence of pulse parameter which is the delay time on the energy efficiency of the high frequency power supply system. Figure 7 shows the variations of energy efficiency of the power supply at different delay times. It appears clearly that the delay time has a significant effect on the energy efficiency of the power supply.

Figure 6. Temperature Rise as a Function of Fluid Level and Flowrate, inside the Ohmic Cell, for 2% (w/w) CMC

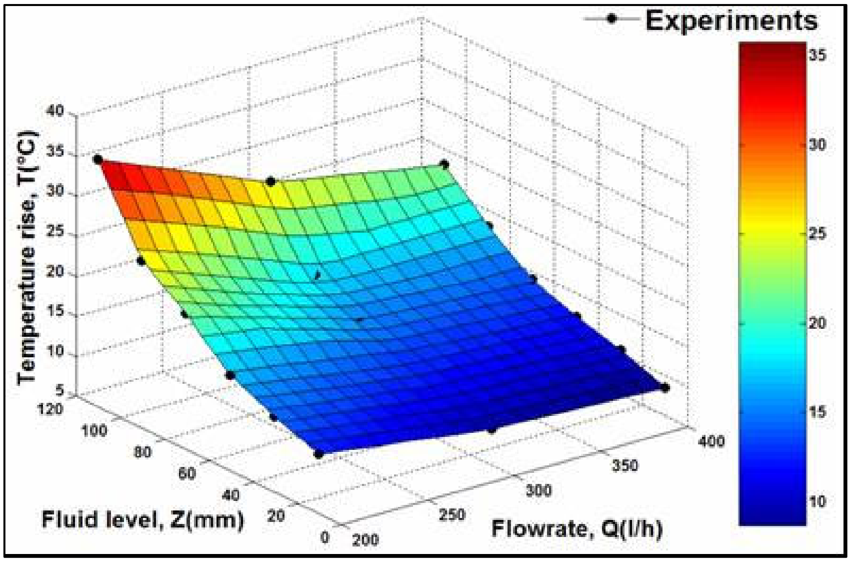
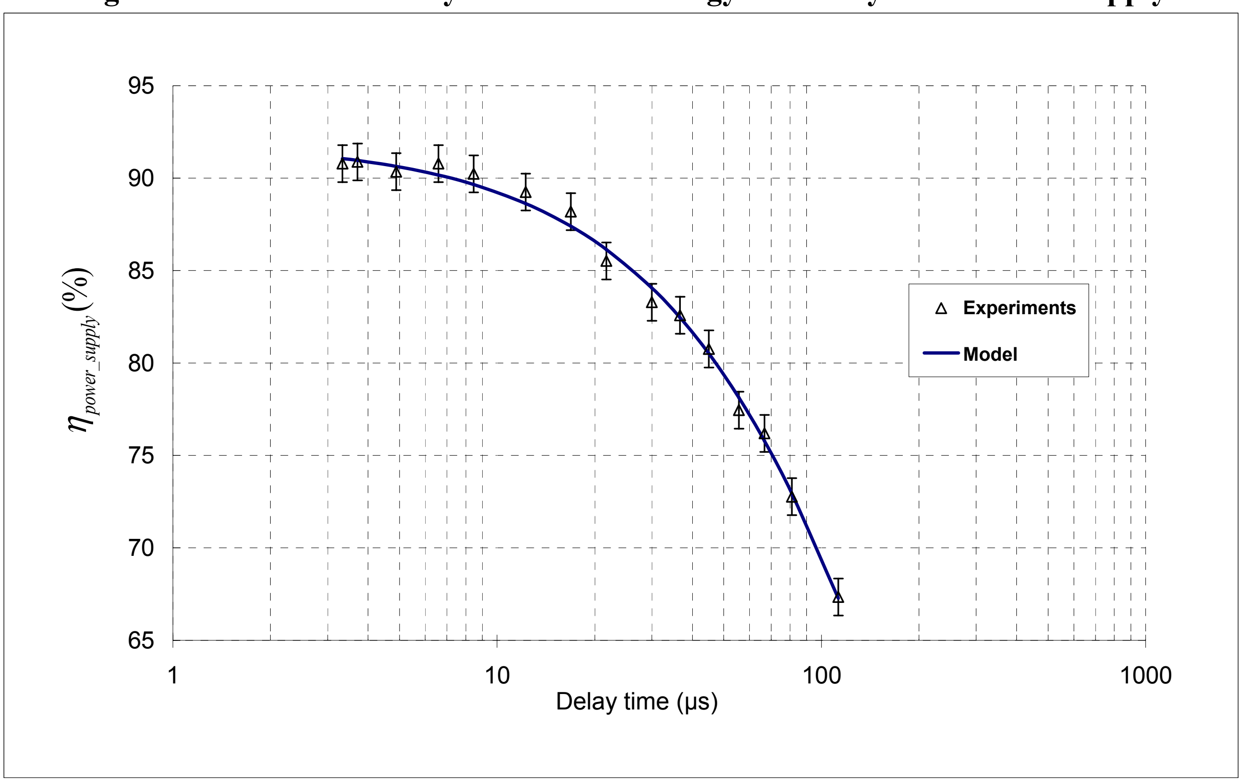


Figure 7. Effect of the Delay Time on the Energy Efficiency of the Power Supply



When there was small delay times (up to 10 µs), the energy efficiency of the power supply is close to 90%. This efficiency can decrease up to 67 %, if we used delay times close to

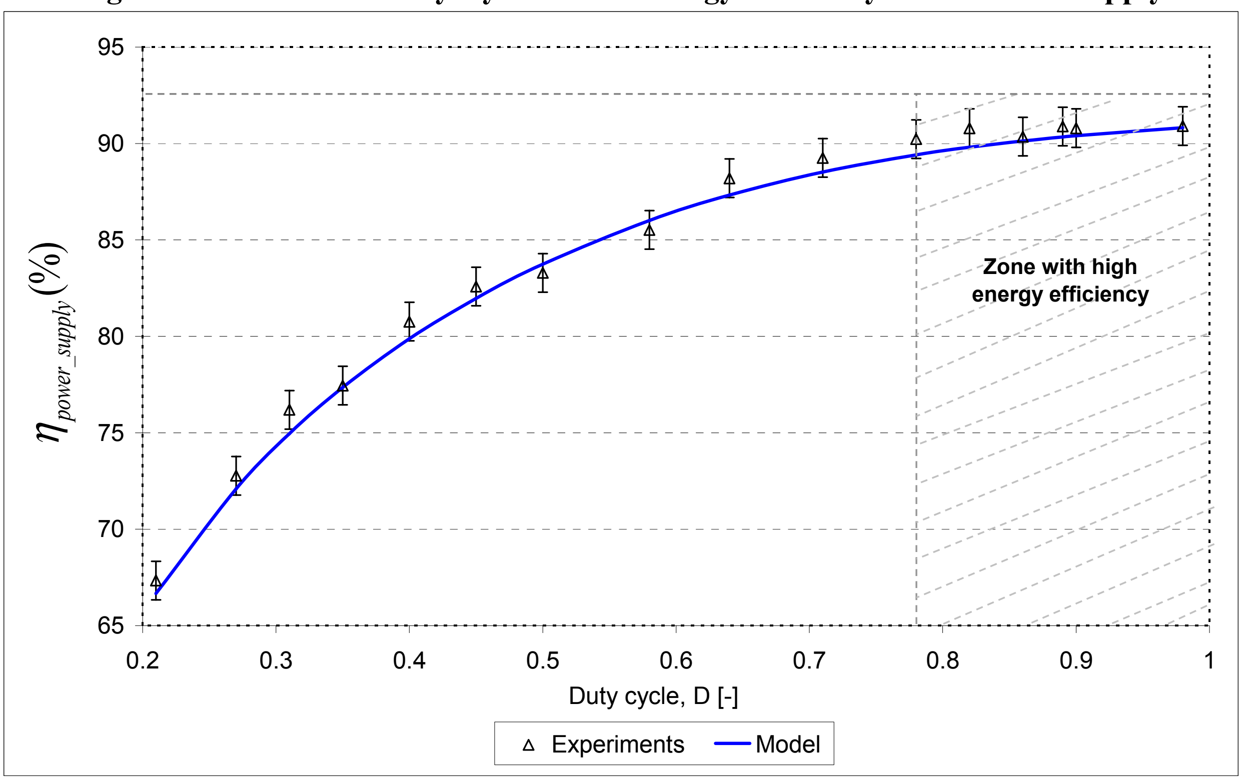
110 μs. An empirical relationship for the prediction of the energy efficiency with respect to the delay time was proposed.

$$\eta_{power\_supply} = 33.2 + 58.8 \exp(-5.10^{-3} t_d)$$

For optimal control of the process, we used the duty cycle (D) as a reference, better than delay time, for the deduction of the energy efficiency of the power supply. As shown in Figure 8, above a threshold duty cycle, which was close to 0.8, the energy efficiency exceeded 90 %. As previously demonstrated, any decrease in duty cycle leads to a large decrease of the energy efficiency of the power supply. As pointed out, an empirical model was suggested to predict the energy efficiency of the power supply according to the duty cycle.

$$\eta_{power\_supply} = 92.85 - 54.77 \exp(-3.69D)$$

Figure 8. Effect of the Duty Cycle on the Energy Efficiency of the Power Supply



Energy efficiency of the Ohmic cell. The electric resistance of the jet can be calculated as a function of the temperature profile along the jet and the liquid level in the receptacle of the Ohmic cell.

$$R_{jet} = \frac{64Q^2}{3k\sigma_0 g\pi^3 d_0^6} \times Log\left(\frac{1+kT}{1+kT_i}\right) \times \left(\left(1+\frac{g\pi^2 d_0^4}{8Q^2}(H-Z)\right)^{\frac{3}{2}} - 1\right)$$

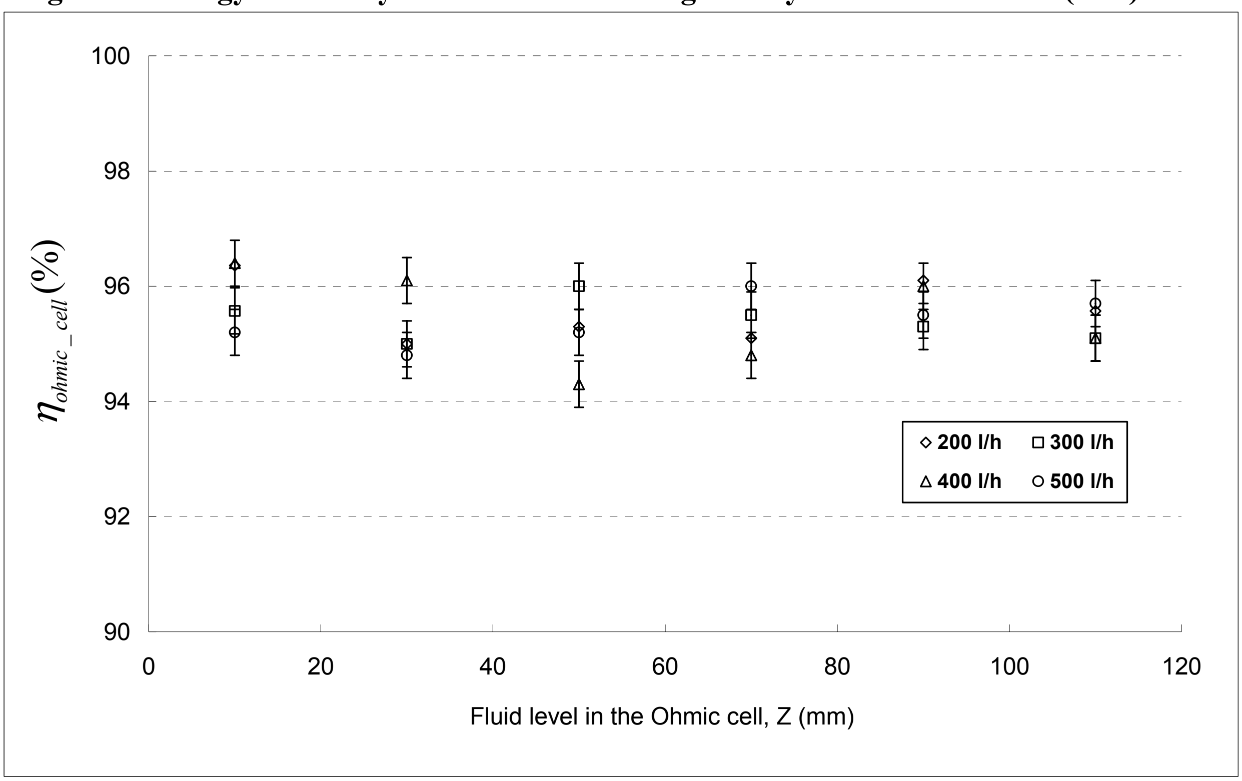
Where Q was the mass flowrate (kg.s^{-1}), g the gravity constant (m.s^{-2}), Z the fluid level inside the Ohmic cell (m), H the distance between electrodes (m), σ_0 the reference conductivity (S.m^{-1}), k the temperature factor (°C^{-1}), T_i the inlet temperature (°C) and d_0 the diameter of the nozzle (m).

Thereby, for a given flowrate, any decrease in the fluid level leads to large increase of the electrical resistance of the fluid. Consequently the input power supplied to the Ohmic cell and the duty cycle decrease at the same time. Hence, the energy efficiency of the power supply goes down until 65 %.

In this part, the energy efficiency of the Ohmic cell was undertaken for different fluid levels and flowrate as shown in Figure 9. We find that the energy efficiency of the Ohmic unit was independent of the flowrate or the fluid level; it remained constant and close to 95 %.

Thus, we can control the process according to the fluid level and not to the heating power. Indeed, to reach the values of duty cycle of the power supply near to 0.8, we varied the fluid level inside the Ohmic heater without decreasing its energy efficiency. In fact, we reached a global energy efficiency of the system (power supply and Ohmic heater) near to 85 %. This high energy efficiency can be means of energy savings compared to traditional processes.

Figure 9. Energy Efficiency of the Ohmic Heating Cell by Fluid Jet with 2% (w/w) CMC



Conclusion

In conclusion, energy efficiency of the power supply during Ohmic heating process can be significantly increased by reducing the delay time between two pulses. However, energy efficiency of the Ohmic cell remains constant and independent of the fluid level or flowrate. Our results may be relevant to both the optimal pilot of the Ohmic heating process, as well as for the understanding of the effect of the pulse parameters on the energy efficiency of the process. Indeed the global energy efficiency of the Ohmic heating process is approximately of 85%. Current research is also oriented to the fouling performances of this innovated process.

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