Studies on Microbial Destruction by Continuous Microwave Heating System through Helical Coils

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Abstract— Three specially designed glass helical coil applicators were introduced to study the effects of microwave heating on microorganisms and following process parameters were evaluated: input power (1200–1800 W) and Flow rate (100-1000ml/min), and inlet temperature (30°C). Water at neutral pH was used to study the heating characteristics. The 2kW microwave heating system consisted of cubical cavity with glass helical coil applicator of different diameters A, B and C separately, which was shown to produce uniform exit temperature throughout the experiment .Process lethality was verified based on inoculation of Aspergillus niger spores in water. From the transit-time and temperature measurements, time-temperature profiles were generated and kinetic data of microbial destruction were evaluated as a function of system variables. Destruction rate is directly proportional to power and temperature. It was found that when velocity increases destruction rate decreases. Energy absorption rate increased with respect to decrease in surface area, tube diameter and with lesser velocity. Tube diameter was the dominant factor affecting heating rate as compared with flow rate and Dean Number.

Keywords*- microwave heating; helical coil; lethality; microbial destruction; Dean number; system variables*

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I. INTRODUCTION

Killing of microorganisms using a clean technology has been of interest lately especially because of an increased concern to protect the environment from the chemicals [1].Several studies have been carried out to evaluate the effect of microwave heating on biological and chemical systems using different approaches , experimental designs and techniques .It is generally believed that the microwave effects on biological systems are mostly caused by the heat generated by the friction of dipole molecules under the influence of oscillating electrical field. Heating by microwaves is influenced by the size, shape and composition of the material as well as the type of equipment. Reference [2] studied that the spores of *Aspergillus niger*, *pencillim* Sp. and *Rhizopus nigricans* by exposure to microwave energy (5 kW, 2450 MHZ) for 2 min wit final temperature of 65- 70°C .Although there is a controversy about the mechanisms of microwave induced death of microorganisms, there is no doubt about the destructive effect of microwaves. Lethal effect of microwave on many bacteria has been reported including *Bacillus cereus*, *Campylobacter jejuni*, *Clostridium perfringes*, *E.coli*, *Enterococcus*, *Listeria monocytogenes*, *staphylococcus aureus*, *salmonella enteridis* [3,4,5].

Inactivation of microorganisms and reduction of quality attributes are both highly dependent on time-temperature treatments during pasteurization, so optimization of this process is crucial in obtaining a safe and high quality product. Because of the potential benefits of delivering reduced thermal exposure to inactivate pathogenic microorganisms while maintaining high quality, continuous flow microwave pasteurization system have created much interest in Newtonian fluids [6,7,8,9,10,11].

Helically coiled pipes are usually used as heat exchangers in food processing and numerous engineering fields. The results from various studies [12] show that the centrifugal force causes secondary flow within the tubes which increases the associated rate of heat transfer as compared with the values obtained for straight tubes. Reference [13] was the first one to study using a perturbation technique, the secondary flow field as a deviation from poiseuille flow. Dean introduced the variable k defined as 2 Re 2r/R where Re is the Reynolds number, r is tube radius, R is coil radius, K is the precursor of the Dean number (De) which is now expressed as in (1):

$$De = \sqrt{\frac{d}{D}} \qquad (1)$$

$$Re = \frac{d\vartheta\rho}{\pi d^2 \mu} \qquad (2)$$

Where Re is Reynolds number, De is Dean Number; D is coil diameter (m); d is pipe diameter. Dean number is used as a measure of secondary flow in helically coiled pipes.

Combining helical technique with continuous –flow microwave heating has been recognized as a promising technique for liquid foods processing due to advantages such as faster heating rate, better quality retention, uniform heating and lower energy consumption . In spite of publication of several studies on enzyme inactivation, heating characteristics and microbial destruction in continuous flow of MW heating system, little attention has so far been given for exploring the influence of system parameters on fungal spore destruction, exit temperature and time to achieve temperature equilibrium .Therefore the objectives of this study were to design and optimize coil configuration parameters for efficient microbial destruction in Newtonian fluids through continuous microwave heating .

II. MATERIAL AND METHODS

A. *Fungal Strain*

Aspergillus niger was obtained from the available stock culture in our laboratory. The strain had an intermediate thermal sensitivity with respect to several *A. niger* strains in our collections.

B. *Stock culture and preparation of spore suspension*

The pre cultures of mold strains were prepared by transferring on to potato dextrose agar plates at temperature 25^{o}C and incubated over 10 days. Spores were collected by washing the surface of the culture with sterile distilled water. The suspension was filtered twice through a glass wool column to remove hyphae. The spore concentration of the suspension was estimated with a hemocytometer. Finally, a spore suspension (about 10^8 to 10^9 SFU/ ml) was prepared in physiological saline.

The microbial populations of these pre-cultures were enumerated by recording as spore forming units (SFU) for mold. Distilled water with a pH of 6.8 was inoculated with pre cultures of fungi to obtain initial viable counts of 10^8 SFU/ml.

C. *Enumeration of spore counts*

The Samples were serially diluted with sterile physiological saline. Initial spore counts were determined by plating 0.1-ml diluted or non diluted samples on triplicate plates of potato dextrose agar (Himedia chemicals). Colonies were counted after incubation at 30°C for 3 days. All experiments were done in triplicate. The data presented are the means of results of three replicate experiments.

D. *Continuous Flow microwave heating set up with helical applicators*

The sample was run through 3 three different helical coils (A, B and C) and separately treated through continuous flow microwave heating system (Fig .1).The coils were made from pyrex glass tubing centrally located within the cubical cavity connected to microwave heating system (2kW-2450 MHz, Model- PTF2620, Enerzi Microwave systems Pvt. Ltd, Belgaum , Karnataka , India).A stainless steel reservoir (40 L capacity) was used to feed the liquid to the system. The sample was pumped at 12 different flow rates ranging from 100-1000ml/min through a calibrated variable speed metering pump. Their input power levels was used as 1.2 kW, 1.5 kW and 1.8 kW, and fiber optic probes (Neoptix model No:Reflex-4) were used to measure time temperature data. Water was run through the system until a steady – state heating condition was established as indicated by a constant temperature. Treated samples were collected into pre cooled sterile tubes at the exit of the microwave cavity. A control was kept for each study. Microbial destruction associating different system parameters were evaluated as detailed in Table 1.To achieve the desired initial temperature, water was kept in a controlled temperature environment before passing into the microwave applicator.

TABLE I. DESIGN OF PARAMETERS IN CONTINUOUS FLOW MICROWAVE HEATING SYSTEM

Coil	Parameters				
	Vol (ml)	***Number of turns***	***Surface area (sq.m)***	***Tube dia (mm)***	***Coil dia (mm)***
Coil A	98	12	0.106487	8	130
Coil B	185	8	0.09927	14	110
Coil C	615	7	0.2287	18	214

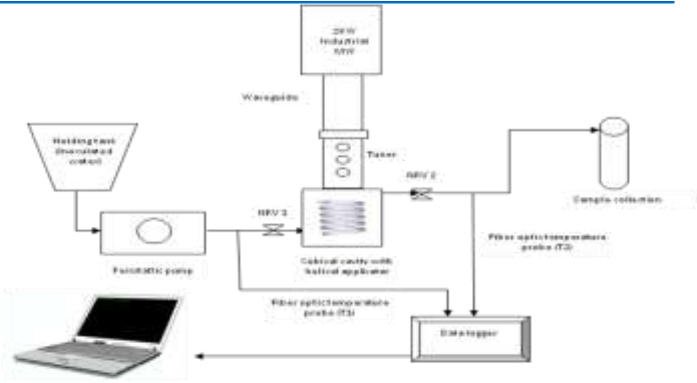

Figure 1. Schematic representation of Continuous flow of microwave heating system with Specially Designed Applicator

E. *Kinetics of microbial destruction*

The lethality of microorganisms is generally modeled based on first order rate reaction kinetics:

$$\frac{dC}{dt} = -kC \qquad (3)$$

where, C = concentration, t = time, and k = reaction rate constant.

The thermal kinetics of microorganisms also is traditionally characterized by by means of the D and z values.

$$D = \frac{2.303}{k} \qquad (4)$$

$$z = (T_2 - T_1)/\log\frac{D_1}{D_2} \qquad (5)$$

The D value (4) represents the heating time at a given temperature to cause one decimal reduction in surviving microbial population. The z value (5) represents the temperature range between which the D values change by a factor of 10. When the thermal resistance of a microorganism is known, it is possible to calculate the equivalent lethality, F (same as equivelent time, tref) necessary for thermal treatment by integration of the time temperature history using (6)

$$F = \int_0^t 10^{\frac{[T(t)-T_R]}{z}}\, dt \qquad (6)$$

where:

T(t) = transient temperature at time t, and TR = reference temperature.

A similar concept can be applied for determining kinetics parameters for the continuous-flow heating systems; however, these cases involve non-isothermal heating conditions: The procedure for gathering kinetic parameters during continuous-flow heating has been detailed in [14]. The D values are computed using (7)

$$D = \frac{t_{eff}}{log(C_0 - C)} \qquad (7)$$

where:

t_{eff} = effective time (same as F in Eq. 6) with TR as exit temperature, and Co,C = initial concentration of microbial cells and final concentrations of microbial cells.

t_{eff} is obtained experimentally from a time-temperature profile. The D-values at the exit temperatures can be first calculated from the regression of log residual numbers of survivors versus residence time. The z value is obtained as the negative reciprocal slope of log D versus temperature plot. The use of approach concerning microwave effects were explained in detail [15].

F. Power absorbed

Equation (8) is used to calculate absorbed power calorimetrically [16].

$$p_{abs} = V\rho C_p \frac{\Delta T}{\Delta t} \quad (8)$$

Where Pabs is the absorbed power (W), V is the volume and is the load capacity within the cavity , ρ is the density of the fluid (kg/m3), Cp is the specific heat capacity (J/kg ^{o}C), and ΔT/Δt is the heating rate (^{o}C/s). Since significant heat loss occurs above 40^{o}C and would compromise the heating rate measurements, the power absorption was measured from heating rates between the inlet temperature and 30^{o}C. The density of water was taken as 1000 kg/m3. The specific heat capacity for water was 4182 J/kg C, and the specific heat capacity for cider was calculated using the Dickerson model for fruit juices [17].

III. RESULT AND DISCUSSION

The influence of different system and heating parameters [surface area, number of turns in the helical turns, coil diameter, tube diameter (Fig 2), dean number, temperature, power absorbed] on heating characteristics and microbial destruction in water in a continuous flow microwave heating system are detailed below.

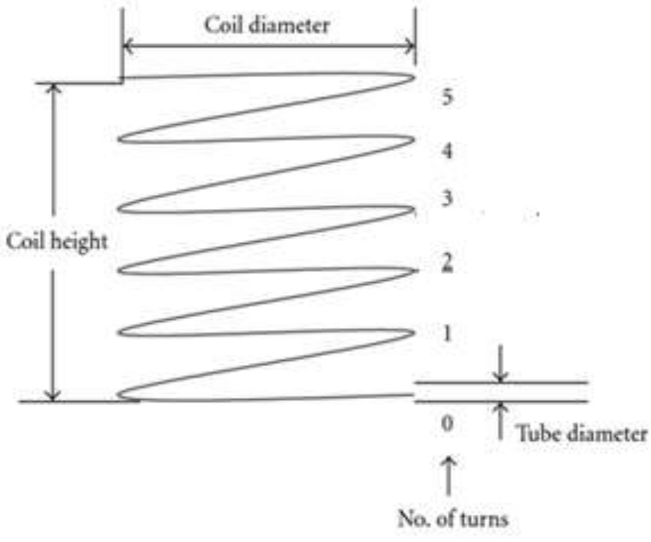

Fig 2. Coil geometric parameters

A. Surface area

The surface area was set as 0.106487 sq m, 0.09927 sq m and 0.2287 sq m for coil A, B and C respectively contributing to different coil sizes. Each coil was evaluated at a range of 100 to 1000 ml / min at three different power levels 1.2 kW, 1.5 kW and 1.8 kW. The output temperature increased with the decrease in surface area of coils (Fig 3).As a result, microbial destruction rate was high in the coil B with lesser surface area. Typical evolution of temperature rising rate for each coil at different flow rates and power levels correlated with the destruction rate indicating that surface area had prominent influence on temperature rise.

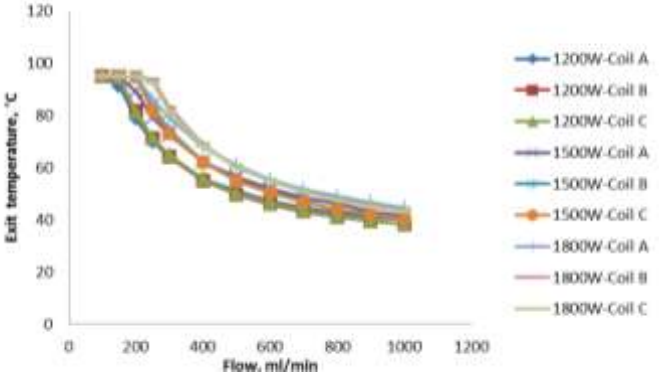

Fig 3: Flow vs. output temperature of helical coils at three different power levels

B. Number of turns in the coil

The number of turns in the coil was set as 12, 8 and 7 for coil A, B and C respectively. The heating rate required to achieve it were dependent on number of turns and flow rate. Coils with more number of turns had a larger coil volume, which resulted in a longer residence time. Fig 4 shows that a faster flow rate would result in a lower exit temperature and increased heating rate in the microwave oven. Fig 5 shows the prevalence of longer residence time caused the higher destruction rate. The faster flow rates slightly increased heating rate probably due to lower heat loss of microwave environment because of lower exit temperature. On the other hand, exit temperature was higher at slower flow rates because of longer residence times and hence resulted with the possibility of higher heat loss and hence resulted in the overall heating rate to be normal.

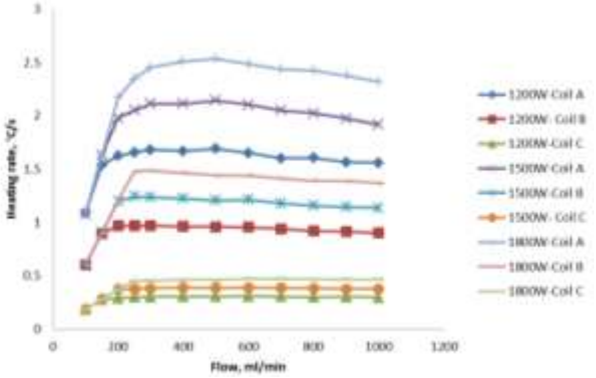

Fig 4: Flow vs heating rate of helical coils at different power levels

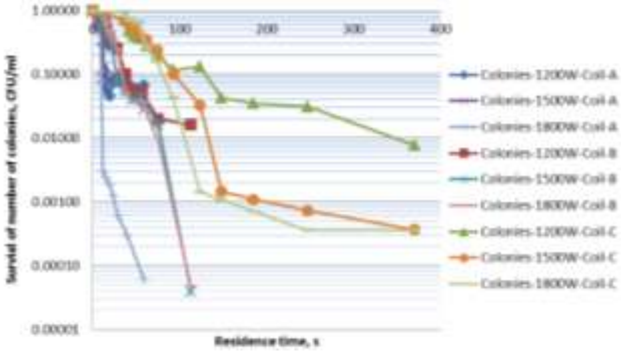

Fig 5: Residence time vs. no of colonies in helical coils at different power levels

C. *Coil diameter*

Different coil diameters were set as 130, 110 and 214 mm for coil A, B and C respectively. Smaller coiler diameter achieved faster heating rate due to the shorter residence time in the microwave, indicating that coil diameter had significant influence on heating rate but does not have effect on microbial destruction, because coil A with diameter 130 mm showed faster destruction rate within a short residence time .

D. *Tube diameter*

In this study, three tube diameters (8, 14, and 18mm) were evaluated. It was observed that smaller tube diameter achieved higher heating rate (Fig 4) as well as higher destruction rate (Fig 5). All the coils showed shower faster destruction rate at higher power level. Under continuous-flow microwave heating condition, tube diameter is one of most important parameters determining coil volume as well as the heating rate in a microwave environment.

E. *Dean number*

Dean number is a measure of secondary flow in the curved tube. Reynolds number (2) associated flow rates under the experimental conditions was ≤2100, indicating that the flow condition was conventionally laminar. Dean number increased with the decrease in tube diameter of coil. Fig 6 show that the coil containing higher dean number increased with increase in flow rate and decrease in tube diameter. These results showed that dean number had a more pronounced effect on microbial destruction rate.

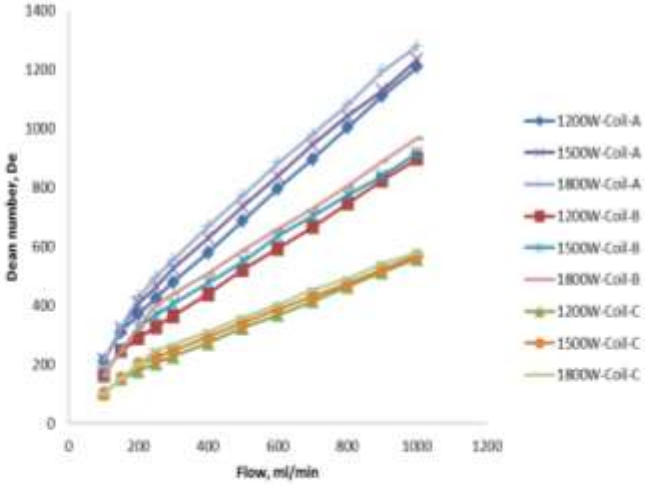

Fig 6: Flow vs. Dean Number in helical coils at different power levels

F. *Temperature*

The initial temperature was kept constant at 30^{o}C throughout the study. Fig 7 show the temperature change (ΔT) for three coils at different power levels. Rise in temperature depends on the flow rate. When flow rate increases, temperature decreases. Change in temperature slightly occurred by increasing the power level. Microbial destruction rate is effective for flow rate between 100 -500 ml/min for all three coils. Higher flow rates resulted in higher Dean numbers possibly contributing to higher degree mixing.

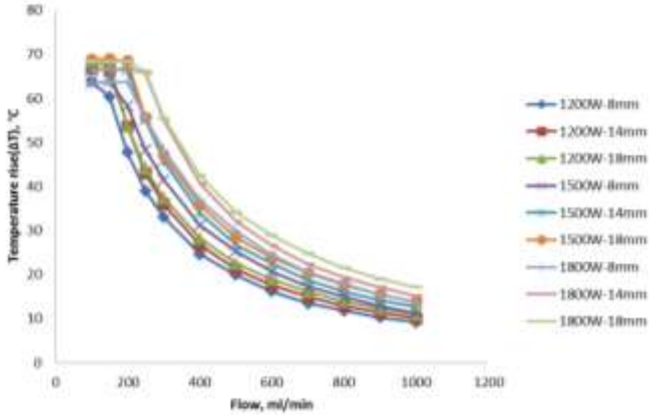

Fig 7: Flow vs. temperature rise in helical coils at different power levels

G. *Power absorbed*

As shown in table 2, coil A, coil B and coil C absorbed more energy at flow rate of 500,300 and 600 ml/min at 1800 W which resulted in 99, 95 and 73 % of destruction respectively. This indicates that smaller the tube diameter, higher the energy absorption as well as higher destruction rate.

IV. CONCLUSION

A continuous-flow microwave heating system was set up to study the microbial destruction in water through optimizing coil configuration parameters such as coil diameter, tube diameter, number of turns, temperature, flow rate, and surface area to improve heating rate, microwave absorption efficiency with reduced heating time and temperature fluctuations. Microwave absorption efficiency and destruction rate was found to be a function of flow rate, initial temperature, and coil configuration under continuous flow microwave heating condition. Coil A and B achieved higher exit temperatures and heating rates than coil C from the obtained results. Results from this study show that (1) Lower surface area resulted in faster microbial destruction rate; (2) higher number of turns resulted in longer residence time therefore result increase in the destruction rate and lower temperature variations; (3) larger tube or coil diameter gave larger coil volume resulting in decreased heating rate; (4) Decrease in tube diameter resulted in higher destruction rate ;(5)Faster flow rates resulted in lower exit temperatures, lower temperature variation, higher Dean number, and slightly higher heating rate; (6) Higher Dean number resulted in more uniform heating and slightly higher heating rate.(7)Smaller the tube diameter, higher the energy absorption and higher destruction rate.

Overall, tube diameter and surface area were the dominant factors affecting heating rate and fungal spore destruction as compared with flow rate and Dean Number.

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TABLE II. EFFECT OF TUBE DIAMETER, HEATING RATE AND ENERGY ABSORBED ON MICROBIAL DESTRUCTION.

Power level W	***Helical Coil***	***Flow ml/min***	***Ini.Temp Ti, °C***	***Exit.Temp To, °C***	***Avg.Temp T1/2, °C***	***Change ΔT***	***Heating Rate ΔT/t, C/s***	***Energy, W Pabs***	***Destruction %***
1200	Coil-A	500	31.26	51.14	44.52	19.88	1.69	685.84	70.90
1500	Coil-A	500	31.34	56.56	48.16	25.22	2.15	868.76	91.55
1800	Coil-A	500	31.21	61.05	51.11	29.84	2.54	1026.74	99.70
1200	Coil-B	300	28.33	64.24	52.28	35.91	0.95	741.18	90.00
1500	Coil-B	250	28.36	83.56	65.18	55.2	1.22	944.18	96.00
1800	Coil-B	300	28.28	83.2	64.91	54.92	1.46	1127.27	95.00
1200	Coil-C	600	27.69	46.54	40.26	18.85	0.31	781.64	71.48
1500	Coil-C	600	26.65	50.46	42.53	23.81	0.39	986.11	64.36
1800	Coil-C	600	26.03	54.95	45.32	28.92	0.47	1197.03	73.93

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