Hindawi Publishing Corporation
International Journal of Microwave Science and Technology
Volume 2011, Article ID 264249, 10 pages
doi:10.1155/2011/264249

Research Article

Influence of System Variables on the Heating Characteristics of Water during Continuous Flow Microwave Heating

Hosahalli S. Ramaswamy and Manguang Lin

Department of Food Science and Agricultural Chemistry, Macdonald Campus of McGill University, 21 111 Lakeshore Road, Ste. Anne de Bellevue, Monterial, QC, Canada H9X 3V9

Correspondence should be addressed to Hosahalli S. Ramaswamy, hosahalli.ramaswamy@mcgill.ca

Received 10 April 2011; Revised 6 July 2011; Accepted 15 August 2011

Academic Editor: Samir Trabelsi

A domestic microwave oven (1000 W) was modified to permit the continuous flow of liquids run through a helical coil centrally located inside the oven cavity. Heating characteristics were evaluated by measuring inlet and outlet temperatures of coil as a function of system variables. The influence of number of turns, coil diameter, tube diameter, pitch and initial temperature were evaluated at different flow rates. The average residence time of water was computed by dividing the coil volume by the volumetric flow rate. The influence of Dean number was evaluated. Results from this study showed that (1) higher number of turns resulted in lower heating rate, lower temperature fluctuations, higher exit temperature and longer time to achieve temperature equilibrium; (2) larger tube or coil diameter gave larger coil volume causing the heating rate to decrease; (3) faster flow rates resulted in lower exit temperatures, lower temperature fluctuation, higher Dean number and slightly higher heating rate; (4) higher initial temperatures resulted in higher exit temperatures; (5) higher Dean number resulted in more uniform heating and slightly higher heating rate. Overall, the coil volume was the more dominant factor affecting heating rate as compared with flow rate and Dean number.

1. Introduction

Curved or helically coiled pipes are usually used as heat exchangers in food processing and numerous engineering fields, such as chemical, food, boiler, refrigeration, air conditioning, and nuclear engineering due to the unique flow patterns resulting from tube curvature and the advantage of volume compactness. Many experimental and theoretical papers have reported on convective heat transfer and temperature profiles in helical coil tubes [2–12]. The results from the above studies generally 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.

Thomson [13] was the first to observe the striking effects of curvature on open-channel flow. Eustice [14] observed the trajectories of ink injected into water flowing in tubes wound around pipes of different diameters. Dean [1] was the first one to study, using a perturbation technique, the secondary flow field as a deviation from Poiseuille flow. As illustrated in Figure 1, Dean indicated that there exists a secondary flow in the form of a pair of vortices rotating in opposite directions. According to Dean, the lines in the figure "represent what may loosely be called the projections of the paths of fluid elements on the cross-section of the pipe". Then Dean began to develop a mathematical framework to explain the streamlines observed by Eustice, and later Dean [15] turned his attention to a mathematical explanation of the reduction in flow rate due to curvature, earlier experimentally observed by Eustice. In attempting to explain the reduction in flow in a curved tube compared to that in a straight tube at the same axial pressure gradient, Dean introduced the variable K defined as $2\mathrm{Re}^2 r/R$ 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):

$$\mathrm{De} = \mathrm{Re}\sqrt{\frac{d}{D}} = \frac{4f\rho}{\pi\mu\sqrt{d * D}} \tag{1}$$

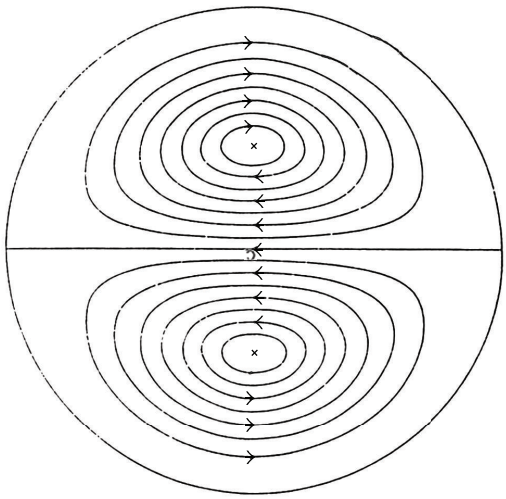

Figure 1: Secondary flow in the form of a pair of vortices rotating in opposite directions [1].

$$\mathrm{Re} = \frac{d\nu\rho}{\mu} = \frac{4f\rho}{\pi d^2\mu}, \tag{2}$$

where Re is Reynolds number; De is Dean number; D is coil diameter (m); d is pipe diameter (m); v is average velocity (m/s); f is flow rate (mL/s); ρ is fluid density (kg/m^3); μ is fluid viscosity (Pa.s). Dean number is used as a measure of secondary flow in helically coiled pipes.

The presence of secondary flow enhances mixing of the lowing fluid and increases heat transfer even under conventional laminar flow conditions. Continuous-flow systems using helical heat exchangers are considered to yield more uniform heat treatment as compared to bulk bath-mode or straight tube heating offering advantages of improved product quality and higher nutrient retention [16, 17]. Microwave heating has advantages such as faster heating rate and more homogeneous heat dissipation in comparison with conventional heat treatment due to volumetric heat dissipation which could provide quality advantage for heat sensitive products [18]. By combing helical technique with microwave, continuous-flow microwave heating has been recognized as a promising technique for liquid foods processing due to fast heating rate, high-quality retention, uniform heating, energy-saving opportunities, prevention of surface fouling, and easy access to clean-up. Since coil configuration influences coil volume and the level of Dean number, they also influence the heating characteristics in continuous-flow microwave heating system.

In a recent study [19], raw milk was subjected to conventional isothermal water bath heating, continuous flow microwave heating, and continuous flow thermal holding in the pasteurization temperature range (60–75°C), and then immediately cooled in an ice-water bath. The associated alkaline phosphatase (ALP) residual activities were evaluated. It was demonstrated that the inactivation of ALP under microwave heating was at least an order of magnitude higher than under conventional thermal heating. These results emphasize that ALP inactivation occurred much more rapidly under microwave heating conditions than under conventional heating thereby confirming the existence of enhanced thermal effects from microwave.

In spite of publication of several studies on enzyme inactivation and microbial destruction in continuous tube flow MW heating conditions [17, 20–22], little attention has so far been given for exploring the influence of system parameters on heating characteristics in continuous-flow microwave heating system such as heating rate, exit temperature, and time to achieve temperature equilibrium which are the objectives of the study.

2. Materials and Methods

2.1. Continuous-Flow Microwave Heating System. A domestic microwave oven with 1000 W nominal output at 2450 MHz (Sunbeam, Model: SMW1150, Curtis International Ltd., Toronto, ON) was modified to accommodate the continuous-flow microwave heating of water (Figure 2). Glass beakers (made from Pyrex glass) with different sizes were used to support high performance Norprene tubing (Cole-Parmer) to form coils (Figure 3) with different geometric parameters. A stainless steel container (25 liters) was used to feed water to a calibrated variable speed metering pump (Masterflex, Model: 7524-40, Cole-Parmer), which circulated water through the Norprene tubing coil centrally located inside the MW oven cavity (dimension: 38.4 × 34.9 × 21.9 cm). In order to maintain a stable flow rate, a plastic buffer (Cole-Parmer) was installed between the metering pump and the microwave oven. The direction of the water flow in the system was upward in order to have a better control of flow rate. The water container and tubing were insulated to prevent heat loss. Inlet and outlet temperatures were continuously monitored using T-type thin-wire (0.381 mm diameter) copper-constantan thermocouples (Omega Engineering Inc., Stamford, Conn, USA) centrally inserted in the tubing just outside the microwave oven with their surface parallel to the direction of the fluid flow. Before installation each thermocouple was welded on a copper fin to permit the measurement of mean temperature of flowing fluid. The modified thermocouples were calibrated against ASTM mercury-in-glass thermometer. The accuracy of the temperature measurements was ±0.1°C. Temperatures were computer recorded via a data logger (Dash-8, Omega Engineering Inc., Stamford, Conn, USA). In order to get better mixing condition and reduce the temperature gradient across the radius of the tube, two static mixers (8 mm diameter, 50 mm length, Teflon, Omega) were installed near each end of coil inside the microwave oven cavity.

2.2. Measurement of Time-Temperature Profiles. Water was run through the system long enough to purge out what was previously present in the system, then the data-logger and microwave ovens were turned on. The system was run for 10 min after establishing steady-state condition indicated by a constant outlet temperature. During microwave heating,

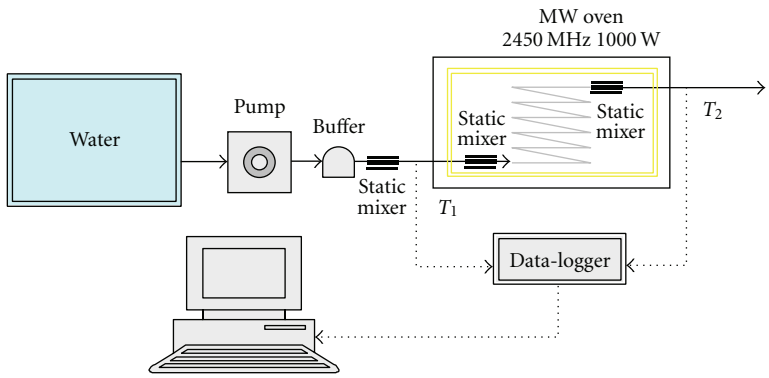

Figure 2: Schematic diagram of continuous-flow microwave heating system.

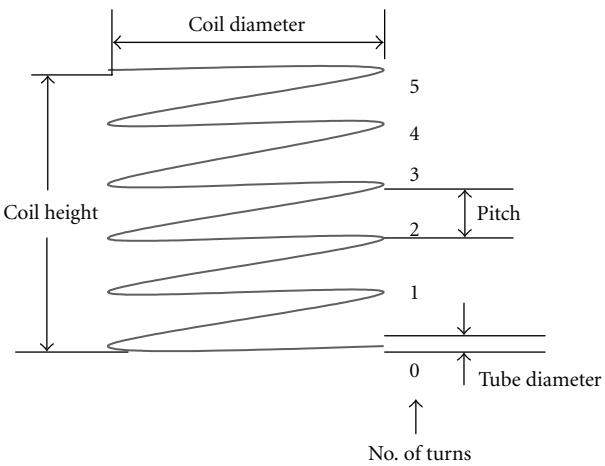

Figure 3: Coil geometric parameters.

inlet and outlet temperatures were recorded every 2 seconds. Heating characteristics associating different system parameters were evaluated as detailed in Table 1. The water to be run through the microwave was kept in a controlled temperature environment for achieving the desired initial temperature. The average residence time of heated water was determined by dividing the sample volume by the steady state volumetric flow rate. Heating rate was calculated according to

$$\mathrm{HR} = \frac{[T_o - T_i]}{\Delta t}, \tag{3}$$

where HR is heating rate (°C/s); T_o is outlet temperature (°C); T_i is inlet temperature (°C); Δt is residence time in microwave oven(s).

3. Results and Discussion

The influence of different system parameters (number of turns in the helical coil, coil diameter, tube diameter and pitch) on heating characteristics of water in a continuous-flow microwave heating system are detailed below. Heating parameters included were heating rate, exit temperature, and Dean number.

3.1. Number of Turns in the Coil. In the first set of experiments, the number of turns in the coil was set at 3.5, 4.5, and 5.5 (contributing to different coil heights) while the coil diameter (120 mm), tube diameter (7.9 mm), and pitch (16 mm) were kept the same. Each coil was evaluated at 240, 270, 300, 320, and 340 mL/min at initial temperature of 20°C. Time temperature profiles for the three coils (Figure 4) were obtained by pumping water through the continuous-flow microwave heating system at different flow rates showing typical lag periods prior to achieving steady state. Figure 4 shows exit temperatures as a function of heating time from the time microwave oven was turned on. The nonlinearity in time-temperature data during early phase of heating (the lag period) can easily be explained by the heat sink contributed by the coil and environment within the cavity as explained by Kudra et al. [23]. The equilibrium exit temperature and heating time required to achieve it were dependent on number of turns and the flow rate. As illustrated in Figure 4, exit temperatures generally stabilized at about 55, 58, and 60°C (indicated by "S" in each figure) after about 1.6, 1.8 and 2.0 min for the coil with 3.5, 4.5, and 5.5 turns, respectively, at a flow rate about 240 mL/min. Coils with higher number of turns had a bigger coil volume, which resulted in a longer residence time and a higher exit temperature. Hence, coils with more number of turns needed a longer time to achieve temperature equilibrium. Figure 4 shows that a faster flow rate would result in a lower exit temperature due to the shorter residence time in the microwave oven.

Typical evolution of heating rate as a function of mean flow rate for different number of turns is presented in Figure 5, showing that number of turns had prominent influence on heating rate. At the same flow rate, the higher number of turns resulted in the higher exit temperature; however, the prevalence of longer residence time and the higher heat loss (due to higher exit temperature) caused the heating rate to decrease. For the same coil, faster flow rates resulted in lower exit temperatures, but achieved higher heating rates. The faster flow rates slightly increased heating rate probably due to the lower heat loss of microwave environment because of the lower exit temperature. On the

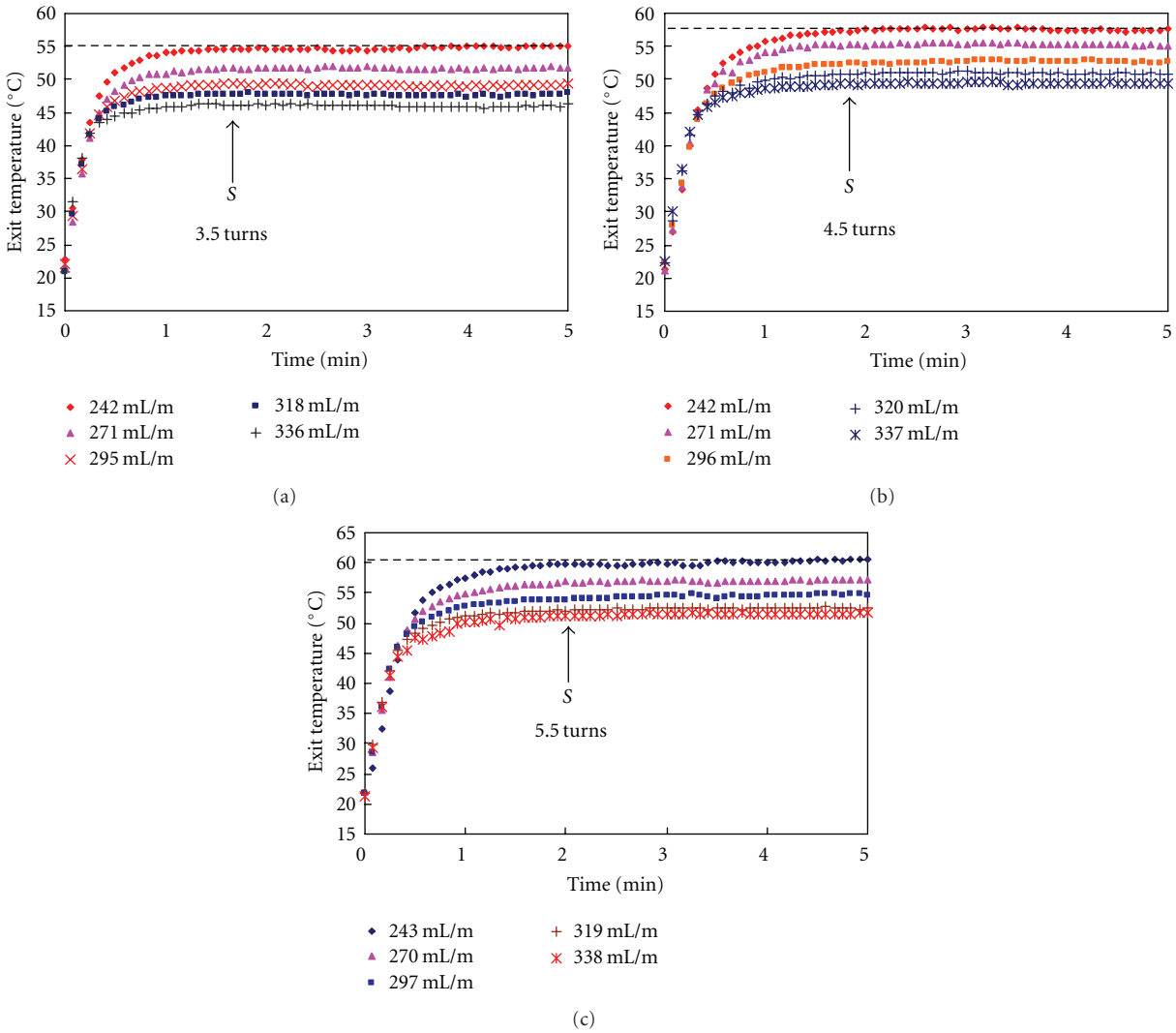

Figure 4: MW heating curves for coils with (a) 3.3 turns, (b) 4.5 turns, and (c) 5.5 turns as a function of flow rate (initial temperature 20°C, S = stabilization time).

Table 1: Design of parameters in continuous-flow microwave heating system.

Flow rate (mL/min)	No. of turns	Tube diameter (mm)	Coil diameter (mm)	Initial temperature (°C)	Different pitch (mm)	Scan time (s)
240			61.5		16	
270	3.5	6.4	88	10	18	
300	4.5	7.9	102	20	20	2
330	5.5	9.7	121	30	22	
370			153		24	

other hand, at slower flow rates, the residence times were longer, exit temperatures higher with the possibility of higher heat loss and hence resulted in the overall heating rate to be lower.

Reynolds number (calculated by (2)) associated flow rates under the experimental conditions was ≤2100, indicating that the flow condition was conventionally laminar. However, the use of helical coil, presumably creating secondary flow within the tube, helped to improve mixing of flowing fluid providing enhanced temperature uniformity even under conventional laminar flow conditions. Dean number is a measure of secondary flow in the curved tube. Tajchakavit et al. [17] used a fiber optic probe to measure temperatures of test samples inside the microwave oven

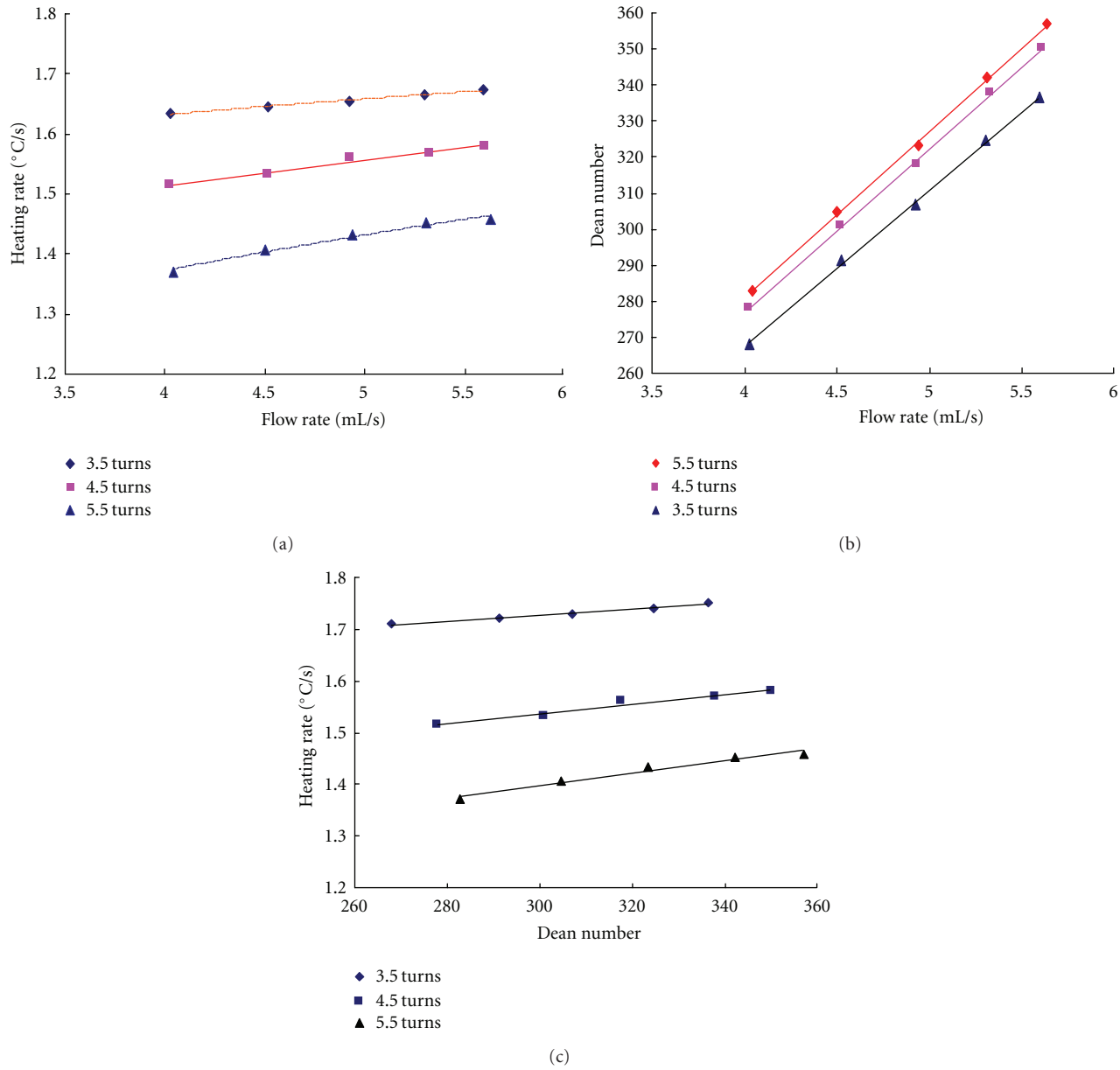

Figure 5: Heating rate as a function of flow rate for coils with different number of turns at initial temperature 20°C.

at three locations (0.25, 0.5, and 0.75 tube length from the entrance) along the coil length for continuous-flow microwave heating system and reported the temperature rise in the microwave oven was somewhat nonlinear with the temperature registered generally higher than in a linearly increasing profile. They generalized that the temperature at 50% of coil length, $T_{1/2} = T_o - 0.333 \times (T_o - T_i)$ (T_o = outlet temperature; T_i = inlet temperature). The mean temperature ($T_{1/2}$) associated density and viscosities were used for calculating Dean number (as per (1)) at different flow rates. Figure 5(b) shows that faster flow rate or higher number of turns resulted in higher Dean numbers. At each flow rate, the number of turns in the coil had a corresponding heating rate (Figure 5(a)) as well as a corresponding Dean number (Figure 5(b)). The associated heating rate and Dean number can be used to establish a relationship of heating rate versus Dean number as illustrated in Figure 5(c), showing that higher Dean numbers (due to faster flow rate) only slightly increased heating rate. However, the higher number of turns prominently reduced heating rate. These results show that number of turns had a more pronounced effect on heating rate than Dean number and flow rate.

3.2. Coil Diameter. Different coil diameters (153, 121, 102, 88, and 61.5 mm) were evaluated while keeping the other parameters at the same level (tube diameter: 7.9 mm, 5.5 turns, coil height: 88 mm). Again, each coil was evaluated at flow rates 240, 270, 300, 330, and 350 mL/min, respectively,

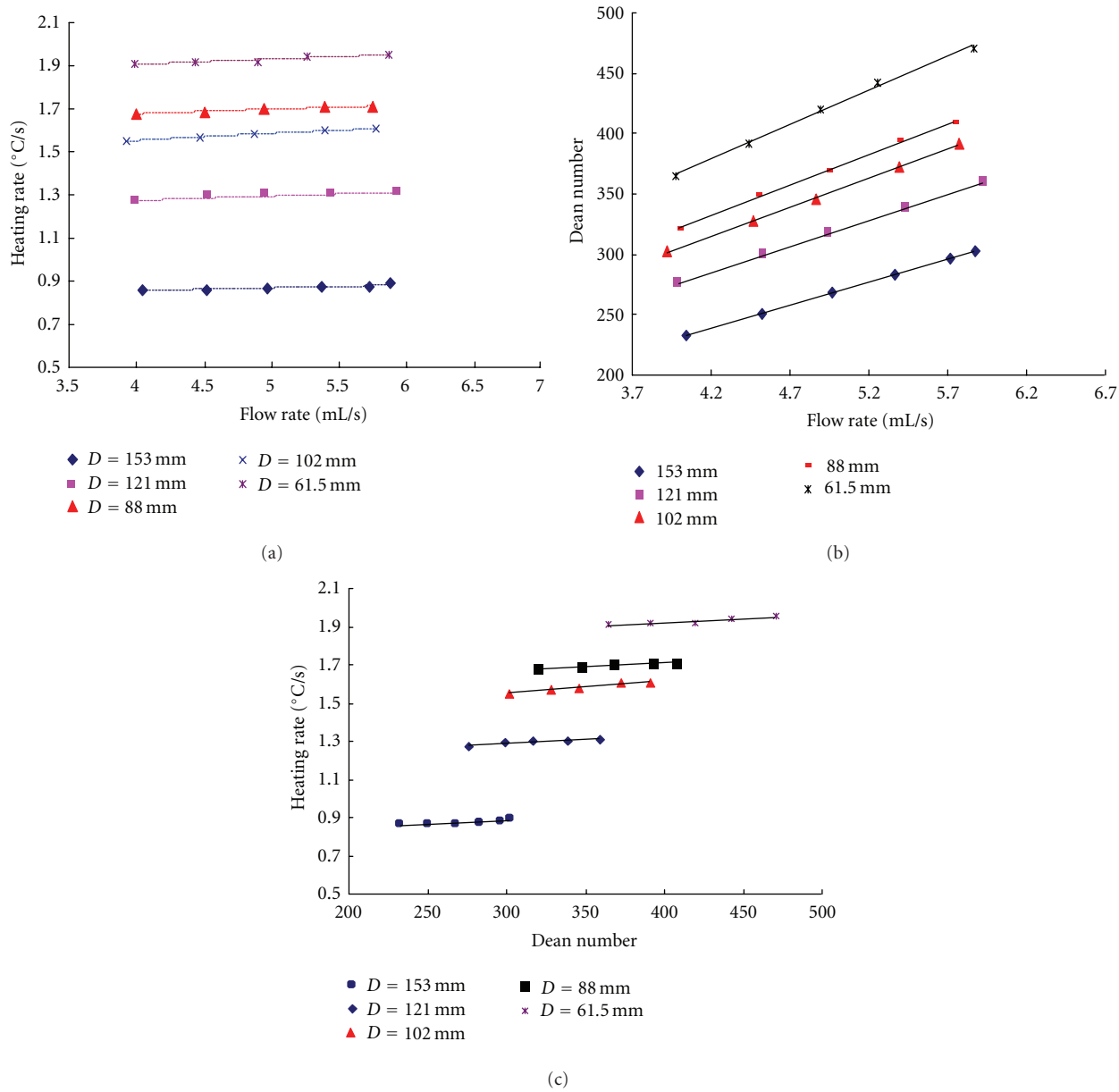

Figure 6: Heating rate (a) and Dean number (b) as a function of fluid flow rate, and heating rate as a function of Dean number (c) for coils with different coil diameter (initial temperature 20°C).

with initial temperature 20°C. Figure 6(a) shows heating rate as a function of flow rate for the tubes of different coil diameters. Under these conditions, flow rate had no major effect on heating rate. Faster flow rates result in shorter residence times and hence lower exit temperatures thus, as determined by (3), flow rate should not have a major effect on the heating rate. However, the associated heat loss in the chamber is probably lower because of the lower exit temperatures at faster flow rates. Hence, faster flow rates slightly increased associated heating rates. Figure 6(a) also shows smaller coil diameter achieved faster heating rate due to the shorter residence time in the microwave oven, showing that coil diameter had significant influence on heating rate. Figure 6(b) shows Dean number as a function of flow rate, indicating a linearly increasing relationship with higher flow rates resulting in higher Dean numbers. More importantly, coils with larger diameters profoundly decreased the associated Dean numbers indicating lower Dean effect in creating secondary mixing conditions. As further illustrated in Figure 6(c), there was no relationship between Dean number and heating rate for the different coils.

3.3. Tube Diameter. Under continuous-flow microwave heating condition, tube diameter is one of most important parameters determining coil volume and hence the heating rate in a microwave environment. In this study, three tube

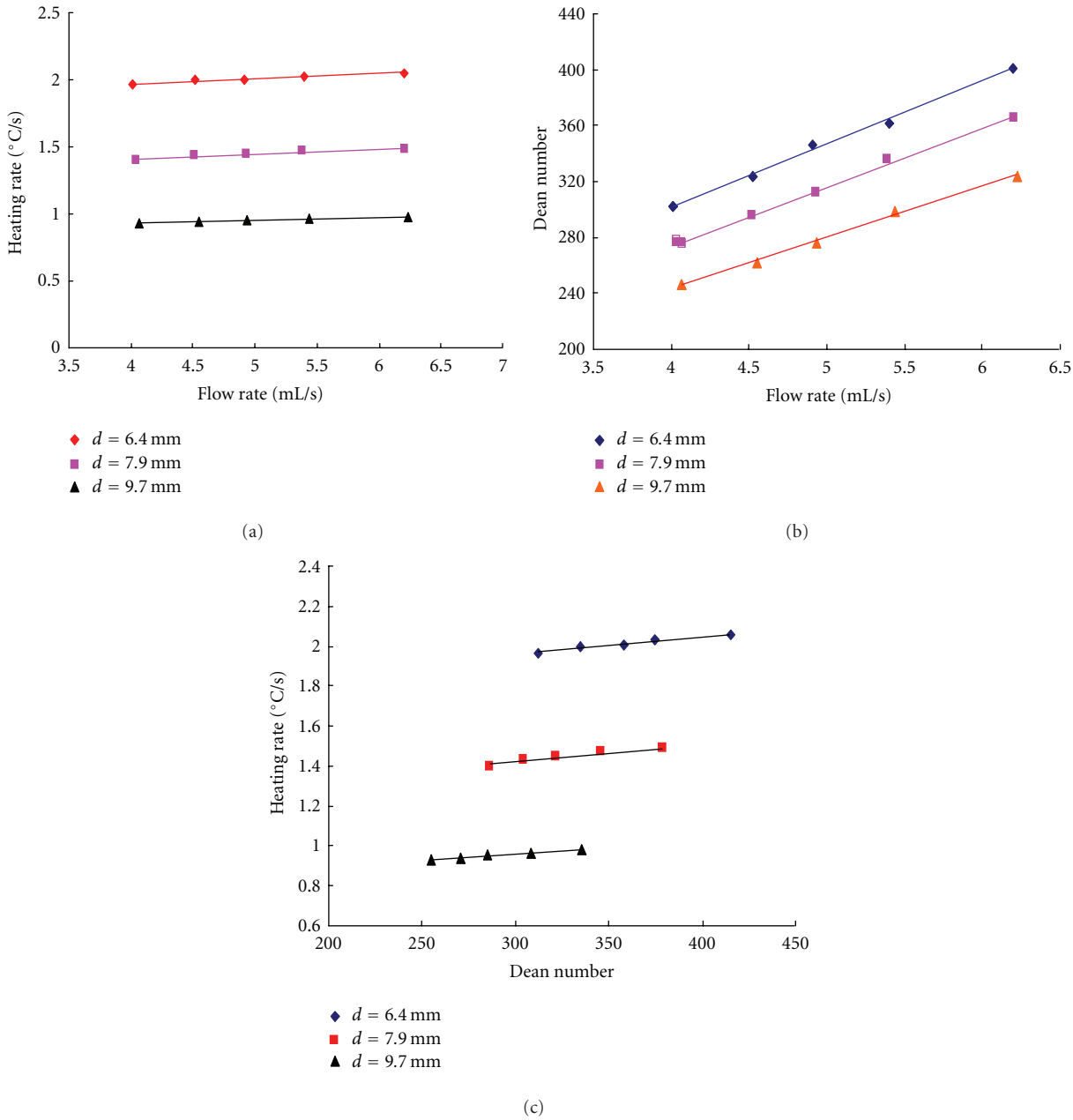

Figure 7: Heating rate (a) and Dean number (b) as a function of fluid flow rate, and heating rate as a function of Dean number (c) for coils with different tube diameter (initial temperature 20°C).

diameters (6.4, 7.9, and 9.7 mm) were evaluated. Except tube diameters, the different coils had the same number of turns (5.5), coil height (110 mm), and coil diameter (108 mm). Experiments were carried out at flow rate 240, 270, 300, 330 and 370 mL/min, respectively, at initial temperature 20°C.

Figures 7(a) and 7(b) show heating rate and Dean number as a function of flow rate and Figure 7(c) shows heating rate as a function of Dean number for different coil tube diameters. Smaller tube diameters achieved higher heating rate due to smaller coil volume; however, the heating rates were mostly independent of low rates. As expected, smaller tube diameters and faster flow rates contributed to increasing the associated Dean numbers. A 50% increase in flow rate resulted in about 25% increase in Dean number with the 9.7 mm diameter tube as compared with over 40% increase with the 6.4 mm diameter tube (Figure 7(b)) indicating the greater importance of tube diameter. Again, there was no relationship between flow rate and Dean number (Figure 7(c)).

3.4. Initial Temperature of Water. With the tube diameter of 7.9 mm, coil diameter of 121 mm, coil height of 88 mm and 5.5 turns, the influence of initial temperatures (10, 20, and 30°C) on exit temperature was evaluated as a function of flow

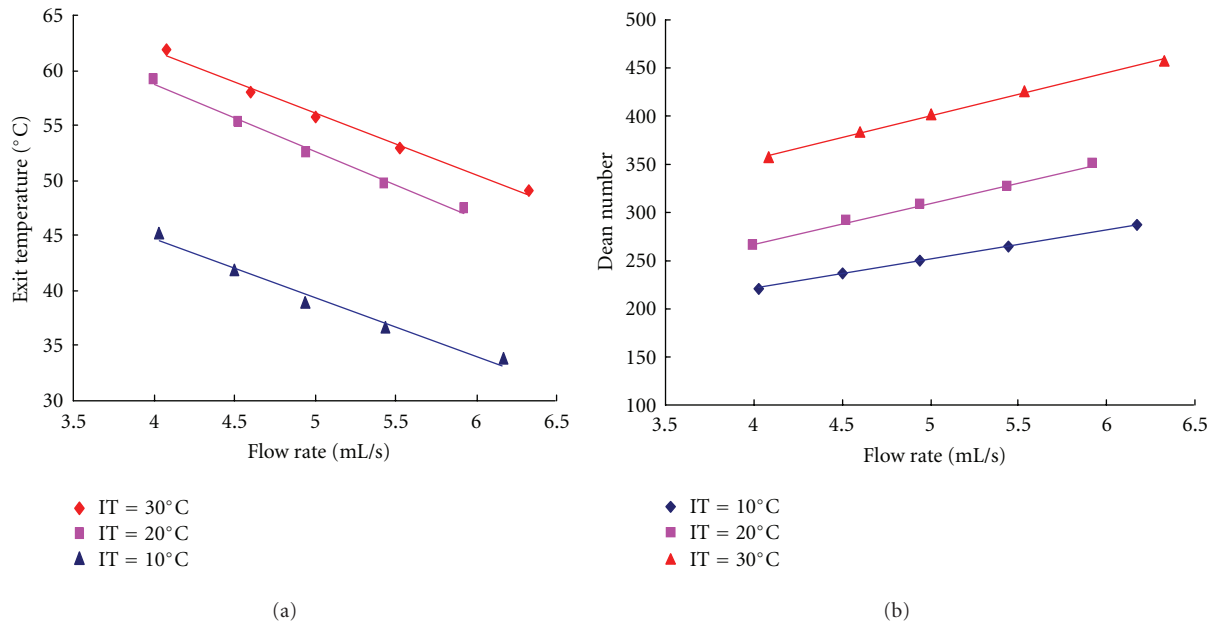

Figure 8: Exit temperature and Dean number as a function of flow rate at different initial temperatures.

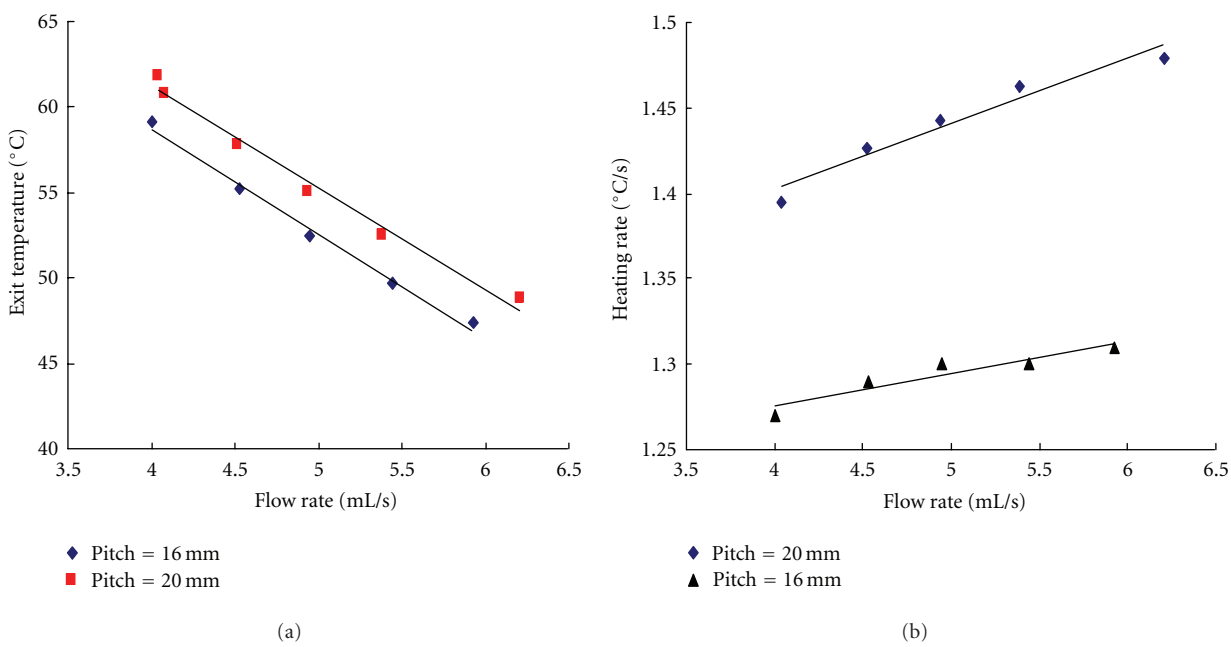

Figure 9: Exit temperature and heating rate as a function of flow rate for coils with different pitch at an initial temperature of 20°C.

rate. Figure 8(a) shows the accepted trends that higher initial temperature results in higher exit temperature, and faster flow rate results in a lower exit temperature. Figure 8(b) also indicated that higher initial temperatures and higher flow rates resulted in higher Dean numbers possibly contributing to higher degree mixing.

3.5. Pitch. As the medium runs through continuous-flow microwave heating system, the curvature of helical coil induces a centrifugal force which created the secondary flow (Figure 1). In the helical coil, flow translation is favored as pitch increases while rotation is favored as pitch tends to zero. The influence of pitch is therefore to alter the relative dominance of translation and rotation. The more dominant the translation, the less one can expect symmetry of the vortices (at conditions at which two vortices exists). As pitch increases, the velocity at which the two vortices are symmetrical is greater (in the limit of infinite pitch, there are never two vortices) [19]. Pitch influences flow motions and patterns in the coil, thus pitch affected heating

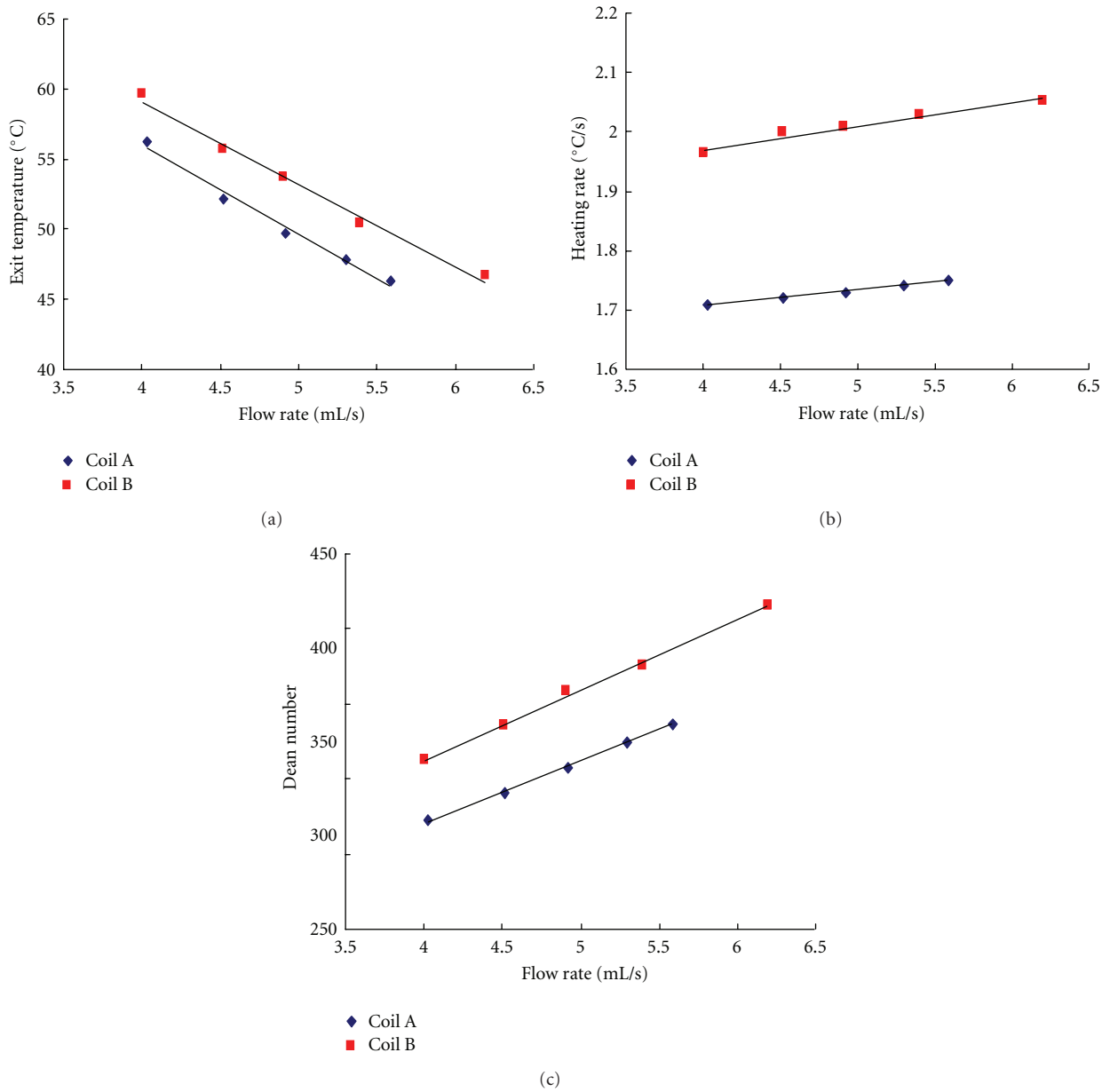

Figure 10: Exit temperature, heating rate and Dean number rate as a function of flow rate for coils A and B at initial temperature 20°C.

characteristics. The influence of pitch on exit temperature and heating rate are illustrated in Figure 9. Figure 9(a) shows that 20 mm pitch achieved higher exit temperature and heating rate than 18 mm pitch (from Figure 8) with a coil diameter of 121 mm, tube diameter of 7.9 mm, and 5.5 turns at initial temperature of 20°C. The heating rate also increased with flow rate and the pitch (Figure 9(b)). This positive influence may, however, decrease at much higher pitch levels because the coil progressively approaches straight tube configurations at very high pitch levels and the characteristic secondary flow may disappear. This opens up possibility for optimization; however, due to the limited space in the microwave oven cavity, the influence of pitch on heating rate or exit temperature could not be investigated extensively.

3.6. Dean Number. As evident from preceding sections, changing the tube or coil diameter results in a change in the associated Dean number in addition to changes in coil volume, and under these specific conditions the influence of Dean number on heating characteristics was accompanied by a change in coil volume. Earlier results demonstrate that coil volume is a dominant factor influencing heating characteristics as compared with Dean number. The effective way is to investigate the influence of Dean number for coils with the same or similar coil volume, but providing different Dean numbers. Exit temperature and heating rate as a function of flow rate for coil A (tube diameter 7.9 mm, coil diameter 120 mm, 3.5 turns, pitch 20 mm, and coil volume 82 mL)

and coil B (tube diameter 6.4 mm, coil diameter 120 mm, 5.5 turns, pitch 20 mm, and coil volume 83 mL) at initial temperature 20°C and flow rates 4–6.2 mL/s are illustrated in Figure 10. Although the two coils had similar coil volumes, co il B achieved higher exit temperatures and heating rates than coil A due to higher Dean number of coil B than coil A as illustrated in Figure 10(c). The results show that higher Dean number resulted in higher exit temperature and heating rate due to the increased heat and mass transfer rates.

4. Conclusions

A continuous-flow microwave heating system was set up to monitor inlet and outlet temperatures of water to optimize coil configuration parameters such as coil diameter, tube diameter, number of turns, initial temperature, flow rate, and pitch to improve microwave absorption efficiency, heating rate, and reduce heating time and temperature fluctuations. Under continuous flow microwave heating condition, microwave absorption efficiency was found to be a function of flow rate, initial temperature, and coil configuration. Results from this study show that (1) higher number of turns resulted in lower heating rate, lower temperature fluctuations, higher exit temperature, and longer time to achieve temperature equilibrium; (2) larger tube or coil diameter gave larger coil volume, which caused heating rate to decrease; (3) faster flow rates resulted in lower exit temperatures, lower temperature fluctuation, higher Dean number, and slightly higher heating rate; (4) higher initial temperatures resulted in higher exit temperatures and Dean numbers; (5) higher Dean number resulted in more uniform heating and slightly higher heating rate. Overall, coil volume was the dominant factor affecting heating rate as compared with flow rate and Dean number.

References

[1] W. R. Dean, "Note on the motion of fluid in a curved pipe," *Philosophical Magazine*, vol. 14, p. 208, 1927.

[2] R. A. Seban and E. F. McLaughlin, "Heat transfer in tube coils with laminar and turbulent flow," *International Journal of Heat and Mass Transfer*, vol. 6, no. 5, pp. 387–395, 1963.

[3] Y. Mori and W. Nakayama, "Study on forced convective heat transfer in curved pipes," *International Journal of Heat and Mass Transfer*, vol. 8, no. 1, pp. 67–82, 1965.

[4] A. N. Dravid, K. A. Smith, E. W. Merrill, and P. L. T. Brian, "Effect of secondary fluid motion on laminar flow heat transfer in helically coiled tubes," *American Institute of Chemical Engineers Journal*, vol. 17, no. 5, pp. 1114–1122, 1971.

[5] S. V. Patankar, V. S. Pratap, and D. B. Spalding, "Prediction of laminar flow and heat transfer in helically coiled pipes," *Journal of Fluid Mechanics*, vol. 62, no. 3, pp. 539–551, 1974.

[6] L. A. M. Janssen and C. J. Hoogendoorn, "Laminar convective heat transfer in helical coiled tubes," *International Journal of Heat and Mass Transfer*, vol. 21, no. 9, pp. 1197–1206, 1978.

[7] R. C. Xin and M. A. Ebadian, "Natural convection heat transfer from helicoidal pipes," *Journal of Thermophysics and Heat Transfer*, vol. 10, no. 2, pp. 297–302, 1996.

[8] A. Le Bail, T. Koutchma, and H. S. Ramaswamy, "Modeling of temperature profiles under continuous tube-flow microwave and steam heating conditions," *Journal of Food Process Engineering*, vol. 23, no. 1, pp. 1–24, 2000.

[9] D. G. Prabhanjan, T. J. Rennie, and G. S. V. Raghavan, "Natural convection heat transfer from helical coiled tubes," *International Journal of Thermal Sciences*, vol. 43, no. 4, pp. 359–365, 2004.

[10] D. G. Prabhanjan, *Influence of coil characteristics on heat transfer to Newtonian fluids*, Ph.D. thesis, McGill University, Department of Agricultural and Biosystems Engineering, 2001.

[11] P. K. Nema and A. K. Datta, "Improved milk fouling simulation in a helical triple tube heat exchanger," *International Journal of Heat and Mass Transfer*, vol. 49, no. 19-20, pp. 3360–3370, 2006.

[12] A. Zachár, "Analysis of coiled-tube heat exchangers to improve heat transfer rate with spirally corrugated wall," *International Journal of Heat and Mass Transfer*, vol. 53, no. 19-20, pp. 3928–3939, 2010.

[13] J. Thomson, "On the origin of windings of rivers in alluvial plains, with remarks on the flow of water round bends in pipes," *Proceedings of the Royal Society A*, vol. 25, pp. 5–8, 1876.

[14] J. Eustice, "Experiments on streamline motion in curved pipes," *Proceedings of the Royal Society A*, vol. 85, pp. 119–131, 1911.

[15] W. R. Dean, "The streamline motion of fluid in a curved pipe," *Philosophical Magazine*, vol. 20, pp. 208–223, 1928.

[16] H. Burton, "A comparison of the direct and indirect heating ultra high temperature processes for milk sterilization," *Dechema-Monographien*, vol. 70, pp. 1327–1350, 1972.

[17] S. Tajchakavit, H. S. Ramaswamy, and P. Fustier, "Enhanced destruction of spoilage microorganisms in apple juice during continuous flow microwave heating," *Food Research International*, vol. 31, no. 10, pp. 713–722, 1998.

[18] R. E. Mudgett, "Microwave properties and heating characteristics of foods," *Food Technology*, vol. 40, no. 6, pp. 84–93, 1986.

[19] M. Lin and H. S. Ramaswamy, "Evaluation of phosphatase inactivation kinetics in milk under continuous flow microwave and conventional heating conditions," *International Journal of Food Properties*, vol. 14, no. 1, pp. 110–123, 2011.

[20] S. Tajchakavit and H. S. Ramaswamy, "Thermal vs microwave inactivation kinetics of pectin methyl esterase in orange juice under batch mode heating conditions," *Lebensmittel-Wissenschaft und-Technologie*, vol. 30, pp. 85–93, 1997.

[21] S. Tajchakavit and H. S. Ramaswamy, "Continuous-flow microwave heating of orange juice: evidence of nonthermal effects," *Journal of Microwave Power and Electromagnetic Energy*, vol. 30, no. 3, pp. 141–148, 1995.

[22] T. Koutchma and H. S. Ramaswamy, "Combined effects of microwave heating and hydrogen peroxide on the destruction of *Escherichia Coli*," *Lebensmittel-Wissenschaft und-Technologie*, vol. 33, no. 1, pp. 30–36, 2000.

[23] T. Kudra, F. R. van de Voort, G. S. V. Raghavan, and H. S. Ramaswamy, "Heating characteristics of milk constituents in a microwave pasteurization system," *Journal of Food Science*, vol. 56, no. 4, pp. 931–934, 1991.