Preheating of a Poly(ethylene terephthalate) Preform for Stretch Blow Molding Using Microwaves

D. U. Erbulut,[1] S. H. Masood,[2] H. Senko,[1] K. Davies[3]

[1]*University of Melbourne, Melbourne, Australia*
[2]*Swinburne University of Technology, Melbourne, Australia*
[3]*Food and Beverages, Visy Industries, Melbourne, Australia*

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ABSTRACT: In this work, a new microwave resonant cavity was developed to completely preheat a poly(ethylene terephthalate) preform efficiently for a stretch blow molding process. Microwave power simulation software was used to design the microwave resonant cavity. An investigation of the inside and outside surface temperature profile along the preform and free inflation experimentation indicated that a cylindrical resonant cavity could efficiently preheat a poly(ethylene terephthalate) preform with the advantages of reduced time and increased energy savings versus a conventional infrared heating system. © 2009 Wiley Periodicals, Inc. J Appl Polym Sci 112: 1670–1679, 2009

Key words: microwave heating; PET; blow moulding; simulations; polymer processing

INTRODUCTION

The two-stage stretch blow molding (SBM) process offers the advantage of producing plastic bottles and containers with less material and better mechanical properties. The stages of the process are as follows:

- In the first stage of the process, poly(ethylene terephthalate) (PET) preforms are produced by an injection molding method and left to cool to room temperature.
- The second stage of the process involves preheating and blowing the preforms into the mold cavity of the bottle shape.

The preheating step is aimed at bringing the PET preform into a pliable state before the blowing stage of the process. During preheating, the preform temperature profile is very critical for manufacturing a bottle with desirable mechanical properties.

Infrared heating is used in the preheating stage of SBM. It is a surface heating technique, and in a typical process, about nine quartz lamps are used for heating a preform to achieve a nonuniform temperature profile along the preform; this is thought to provide reasonable uniform stress spreading in the width of the preform. Numerous articles have been published on the infrared heating of PET preforms and its effects on the end-product quality and process time.[1–8]

Today, microwave heating technology assists in many industrial processes involving a wide range of ceramic and composite materials.[9] Moreover, microwave heating has certain remarkable advantages over infrared heating, including less energy consumption and a shorter processing time, because it is a volumetric heating method.[10] However, the technology remains largely underused for manufacturing processes. The biggest reason might be the perception that microwave power is not safe to use for processing. Furthermore, the cost of microwave equipment is extremely high in comparison with conventional processing machines. A third reason is the limited opportunities for learning about microwave engineering in universities and colleges.[11]

In this study, microwave heating technology was used to preheat PET preforms for the blow molding manufacturing process. The preform was made from resins characterized by intrinsic viscosity values of 0.80 ± 0.02 dL/g. First, the dielectric properties of a PET preform exposed in a WR340 rectangular wave guide were studied.[12] The same wave guide was used to heat the preform partially. An additional cylindrical resonant cavity was designed with CST Microwave Studio simulation software to achieve a more suited profile of the electric field along its axis. Measurements of the temperature distribution of the PET preform walls were carried out for both the

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Correspondence to: D. U. Erbulut (erbulut.deniz@gmail.com).

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rectangular wave guide and resonant cavity heaters and were used for comparison with infrared heating. The results showed reduced power consumption and reduced heating time in comparison with infrared heating. Finally, the preform was free-blown, and the results showed good optical clarity along with a reasonable bottle shape of the blown bottle.

THEORETICAL

Current preform preheating technology

Infrared ovens are used for preheating PET preforms before SBM. Preforms travel inside the oven, rotating with the mandrels, to reach certain temperature profiles by radiation. PET is a semitransparent material to infrared radiation. Although the absorption of emitted radiation takes place at the surface of the preform, a certain amount of reflection and transmission occurs. The cooler side of the preform is then slowly warmed by the conduction of heat from the outside. However, because the heat conductivity of PET is not high enough, temperature equilibrium is achieved by forced air circulation with a certain temperature inside the oven. There are some issues that are important to consider for infrared heating with PET preforms.

Energy consumption

The ratio of power consumption to absorbed power is about 20%.[4] It has also been reported that the PET absorption of emitted radiation depends on the wavelength. Moreover, between the wavelengths of approximately 1000 and 2200 nm, the absorption is 20%.[13] This is mainly because heat radiates in a wave form for surface heating. Therefore, a significant amount of energy is wasted during equilibration.

Equilibration

Balancing temperature differences in cross sections of the preform walls is an important step. Equilibration takes extra time that depends on the preform dimensions, ambient temperature, and process parameters.[13,14]

Stretch ratio

The thickness of a 26.5-g preform is about 3.30 mm, and this affects the cross-section temperature distribution of the preform wall. Although the outside wall of the preform absorbs infrared radiation and becomes warmer, the inside wall stays cooler. A huge temperature difference occurs between the preform walls, and this has a big impact on the stretch ratio. The stretch ratio is defined by the ratio of the bottle dimensions to the correlated preform dimensions.[13]

Lebaudy et al.[3] studied the influence of temperature profiles on stretching. They showed that the stress on the material is a function of the stretch ratio and temperature. Optimum temperature profiles along the preform are deliberately nonuniform to achieve a uniform stretch ratio across the thickness of the material. In addition, air cooling and equilibration of nonuniform temperature profiles along the PET preform helps with uniform stretching. This study indicated that the stretch ratios differ by at least 50% between the inside and outside surfaces of the preform. Therefore, the stress is higher on the inside surface versus the outer face of the material. The investigation showed that the inside wall temperature should be higher than the outside wall temperature because of the higher stretch ratio on the inside surfaces; this again is not possible with the infrared heating method.

Venkateswaran et al.[15] studied the prediction of PET container properties using film data. They reported considerable amounts of variation in the orientation through the thickness of the preform wall with respect to the temperature distribution on the preform. This variation in orientation was caused by an uneven temperature gradient in the wall and variation in the stretch ratio.

Table I shows the hoop stretch ratios of the preform and bottle for this work. The inside wall stretch ratio is around 60% higher than the outside wall stretch ratio for a 600-mL bottle.

Density

Venkateswaran et al.[8] reported that bottle density is increased when the temperature is higher on the inside surface than on the outside surface. Low density results in imperfection in the material orientation.

Microwave heating

There is a clear advantage in using microwave technology to heat a PET preform before blowing. It offers high potential for rapid heating as well as energy saving. Microwave heating is a volumetric heating technique, and heating starts from inside the preform, unlike infrared heating. Therefore, one should expect to gain a desirable temperature profile across the wall of the preform with microwave

TABLE I
Hoop Ratios of the Preform and Bottle

	Outer	Inner
Bottle hoop dimensions	70	69.4
Preform hoop dimensions	19.84	12.24
Hoop stretch ratio	3.528	5.67

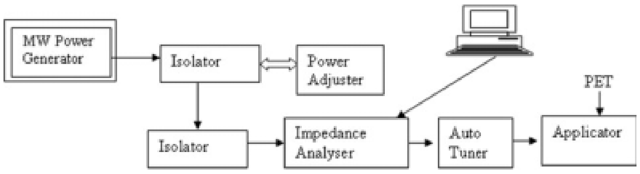

Figure 1 Experimental apparatus (MW = microwave).

heating. Not only does it offer reduced heating time and energy saving in the reheating stage, but it also provides an acceptable temperature profile by heating the inside wall of the preform to a higher degree than the outside.

To achieve a successful outcome, at least three challenges have to be faced. The dielectric properties of the preform must be determined accurately and in its "as is" state. Any adulteration to the preform sample during the measurement of the dielectric properties may cause the dielectric properties of the material to change. Second, the dielectric loss factor of the "as is" PET preform is very low, and a standard wave guide fails to provide efficient heating. This leads to the third challenge, that is, how to make the preform absorb microwaves efficiently with a uniform electric field distribution along its entire geometry. We solve the first problem by measuring the dielectric properties of the preform "as is" using a network analyzer and simulation software. A novel approach for measuring a PET preform "as is" has been explained in a previous work.[12] By using the simulation software, we arrive at the dielectric properties through an optimization process without having to resort to any mathematical computation involving complex variable transcendental equations. The equation for the microwave absorption [P (W/m^3)] of a material is given by eq. (1):[16]

$$P = 2\pi f \varepsilon_0 \varepsilon'' E^2 \tag{1}$$

where f is the frequency (Hz), ε_0 is the space permittivity, E is the electric field strength (V/m), and ε'' is the dielectric loss factor. If ε'' is very small, the material to be heated will not absorb much power. One way of overcoming this problem is to increase the amplitude or intensity of the electric field (E). E can be increased by automatic matching with an autotuner. It can also be increased by an increase in the microwave power, but this may not be practical because of the lack of efficiency. Another way of increasing amplitude E is the cavity resonator technique.[16,17] By designing a single-mode cavity to heat a preform with a low electric loss, we virtually apply a very high amplitude electric field using low microwave power levels to the preform itself. Therefore, we can achieve efficient heating at a low power.

In this work, the measured dielectric properties of a PET preform were used to design a single-mode cavity applicator by software simulation. Two objectives were achieved: the first objective was to increase microwave amplitude E through the use of a resonant cavity with a coupling aperture (which will be explained in detail), and the second objective was to achieve uniform heating over the entire preform by careful selection of the guide wavelength inside the cavity dimensions. Microwave power was applied to the cavity containing the preform, and the results showed that desired heating profiles as well as efficiency were achieved. The article also discusses the design of the cavity and the heating of the preform in detail.

EXPERIMENTAL

Figure 1 shows the experimental setup used for the microwave heating of the preform. A 2.45-GHz microwave generator with a maximum output of 1000 W was used in this work. This setup also contained additional microwave components. An isolator was used to protect the magnetron from reflected or unabsorbed microwave power. A high-power impedance analyzer was interfaced to a computer through a software interface to adjust the auto tuner

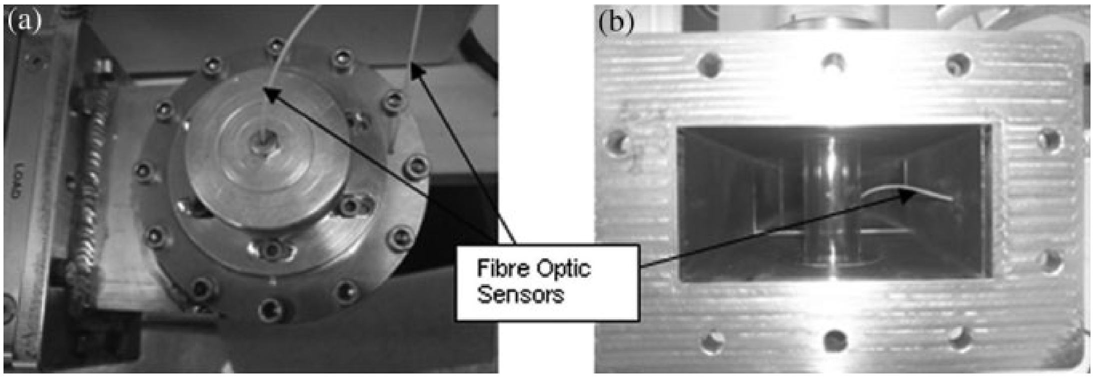

Figure 2 (a) Cylindrical cavity and (b) WR340 rectangular wave guide.

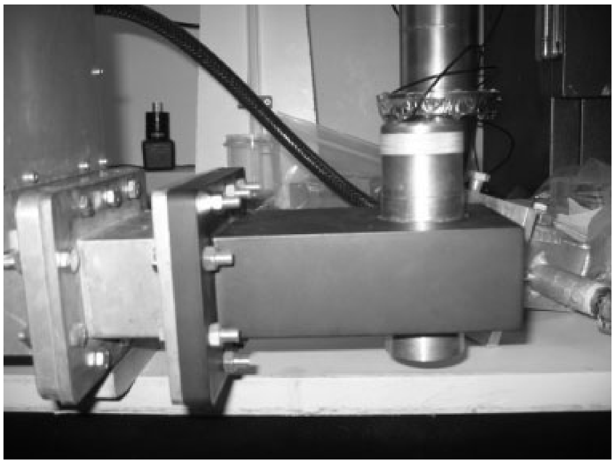

Figure 3 WR340 rectangular cavity attached to the experimental apparatus.

and monitor the microwave absorption by the preform.

A fiber-optic temperature sensor was used for the temperature measurements of the inside and outside surfaces of the PET preform. The polytetrafluoroethylene (Teflon) cable was 1.15 mm in diameter and was positioned on the preform surface through a small opening in the applicators. Figure 2 shows the fiber-optic sensors attached to the preform.

Preform heating with a regular wave guide

In this experiment, the same single-mode WR340 type of rectangular wave guide was used to determine the dielectric characteristics of the PET preform "as is" during heating.[12] The wave guide with a sample holder, shown in Figure 3, was designed with simulation software called CST Microwave Studio. Details of the design work can be found in a previous work.[12] The wave guide had a short circuit at one end and a flange on the other end. The position of the preform was determined according to the electric field profile inside the wave guide with the simulation program and a network analyzer. A specially constructed sample holder for the 26.5-g preform was placed on the wave guide, exposing it to the maximum electric field strength.

The temperature measurement of the PET preform was performed with the wave-guide applicator during the microwave heating. Side and back wall temperature values were determined for the inside and outside walls of the preform. The reason for measuring additional side and back wall temperatures was that the electric field distribution was not uniform inside the single-mode WR340 rectangular wave guide, and this could cause problems. The temperature was not measured in the cross section of the preform but was measured only on the surfaces.

Preform heating with a resonant cavity

High microwave absorption in low-loss dielectrics can be achieved with resonant cavities. A cylindrical cavity in the TM_{010} mode was used for this work (Fig. 4) TM_{010} identifies the electromagnetic field configuration in cylindricol waveguides. The electromagnetic field distribution was stationary and symmetrical along the central axis. The transverse magnetic (TM) mode provides an optimum solution for uniform energy absorption in hollow-shape PET preforms.[16] Designing an efficient resonant cavity for a specific dielectric requires an in-depth knowledge of electromagnetic field theory. In this case, simulation software was used to understand the field profile and interaction with the low-loss material, as will be explained in the next section.

Three different incident powers were tested with the resonant cavity: 700, 800, and 900 W. The PET preform was heated under microwave power for only 5 s at each incident power. The reason for selecting these power ranges for heating was that a microwave generator with a maximum power of 1000 W was used and the shortest heating time was of interest for the specific temperature range. The heating time was optimized to 5 s because a heating time longer than 5 s would have increased dielectric loss in the preform, hence resulting in higher power absorption and melting. Therefore, controlling the heating process may have become harder.

Resonant cavity design

Microwave simulation software allows developers to design cavities with optimum electromagnetic energy transferred to dielectric materials. CST Microwave Studio is high-frequency, three-dimensional electromagnetic simulation software using the finite different time domain technique.

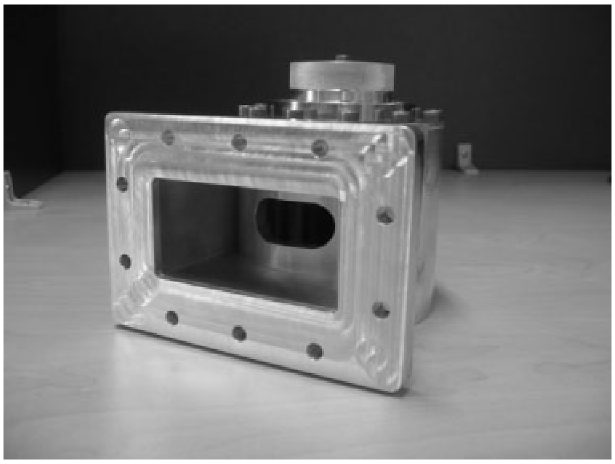

Figure 4 Actual cylindrical cavity.

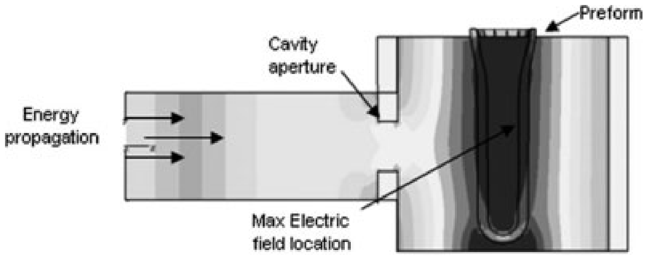

Figure 5 Two-dimensional scalar electric field generated by an electromagnetic simulator.

It is important for the dielectric material inside the cavity to be located in the position of maximum electromagnetic field strength. Even though the electric field distribution can be calculated for an empty cylindrical cavity, the inserted dielectric distorts the field distribution, which depends on its shape and dielectric properties. Therefore, simulation software offers an easy-to-use, effortless, and effective design tool. A few successful studies on the use of Microwave Studio simulation software have been conducted.[12,18–20] There is no need for calculations of complex equations or applying the trial and error method to a cavity to achieve effective results, unlike in the studies of Metaxas[17] and Sangdao et al.[21] Although the Microwave Studio simulation software can make nearly precise predictions for cavity design, a good knowledge of electromagnetic filed distribution is necessary.

The range of the length and diameter aspect ratio of the cylindrical cavity for the simulation trial was 0.5–2. The cavity was designed in such a way that the bottom of the preform deliberately absorbed less energy to become cooler than the actual body of the preform. In fact, the temperature profile was controlled to make both ends of the preform cooler while the body attained the desired temperature. In particular, the bottom end of a preform must remain cooler to withstand the pressure of the stretch rod.[22]

The cavity aperture dimension was also tested in parallel with these trials, as explained in the next subsection. The electric field distribution is shown in Figure 5. The dark color field indicates the maximum electric field strength where the preform was placed. The electric field strength around the bottom of the preform was not as high in comparison with the rest of it, and this caused less heating.

Cavity aperture design

The cavity aperture was designed to provide a narrow-frequency bandwidth to obtain high impedance matching between the rectangular wave guide and cylindrical cavity.[16]

The opening, in the shape of a rectangle with rounded corners and with dimensions in the range of 15 mm × 35 mm to 25 mm × 45 mm, was considered. The optimum opening dimensions were determined through minimization of the reflection coefficient (S_{11}), which can be obtained as an output from the simulation. S_{11} (0.4819) against the frequency graph is shown in Figure 6. In addition, the opening had to be balanced in terms of size because a smaller opening would provide a higher Q factor in the resonant cavity, whereas a bigger opening would provide easier matching. The Q factor is also known as the quality factor of a resonant cavity and indicates how high the amplitude of the electric field inside the cavity can go, corresponding to excitation inside the regular wave guide.

RESULTS AND DISCUSSION

Microwave heating

Regular wave guide

The temperature profile along the preform was obtained with the regular WR340 wave guide. Several incident microwave powers were investigated. However, the use of more than 300 W of power caused an undesirable temperature rise at a certain location of the preform. Therefore, only a 300-W incident power for the 25-s process is presented in

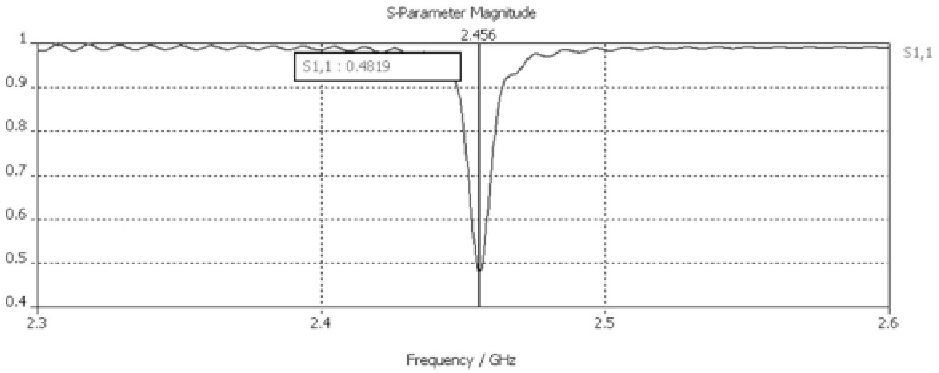

Figure 6 S-parameter phase at the frequency of 2.45 GHz.

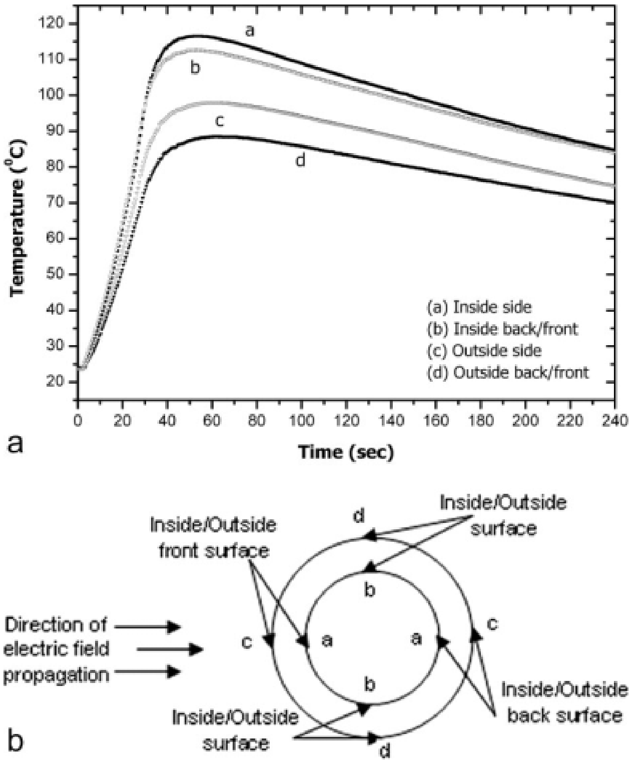

Figure 7 (a) Preform wall temperature measurements using 300-W incident power for 25 s, (b) fiber-optic sensor attachment point on the preform for temperature measurement.

this report. Figure 7(a) shows the maximum temperature rise on the surface of the preform. Figure 7(b) presents the sides of the preform according to electric field propagation. The results show that there was a temperature difference not only between the inside and outside walls but also along the sides on the same wall (Table II). The maximum temperature difference occurred between the inside and outside walls (23.9°C). A significant dissimilarity in temperature, which was caused by the electromagnetic field distribution inside the wave guide, led us to study the design of the cylindrical resonant cavity as an efficient way of heating a PET preform with microwave energy.

Cylindrical resonant cavity

A PET preform was placed symmetrically along the central axis of the TM_{010}-mode cylindrical cavity. Temperature measurements were performed in two different areas: the body and the bottom walls of the preform. There was no need to measure side and back/front temperatures separately for the cylindrical cavity because uniform heating was achieved with the cylindrical cavity on the side and back/front surfaces. In addition, the whole body

TABLE II
Temperature Differences Between the Walls and Sides Corresponding to Figure 7(a,b)

	a − c	b − d	a − b	c − d
Temperature difference (°C)	23.9	18.5	4	9.4

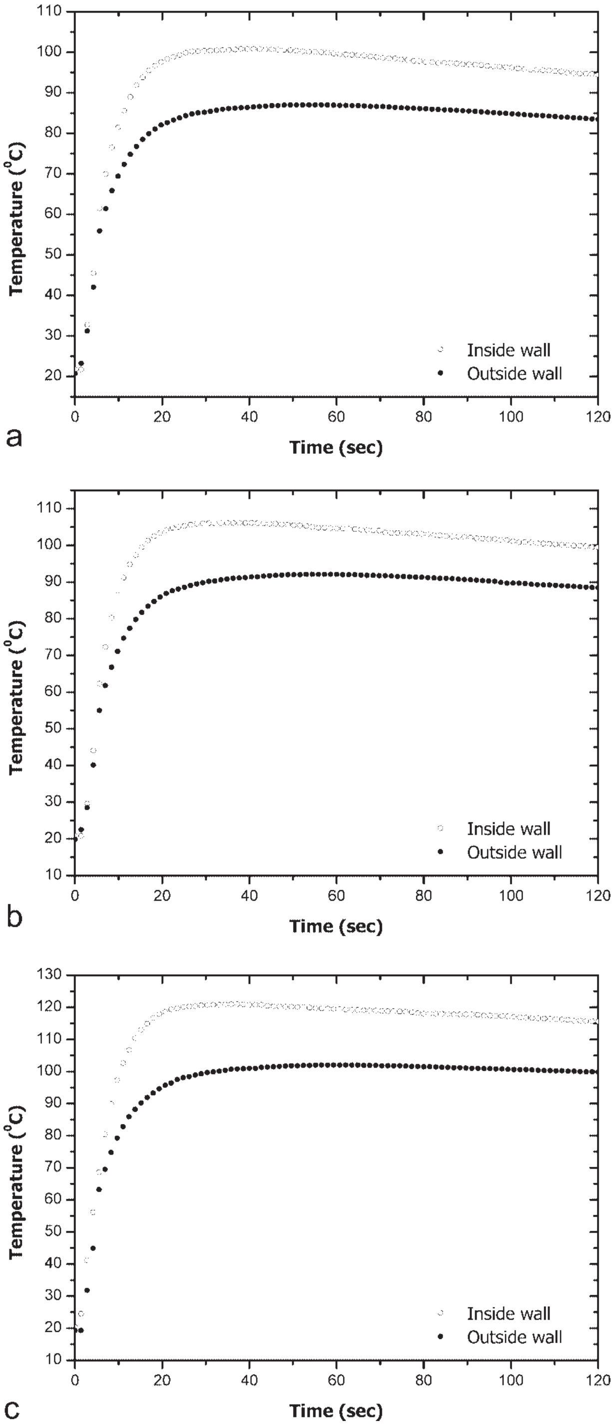

Figure 8 Transient evolution of the preform body temperature with (a) 700-, (b) 800-, and (c) 900-W incident power.

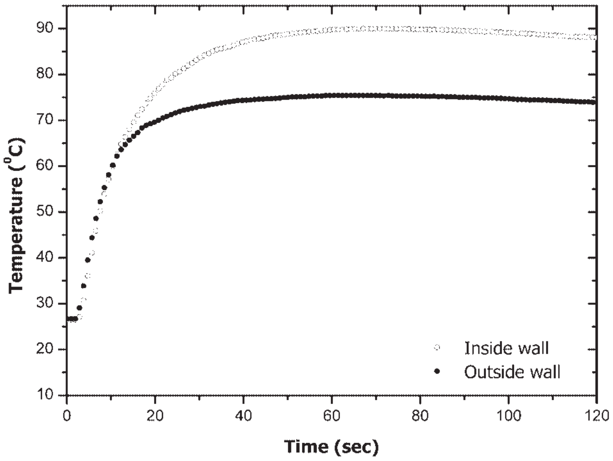

Figure 9 Preform bottom area temperature measurement using 700-W incident power.

temperature was almost the same everywhere. Measurements were taken for 700-, 800-, and 900-W incident powers [Fig. 8(a–c)]. The heating time was fixed at 5 s. Differences in temperature between the walls were found to be in a reasonable range in comparison with the infrared heating technique without equilibration.[14] Kim[14] studied the effect of the equilibration time on PET preform properties and suggested that equilibration times longer than 20 s should result in desirable temperature profiles during 95 s of preheating, On the other hand, a desirable temperature profile (hotter inside than outside) was achieved with microwaves. When the incident power was increased, the temperature difference between the inside and outside wall was also forced to increase.

Power absorption at the bottom of the preform was less than that at the wall sections. Therefore, the temperature along the bottom was slightly different. Figure 9 shows the temperature profile at the bottom section of the preform with a 700-W incident power. The temperature reached 89.95 and 75.7° inside and outside the bottom walls, respectively.

Figure 10(a–c) shows the power absorption of the preform for various incident microwave power values (700, 800, and 900 W). These graphs were gathered from the impedance analyzer, which was part of the experiment apparatus. The *x* axes of the graphs show the measurement count of the power absorbed by the sample. In Figure 10, there are around 10 measurements of absorbed power in 5 s. The microwave power absorption dramatically decreased in 5 s. We also know that the dielectric properties of a preform are highly temperature-dependent. Therefore, changing the dielectric inside the resonant cavity alters the resonant frequency of the cavity. Hence, the energy transfer into the cavity from the opening is reduced. Table III shows the range of the power absorption by the preform in 5 s for different incident power values.

Table III also presents the relative temperature values between walls for different incident powers. There was an approximately 14° difference between the body of the preform and the bottom of the preform.

Figure 11 shows a graphical comparison of the preform performance in response to three different microwave incident powers (700, 800, and 900 W).

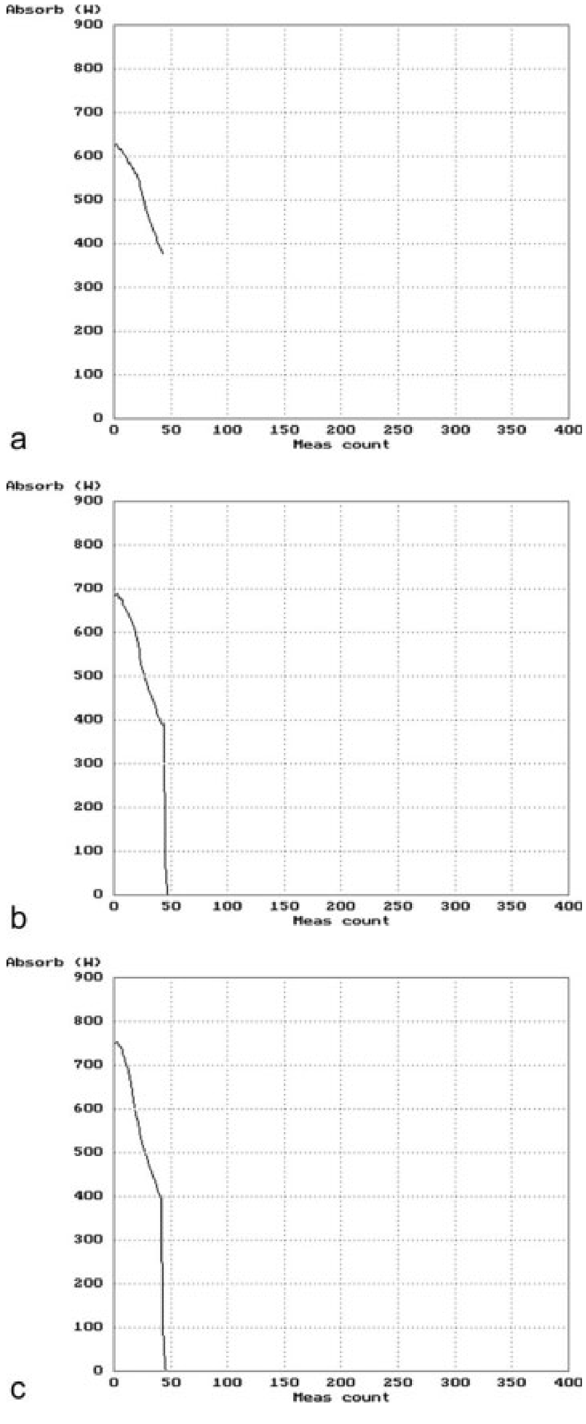

Figure 10 Five seconds of power absorption by a preform with (a) 700-, (b) 800-, and (c) 900-W incident power.

TABLE III
Temperature Differences on the Preform Walls and Power Absorption in Different Incidents

5-s heating time	700-W incident power for the bottom part	700-W incident power for the body part	800-W incident power for the body part	900-W incident power for the body part
Maximum inside temperature (°C)	89.95	100.8	106.1	121
Maximum outside temperature (°C)	75.7	87	92.1	102
Difference in the wall temperature (°C)	14.25	13.8	14	19
Power absorption range in 5 s (W)	620–380	620–380	690–390	750–400
Power absorption start form (%)	88.5	88.5	86.2	83.3

Figure 11(a) indicates the initial and final values, within 5 s, of power absorption of PET. Power absorption dropped more rapidly for higher incident powers than for lower ones. The reason is that the magnetron spectrum was narrower when the incident power was higher. Figure 11(b) shows that the temperature difference between surfaces for a 900-W incident power was 19°C; this is remarkably high in comparison with the values for 700- and 800-W incident powers. On the other hand, temperature differences between the surfaces of the preform were almost the same for 700- and 800-W incident power usage. These results indicate that the design of the cavity and the aperture can be used for narrow-range incident power. The reason, as mentioned previously, is that the optimum cavity size and opening dimensions are determined in a narrow spectrum of microwave power reflection.

The microwave-heated preform obtained from the experimental setup was subjected to an air blowing process to determine the visual effect of the blowing of the preform under the microwave-heated condition. Several trials were made. The final result for the blown bottle is shown in Figure 12. The fully blown preform indicated that the resonant cavity worked for the 26.5-g preform.

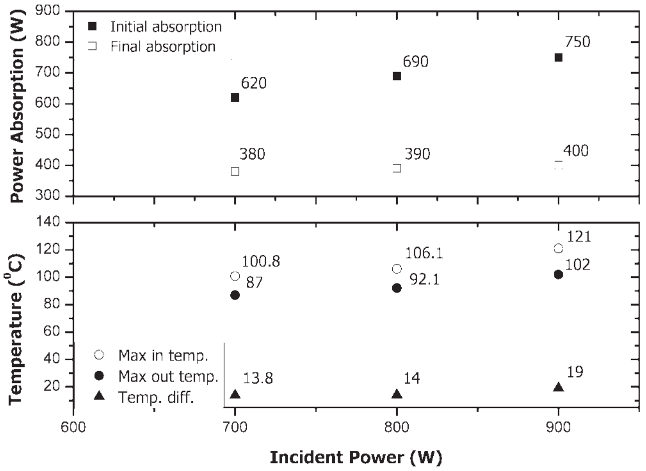

Figure 11 (a) Initial and final power absorption of a preform in 5 s and (b) temperature differences between surfaces for three different incident powers.

Comparison of the WR340 wave guide and TM_{010} resonant cavity results

There are a few points to mention for a comparison of the WR340 wave guide and cylindrical cavity. First, the electromagnetic field profile inside the wave guide was not suitable for a relatively large preform. This led to the second problem with the regular wave guide, which showed a nonuniform temperature profile along and through the portion of the preform. On the other hand, the results showed that the preform could be heated fully and uniformly with the cylindrical cavity.

Power absorption was far less with the regular wave guide than the resonant cavity, and hence the heating time was longer. Energy was focused right into the preform through the aperture of the resonant cavity, so the higher absorption helped with the heating time.

Comparison of microwave and infrared heating

The following conclusions have been drawn from the results:

Figure 12 Final result of a free-blown preform after microwave heating.

- The air temperature inside the oven is not easy to control and is a very important consideration when one is trying to achieve equilibration between the inside and outside surfaces of a preform. It is highly dependent on environmental conditions.[13] However, as shown in this work, once the electromagnetic filed inside the applicator is determined for uniform heating, it is easier to achieve a desirable temperature profile because it is a volumetric heating technique.
- The ratio of power lost to incident power is about 80% for infrared heating of a PET preform.[4] In general, a microwave oven converts around 70% of its electrical input into microwave energy (at 2.45 GHz).[23] Specifically for the PET perform used in this work, the average microwave power absorbed by the preform was around 540 W in 5 s, whereas the incident microwave was kept at 800 W. The absorption efficiency recorded in this experiment was around 67.5% (540 W/800 W). Therefore, the overall microwave heating efficiency was found to be around 47.5% (0.7×0.675). It is noted that the absorbed power efficiency is more than double with microwave heating versus infrared heating.
- The heating time for PET preforms with infrared heating technology is about 35 s for an industrial process.[4] On the other hand, a PET preform was heated to a desirable temperature in 5 s in this work.
- Maintenance of the reflectors inside the oven is essential; otherwise, energy consumption will increase. In addition, air or water cooling (or both) must be applied to the reflectors to prevent oxidation.[13] However, in microwave heating, there is less maintenance because only the transmission line needs to be dust-free,[24] and there is no need for air cooling.
- In a typical blow molding process, there are about 63 different voltage regulators in one rotary machine, which includes 14 ovens and 9 lamps in each oven. Therefore, the control of infrared lamps is extremely complex[13] in blow molding. However, microwave power offers a less complex heating process because there is no need for an additional power control system.
- Conventional infrared heating includes surface heating that results in an undesirable temperature profile on the PET preform. It heats the outside surfaces of the PET preform first. This leads to a higher temperature gradient on the outside surface, where the stretch ratio is lower.[25] In contrast, in our work, a higher temperature degree was achieved on the inside surface, where the stretch ratio was higher, and hence it offers desirable material orientation.

Because this study is an initial investigation with a cylindrical cavity, it is suggested that more research has to be conducted to obtain better power absorption and specific temperature profiles on preforms. Further work is also required to investigate the feasibility of this technique for continuous operation in an SBM process. Erbulut et al.[26,27] have indicated that SBM simulation software can be used to optimize the SBM process and SBM products. Further SBM simulation study can be carried out with temperature profiles obtained from microwave heating to predict the thickness and stress distribution of the final product.

CONCLUSIONS

This study has explored a novel technique to obtain a desirable temperature profile on a preform with microwave heating in a short time for the SBM process for bottle production. It has been found that a rectangular cavity is not good enough in terms of the power absorption by the preform and the heating time. A cylindrical resonant cavity was designed with electromagnetic simulation software as a microwave heating applicator. The results showed that both the objectives of uniform heating along the preform and reduced heating time were successfully accomplished with the cylindrical resonant cavity.

In this work, the electric field strength was increased with the resonant cavity. The preheating time was reduced with a higher amplitude electric field. Moreover, uniform heating along the entire preform was achieved in a short time (5 s). This also shows that the temperature gradient on the preform can be manipulated for different process scenarios with a cylindrical cavity. A higher temperature gradient on the inside wall of the preform was a positive outcome of the study as well. Successful experiments with a free-blown bottle from the microwave-heated preform validated that the designed cavity worked perfectly for the purpose of heating. More importantly, clear advantages in using microwave technology over infrared heating technology for preheating a PET preform were observed through the experimental investigation. These included rapid heating and energy savings for the SBM process and a desirable temperature profile on a PET preform.

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