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ORIGINAL ARTICLE

Research on both the radiation heating and the cooling system inside the stretch blow molding machine CPSB-LSS12

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Abstract

One of the most classical methods of producing plastic bottles which are commonly made from polyethylene terephthalate (PET) is the stretch blow molding (SBM). A new manufacture procedure of the SBM machine is designed in this paper for getting better quality of the PET bottles. The main idea of this new method focuses on providing both heating and cooling. The implements of the idea rely on the software package COMSOL 5.2a. Subsequently, four validate experiments were conducted to see the advantages of the improved system, as a result, the temperature distribution of performs is satisfied. Moreover, the energy consumption during heating is 10% less than that of the original manufacture procedure. As another advantage, the developed method not only reuses the residual energy of the cooling gas but also increases the unit time production of the machine for 5% indicating an improved efficiency in heating, thanks to the residual energy of the cooling gas.

Keywords Heating PET · Stretch blow molding machine · Cooling system

1 Introduction

Nowadays, almost all bottles used for the beverage market are manufactured by the SBM machine. Reheating is a significant step in the SBM process, which is also necessary for heating the preform to the appropriate temperature distribution above the glass transition. Finally, a bottle is produced by stretching and blowing inside a mold [1–7]. Remarkably, this stage is performed using infrared (IR) heaters. The IR heater is a stable heating source which is easy to use and adjust. On one hand, using an infrared lamp is necessary to obtain the utmost infrared radiation with a smaller amount of electric power. On the other hand, the entire system heating box will increase the temperature, which leads to shortening the working time machine. The most important point is how to design and use the cooling system without affecting the heating system. The power of the lamps is always at 1000 and 2000 W; therefore, if the heating system works for a long period, the machine will get high temperatures to continue functioning. Due to the high fan speed, the temperature of the preform will drop, which causes of effecting the crystallization and orientation of the molecules within the bottle's walls [8]. The analytical approach is to calculate the heat flux from an analytical solution of the one-dimensional transient energy equation with a transient boundary condition using the Laplace transformation [9]. The space and time-dependent heat flux [10–12] at the upper wall is estimated from the temperature measurements taken inside the flow [13]. On production, the considerable effect of temperature distribution decides the material thicknesses on the bottle [14] and the deformation of a bottle after blowing.

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2 Research method

The heating temperature inside the heating box could follow the transient heat balance equation:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla * (k \nabla T) - \nabla * q_r \tag{1}$$

where T = temperature, t = time, ρ = density, C_p = specific heat, k = thermal conductivity, and q_r = irradiative heat flux density. $\nabla = \frac{\partial}{x}\overrightarrow{i} + \frac{\partial}{x}\overrightarrow{j} + \frac{\partial}{x}\overrightarrow{k}$ is the operator in the rectangular Cartesian coordinate.

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Assuming that the inside surface of the preform is adiabatic:

$$-k\frac{\partial T}{\partial n}\bigg|_P = h_c(T_P - T_\infty) + \varepsilon_{PET}\sigma\left(T_P^4 - T_\infty^4\right). \quad (2)$$

where h_c = convection heat transfer coefficient, ε_{PET} = PET's mean emissivity, σ = Stefan-Boltzman constant, T_P = outside surface temperature, and T_∞ = air temperature inside the oven. Equation (2) is the boundary condition of the outside surface of the preform [3].

Another way is to consider a thermally developing, hydrodynamically developed turbulent flow through a horizontal plane channel. The flow is assumed to be two-dimensional, and the fluid is Newtonian and constant properties. Initially, the flow and the channel are at the same temperature T_0. Fluid enters the channel at a uniform temperature T_0. At $t > 0$, the lower wall is maintained and insulated while the upper wall is subjected to a wall heat flux *q(x;t)*. The governing equation in dimensionless form is given by

$$\frac{\partial\theta}{\partial\tau} + \frac{1}{2}PrReU\frac{\partial\theta}{\partial X} = \frac{\partial}{\partial Y}\left[\left(1 + \frac{Pr}{\,}Pr_t\varepsilon^+\right), \frac{\partial\theta}{\partial Y}\right] \quad (3)$$

where ν is the kinematic viscosity, α is the thermal diffusivity, k is the thermal conductivity, u_0 is the inlet velocity, ν_t is the turbulent diffusivity of momentum, α_t is the turbulent diffusivity of heat, and q_{ref} is the reference heat flux. The heat transfer into the fluid is assumed to be positive. The fully developed turbulent velocity profile u and the turbulent diffusivity of momentum ν_t are solved by the low Reynolds number k-ε model used in ref. [15–25]. The value of the turbulent Prandtl number Pr_t is taken to be 0.9.

3 Experiment device

The IR heating resource of an SBM machine was used to complete the experiments. The heater is composed of three halogen lamps Philips-15004Z (1000 W nominal power) and two halogen lamps Philips-15004Z (2000 W nominal power), and the power of lamp is 50%. The times of the heating belong to the production speed of the machine; the preform is taken to measure the temperature by an IR camera. After that, the ventilation system will change the speed and measure the temperatures of the fan speed. The temperature measurement has been performed by an IR camera, and the frequency of the analysis is 15 frames/s. The long wave spectral range is 8–12 mμ. At this spectral band, the preform behavior is like an opaque body so that the IR camera measures the temperature distribution on the inside and outside of the preform surface.

4 Experiment model

The SBM machine uses three fan systems inside for cooling, which is shown in Fig. 1. A box blower mainly uses the pressure as a thermal convection effect for the outside PET preforms, and the outside PET increases the heat transfer embryos phenomenon. When the infrared lamp heats the PET preforms, heat radiation penetrates the heated outside and the inside PET was better, the temperature of the PET will be different between the inside and outside. In this case, if the temperature of the outside preform is too high, the PET preform will change the crystallize temperature, resulting in a crystalline surface. In order to ensuring the stability of the product's quality, the cooling effect is provided in two parts, which can be used to adjust the reflector oven blower fan and inverter fan, increase productivity, and thereby achieve stability.

In this model, the cooling system is a new design for the advanced machine performance, and the cooling system has input some fans for heating box like Fig. 2. This fan system will create a circulating air flow inside the heating chamber. The hot air will be pushed from the bottom to the top of the heating box and re-heat PET bottles. Additionally, the reheating PET process in this cooling system already has energy recycling and gives the machine working for steady. The nominal power of each fan is 20 W, and it is minimal for the nominal power of five lamps having total nominal power 7000 W. Besides, this cooling system will reduce the temperature of the outer shell of the heating chamber which leads to being operated stably for a longer period.

As previously mentioned, the importance of the air cooling system to the blowing PET preform production quality is the reflector oven blower fan and the inverter fan which are the two significant factors in this research as the main parameters of the experiment.

The first experiment was measuring the PET heating with the reflector oven blower fan system while the other fan is off. Experiment in the first suction blower with the control power output being 0% was conducted, after that, the setup power is 0, 10, 20, 30, 40, 50, and 60% (CPSB-LSS12 programming models reflecting blower box maximum output). The single preform independent heating, the preform temperature

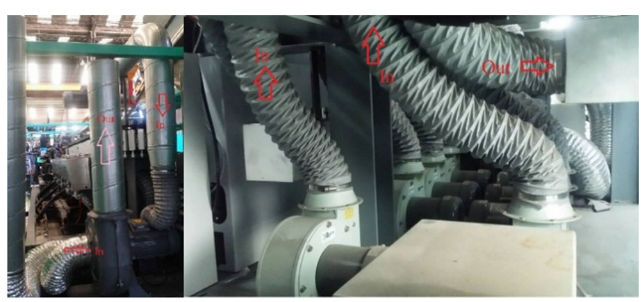


Fig. 1 The prototype of the new machine

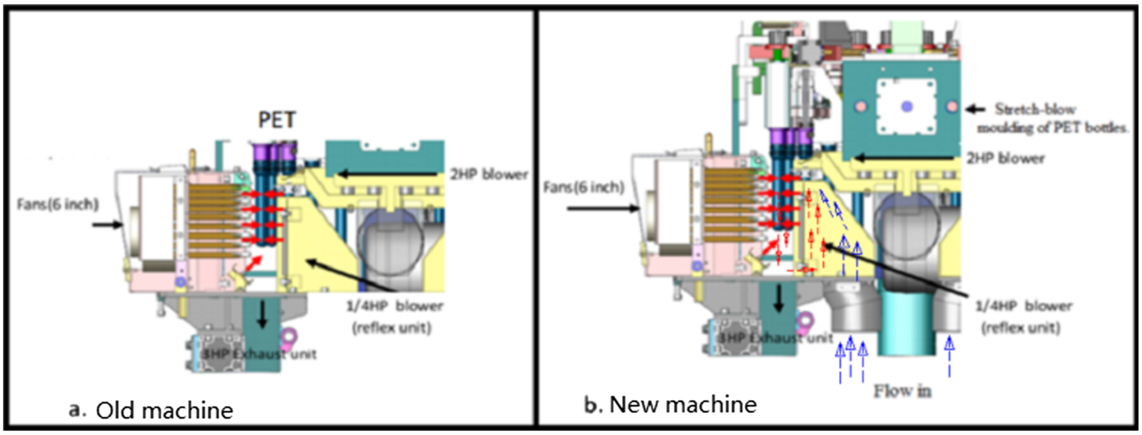


Fig. 2 The new design cooling system inside the machine (**a**) the original machine (**b**) the new design machine

conditions, and then continuously the preform heating were tested, to test when the heating box is in full embryo state. In this case, the temperature measurement is the outside temperature of the PET preforms. The result is the effect of the reflector oven blower fan system to heating the PET. The purpose of this experiment is to find out the effect of the reflector oven blower fan to heating PET and the temperature distribution on the PET.

The second experiment was measuring the PET heating outside the PET preform with the inverter fans system. The power of the inverter fan speed was 0, 10, 20, 30, 40, 50, and 60% (CPSB-LSS12 programming models reflecting blower box maximum output), and the temperature of the PET is the temperature inside and outside of the preform which reasons for the effect of the inverter fan system to heating the PET. The major idea of this experiment is the change in the temperature distribution of PET depends on the change power of inverter fans.

The third experiment was checking the effect of the rotating speed and time heating PET with the ability to heat the PET. In this experiment, the temperature of the PET preform when the control production speed changes from 6000, 7000, 8000, 9000, 10,000, 11,000, 12,000, 1300, 1400, 1500, 1600, 1700, to 18,000 bottles/h was measured. The experimental parameters could be controlled to produce energy (the control parameter means that the preform, during the heating, and the moving speed of revolution and rotation unit, indicates when the preform is in a heating unit in the heating time).

The fourth experiment was measuring the temperature outside of the heating box which belongs to the reflector oven blower fan and inverter fan speed. In this experiment, to measure a point on the heating box (one part of the SBM machine), the reflector oven blower fan and inverter fan speed change from 0, 10, 20, 30, 40, 50, to 60%. The infrared cameras will measure the temperature of the heating chamber when the reflector oven blower fan and inverter fan changes speed (Fig. 3). The aim of this experiment is to cool system what effects to temperature outside of heating chamber and maintains working of machines this determines the lifetime of machine.

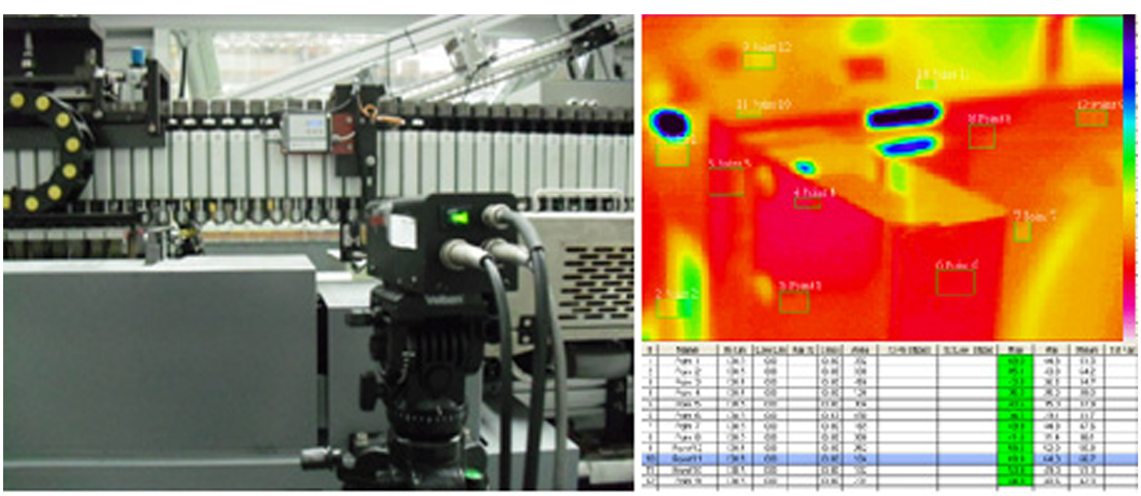


Fig. 3 The infrared camera and the measurement temperature picture of the outside heating chamber

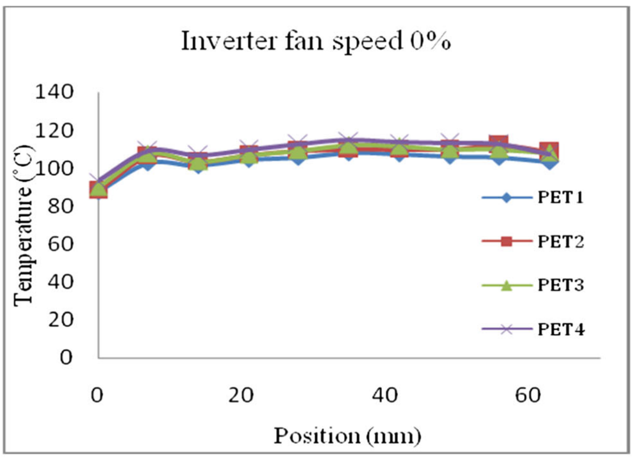
5 Results and discussion

The temperature of working machines is effectively maintained from − 15 to 60 °C because almost all the electronic devices have limited working temperature from − 15 to 60 °C except heating box, and the temperature inside the heating box will influence other plates inside machine. Then, the cooling system with considerable each of system fan will help the machine reduce the heat transfer from the heating box to other place other way this cooling system cannot influence to heating system inside heating box. This will reduce the heat capacity for PET in the manufacturing process. The task of the cooling system is to prevent the transfer of heat from the heating box to other parts of the machine; at the same time, it must not affect the heating process for PET. The temperatures at different time and locations inside and outside the PET cavities were recorded during the heating and cooling period by infrared camera.

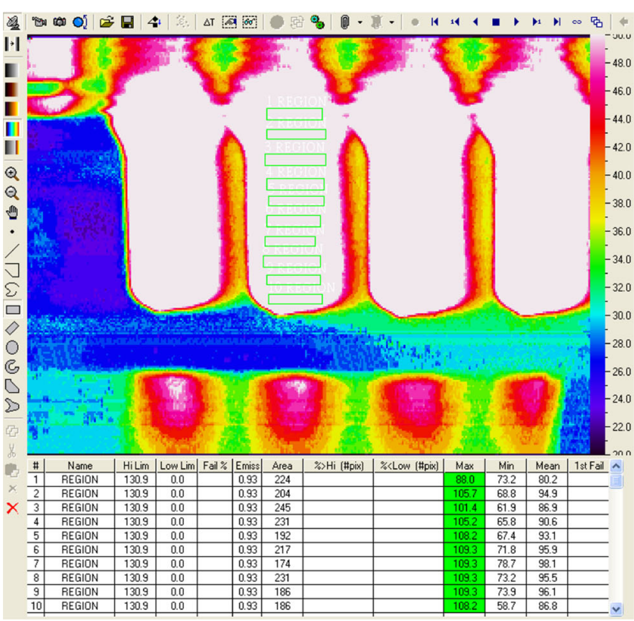
This experiment will setup the inverter fan speed from 0 to 60%, while the other fan is off. The SBM machine starts running, when the system has a stable operation, the PET begins to be put into the heating start one by one, after three to five PET, put more PET into the heating, as there is one infrared camera from outside the heating box to measure the temperature inside and outside of the PET. The experiment will end when the inverter fan speed is 0%, which is shown on Fig. 4 and Table 1.

According to Fig. 4a, the temperature heating interruption time had a different temperature of the four preforms from the first PET1 to PET4 and had a temperature increase (maximum 6 °C), because the first PET in the heating box just opened, and then the temperature inside was lower than when the input PET4 was heating. If the heating was intermittent, the temperature of some of the first PET will have a temperature higher than before. The continuous PET cannot heat fully the outside body, because the first PET and the last PET have area heating more than 50%, for other PETs have areas heating less than 40% like Fig. 5c. When the PET moves and rotates from outside heating box go through four heating box, then all of PET can heat over the whole surface area of PET as shown on Fig. 5.

When the machine is working, the heating process for PET has two heat flows. The first heat flow is heat flow from lamps system, the second heating flow is generated by the new cooling system. Under the influence of heat from the heating system, the air inside the heating chamber warms up and transfers heat to the PET. With the new cooling system, it will



a. Heating interruption time



b. Measurement heating continuous PET

Fig. 4 The temperature distribution of bottles under Inverter Fan speed at 0%. (**a**) Heating with interruption time (**b**) the measurement table under the heating continuous PET case

Table 1 The PET temperature w.r.t. its position and the fan speed (results of Exp 2)

Compare inverter fan speed result							
Position	Speed						
	0	10	20	30	40	50	60
0	93.3	93.1	93.8	88.8	87.4	86	88.6
7	109.3	111	112.1	104	103.3	96.9	100.4
14	107	108.2	109.3	103	100.4	96	98.5
21	110	112.1	115	104.3	104.3	100.1	102.4
28	112.8	113.8	116.5	104.3	104.3	103	102.4
35	115	115.5	118.8	104.3	104.3	104.3	104.3
42	113.8	115.5	118.8	104.3	104.3	104.3	104.3
49	113.3	115.5	118.2	104.3	104.3	104.3	104.3
56	112.8	115.5	119.3	104.3	104.3	104	104.3
63	108.8	111	115	104	104	97.2	101.4

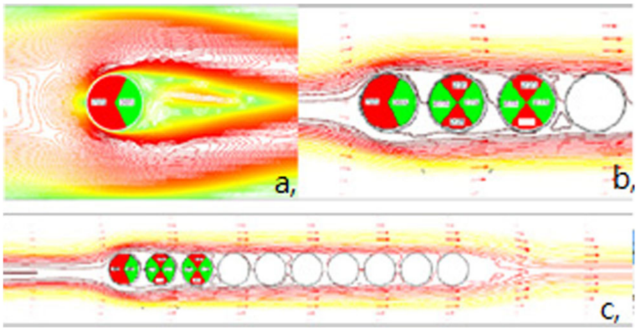


Fig. 5 The intensity of the flow energy field for heating PET (**a**) the single heated PET case (**b**) an enlarge chart of part of heated preforms (**c**) a series of heated PET case

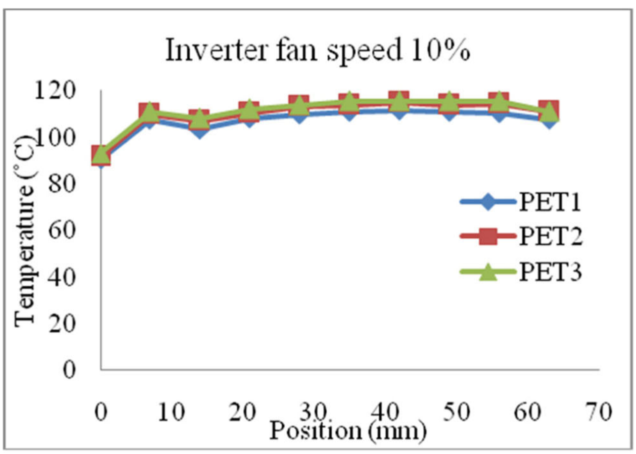
create new heat flow air for heating PET. Specifically, the energy from the heating lamps transfer to air inside heating box and then slowly goes down. After that with the new cooling system, the hot air moves downward aspirated and pushed up for reheating PET like Fig. 2b.

As shown on Fig. 5, if the system input one time is one PET, the heating area will be more than the system input of a continuous PET, as in Fig. 5a, as the heated area accounts for about 70% instead of 46% when the PET is input continuously, then the temperature of the PET will become higher. This is very important for producing because when we put a new molding into a system, the workers need time to control the intensity of the lamp in order to heat the PET to the appropriate temperature. Through the experiment (Fig. 6a, b), we can see the temperature of the PET is heating singly, and the first PET (when heating the PET continuously), the temperature is always higher than another PET (heating PET continuously).

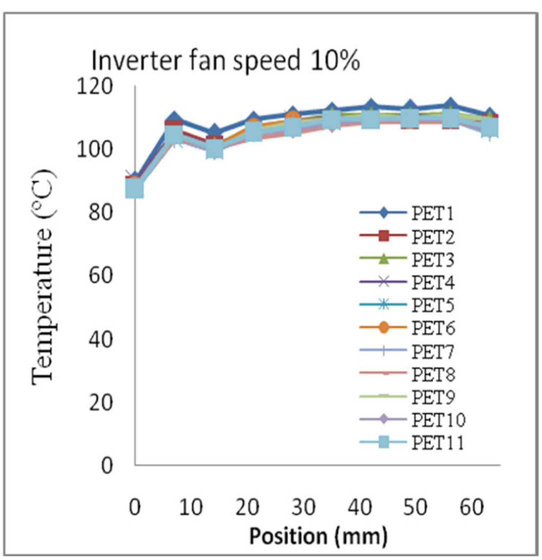
As shown on Fig. 7 and Table 1, when the inverter fan increases speed, the temperature of the PET will decrease, but when the inverter fan speed changes from 30 to 60%, the temperature remains stable. As a result, we can control the speed of the inverter fan from 30 to 40%, which is better for heating the PET and will save energy.

The range of machine allows to cover more quantity producing from 6000 to 18,000 bottles per hour consuming half intensity as shown on Fig. 10. The PET temperature is so high (nearly 300 °C) when the production speed is 6000 bottles/h. Moreover, when the temperature of the PET is higher than 130 °C (Table 2), the PET will be a crystalline PET bottle, which cannot stretch blow on the machine. Therefore, a blowing machine can work well for a long time producing good quality products with the aim of adjusting the cooling system and the heating intensity of the light system appropriately for the manufacturing output of the machine.

The experiment result in Fig. 8 shows that the temperature of the PET heating belongs to the reflector oven blower fan



a. Heating only one PET



b. Heating PET continuously

Fig. 6 The temperature distribution of PET bottles with Inverter Fan speed at 10% (results of Exp 2)

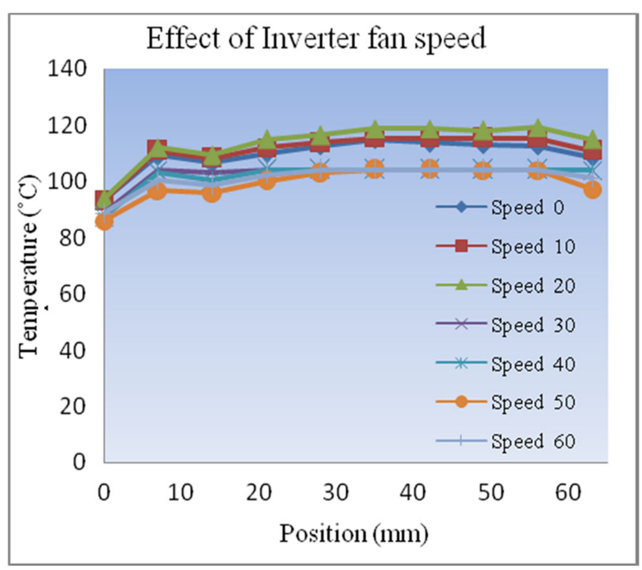


Fig. 7 The temperature of PET with different speed of Inverter fan (results of Exp 2)

Table 2 The experiment result of the production speed (results of Exp 1)

Position (mm)	Compare reflector oven blower fan speed result												
	Production speed (bottle/h)												
	6000	7000	8000	9000	10,000	11,000	12,000	13,000	14,000	15,000	16,000	17,000	18,000
0	176.8	157.1	139.7	138.8	123.8	121.1	106.9	100.4	99.5	96.1	97.1	89.2	90.3
7	209	194.3	182.7	178.7	155.5	145.4	136.1	128.3	122.9	117.2	120	109.1	111.2
14	217.5	202	186	180.7	158.4	146.2	136.1	127.3	122.9	116.2	116.2	106.1	109.1
21	218.8	210.2	192.4	187.2	166.4	153.9	142.1	131.8	127.6	120.1	121.1	110.2	112.1
28	218.8	212.9	196.2	190.5	170.6	157	143.7	133.6	129.3	121.1	122.9	110.2	113.2
35	219.5	214.9	199.5	192.3	171.9	159.9	145.4	135.3	131.1	122.9	124.7	112.1	116.1
42	219.5	214.9	200.1	192.3	171.3	159.2	145.4	135.3	131.1	122.9	124.7	112.1	115.2
49	218.8	214.2	200.1	191.7	171.3	159.2	144.5	134.5	130.3	122.9	124.7	112.1	116.1
56	218.8	210.2	195.6	190.5	169.9	165.8	143.7	136.2	129.3	122.9	123.8	110.2	114.1
63	218.8	187.2	173.4	169.2	119	131	127.3	126.5	122.9	118.2	120	109.1	113.2

speed. From Fig. 8, the temperature of the PET decreases when the reflector oven blower fan runs faster. The speed of the reflector oven blower fan has some curves which are similar to the initial and optimized temperature distributions along the preform length, as shown on Fig. 9 [1]. Therefore, this fan is very important for heating the PET and for making good products on the SBM machine (Fig. 10).

The final point is an experiment about the changing speed of a cooling system with the outside temperature of the heating chamber. This experiment uses an infrared camera to measure 12 points on the heating chamber with a different power of the fan on the cooling system. The result is the change of temperature outside the heating chamber by using the cooling system time. The result is described on Fig. 11 as point 2. Namely, the temperature is recorded as a significant increase, from 30 to 68 °C in 30 s, then rises to 80 °C in 60 s. The temperature outside the heating chamber will decrease after raising the fan speed. As can be seen from Fig. 11, if the cooling fan system speed climbs from 0 to 60%, the temperature will decline by 10 °C. Besides, if the experiments are ensured of more time, the temperature will become more instinctive with each fan speed. After the first 100 s of period with the same temperature, the difference between the fan speeds becomes more obvious.

Each type of machine produced by the company has a limit on the average output of the machine operating continuously for each shift. However, as shown above (Figs. 6, 7, 8, 9, and 10), if the machine is operating at maximum output for a long time, the temperature outside the heater box will increase (Fig. 3). High passes the elastic limit of the material (Fig. 12). Making the material harden up greatly influences the PET bottle blowing process afterwards. To ensure the product quality and long life of the machine, manufacturers

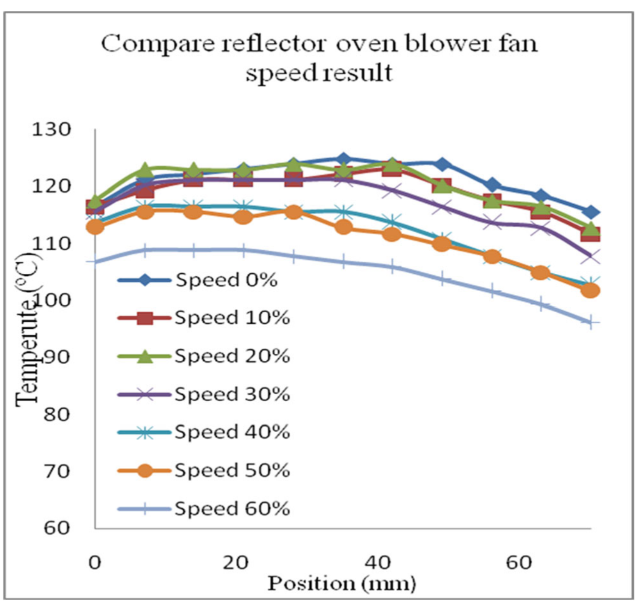


Fig. 8 The temperature distribution of PET with different speed of the reflector oven blower fan (results of Exp 1)

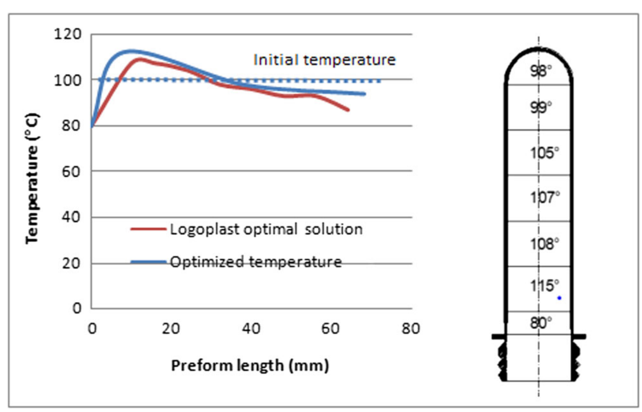


Fig. 9 Initial and optimized temperature distributions along the preform length

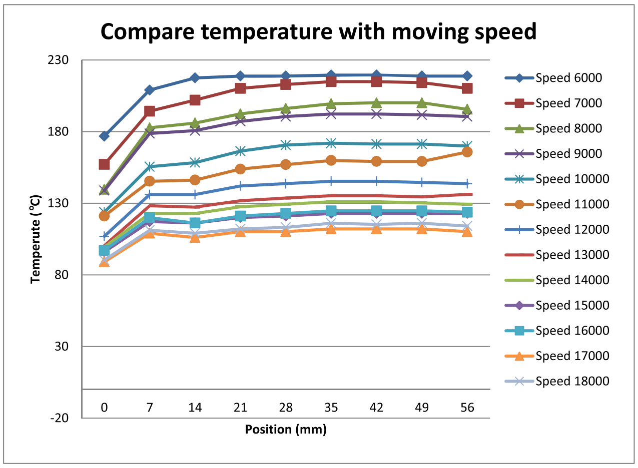


Fig. 10 The effect of time speed for heating PET (results of Exp 3)

generally recommend to companies that they should use machines less than 80% of the maximum power. With this new cooling system, the temperature outside the heater box is reduced to 10 °C (shown on Fig. 11) so the machine can operate at up to 85% or even 90% of its power output, product will increase 5 to 10% nevertheless, majority of electronic devices have limited working temperature from − 15 to 60 °C then temperature inside of machines cannot over 60 °C, and this will make the electronic devices inside the machine transmission incorrect data or damaged. Furthermore, how to keep the temperature inside the machine smaller than 60 °C is essential. With this new cooling system model, it is able to make the temperature outside the heating box degree 10 °C, before the lower temperature of machine.

On Table 3, it illustrates an important consequence that we can lessen energy consumption to get purpose. The total power of lamps for each of the heating boxes will decrease from 435 to 392 W equivalent of 10% power off to get the same

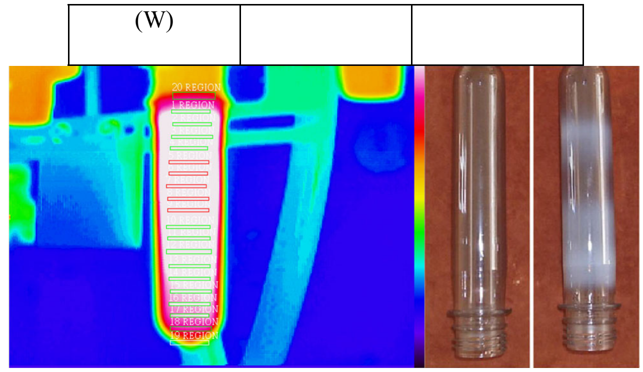


Fig. 12 Overheated PET preforms

purpose like Fig. 13. Then, the energy consumption during heating is 10% less than that of the original manufacture procedure.

6 Conclusions

On the whole, the major point for operating the SBM machine is how to control the heating system, the cooling system, and the production speed, in order to optimize the temperature

Table 3 The power of lamps for the old and the new model

	Old model	New model
Lamp 1(%)	60	50
Lamp 2 (%)	75	67.5
Lamp 3 (%)	60	56
Lamp 4 (%)	55	53
Lamp 5 (%)	50	48
Σ (%)	300	269
Total power (W)	435	392

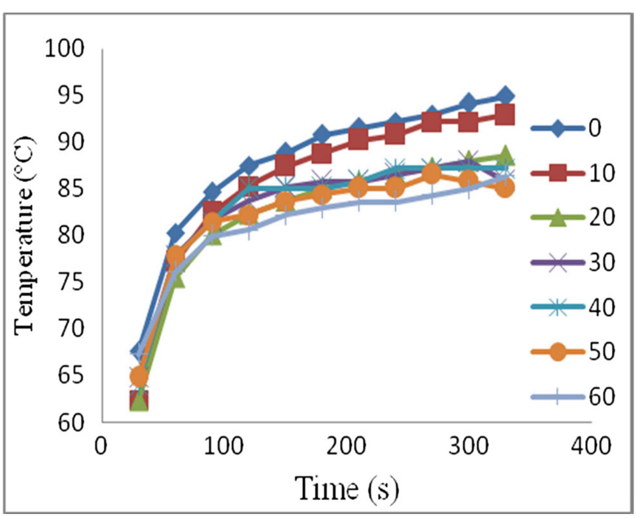


Fig. 11 The temperature on the wall of heating chamber (results of Exp 4)

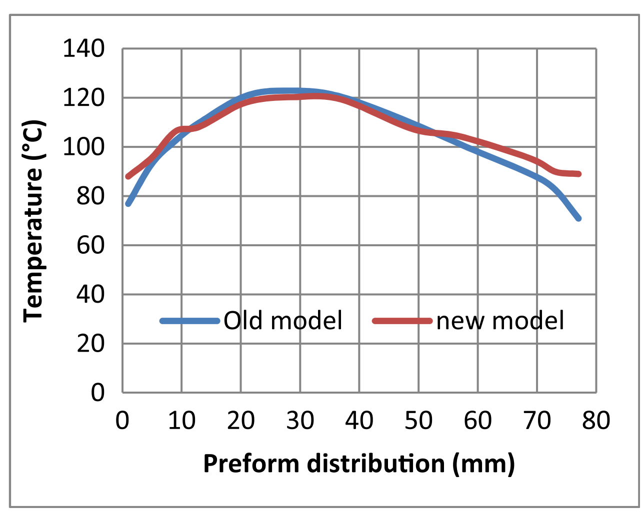


Fig. 13 The comparison of the temperature distribution for two models

distribution on the preform surface. The goal of the SBM machine is to provide a homogeneous thickness for the bottle. In this study, four experiments on Figs. 4, 5, 6, 7, 8, 9, 10, and 11 showed that this cooling system is very important for helping the SBM machine to optimize the temperature distribution of the PET like Fig. 9 and also makes a temperature profile along the length of the preform, shortens the heating time, and saves 10% (in Table 3) of the energy consumption. Moreover, the reusing cooling gas will cool down the temperature of the machine 10 °C. This is helpful for the machine to be capable of operating in a longer time period. The result of this paper encourages us to analyze how to multiply the cooling system, and lamps heating in order to develop the desired temperature distribution for the PET. We will therefore continue to study more about the interior temperature distribution of the bottle in the near future.

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