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Simulation of infrared rapid surface heating for injection molding

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Abstract

In this study, a three-dimension ray tracing and transient thermal simulation is developed to evaluate the thermal condition of injection mold surface with infrared surface rapid heating system. Several types of reflectors were applied to study the heating ability of the rapid surface heating system. A commercial available optical analysis program, TracePro, was used to simulate the infrared absorption of the mold surface. The surface temperature of the mold insert was evaluated by 2D and 3D transient thermal analysis with a commercial software, ANSYS. The results from simulation and thermal video measurement system agree well. Besides, the temperature distribution of the mold surface can be better observed via the 3D thermal analysis developed in this article.

Keywords: Surface rapid heating; Infrared; Variotherm

1. Introduction

The variotherm technology can be adopted for micro-injection molding processes [1–3]. The variotherm process could be applied before or after mold clamping just depending on the type of variotherm system. With variotherm process, the temperature of the micro-featured mold insert will be higher than resin heat deflection temperature. When resin fills the cavity of the mold insert, higher mold temperature will delay the solidification time of the resin near mold surface and keep the resin in liquid state. Thus, the micro features in a micro-injection molded part will be well preserved. Despa et al. [4] has duplicated high aspect ratio micro-features and studied the injection molding process conditions. They demonstrated that high mold temperature, generally higher than heat deflection temperature, is helpful for micro-featured molding. If the variotherm process is adopted, the cycle time of the injection molding will be longer.

In general, practical variotherm system is surface rapid heating technology, which raises the surface temperature of the mold insert before injecting resin. Chen et al. [5] have studied the electromagnetic induction heating on a mold plate. The maximum temperature of the mold plate can be raised from 40 °C to 100 °C in 14 s and the location of maximum temperature is located near the inductive coils. The power of the induction system is 30 kW. Jansen [6] has derived and tested an one-dimensional layer analytical model or heat transfer in injection molding systems with coating layers or active heating systems attached to the mold walls. Further, the heating element model was tested with a specially designed heater cell. The measurements agree reasonably well with the predicted temperature response. Yao and Kim [7] also have developed a rapid thermal response molding technique by coating two layers, one metallic heating layer and one oxide insulation layer, on the mold insert. The surface temperature of the mold insert could be raised from 25 °C to 250 °C in 2 s. The thermal stresses built up due to thermal mismatch between the heating layers during heating and cooling will influence the surface reliability of the mold insert. So, the material and the quality of coating layers are very important.

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Rapid thermal processing (RTP) using radiation heat transfer is a popular technology that is widely used in semiconductor manufacturing processes such as chemical vapor deposition (CVD) on silicon substrates. Because of vacuum environment in the CVD chamber, radiation is a more efficient heat transfer mode to heat the silicon substrates rapidly. The short wavelength (∼1 μm) halogen lamps are used as the infrared source. The silicon substrate is insulated by quartz pillars and the temperature of silicon substrate can be raised from 300 K to 1300 K in 10 s. Some researchers have studied the temperature control of the RTPCVD system [8,9]. Habuka et al. [10,11] have used a direct approach using the three-dimensional ray-tracing simulation (DARTS model) to evaluate the thermal condition in a RTP system. The system is composed of tungsten/halogen filament lamps, specular reflectors and the silicon substrate. The paths of the infrared rays emitted from the tungsten/halogen filament lamps and traced following reflectors at the surface of the specular reflectors and the polished surface of the silicon substrate. Pettersson and Stenström [12,13] have developed a model for an electric infrared heater. The model includes non-gray radiative heat transfer between the different parts of the IR heater, as well as conduction in reflector material and convective cooling of the surface. Then, an infrared paper dryer was used to investigate the model. Miyanaga and Nakano [14] have also developed a method of numerical calculation for radiation heat transfer in a three-dimensional closed space including diffuse and specular surfaces. The improved heat ray tracing method was presented to calculate view factors accurately.

Although the cycle time of the injection molding with infrared mold surface rapid heating will be longer, for example, increase 10–25 s for small parts, it is one of the best solutions to improve the replication of molding high end parts, i.e., precise micro parts, high aspect ratio micro-featured parts with high viscosity resin. With the modification of the infrared rapid surface heating technique for injection molding, e.g., increase power of bulbs, focus the energy at the area of mold insert and lower the mold temperature, the cycle time of the high end parts injection molding can be kept within an affordable period of time. In this study, an easy and quick two-stage analysis approach was developed to evaluate the thermal condition of the injection mold surface heated by infrared rapid surface heating system. A commercial optical analysis program, TracePro, was used to simulate the infrared absorption of the mold surface for the first stage of analysis. Then, the result of the infrared radiation can be loaded as the heat flux of the thermal analysis. The surface temperature of the mold insert was evaluated by transient thermal analysis with a commercial software, ANSYS. The flowchart of simulation algorithm is shown in Fig. 1. In order to verify the simulated surface temperature of the center mold insert, a thermal video system was used to record the thermal condition on the mold surface after infrared heating. To make sure the correctness of the simulation, a recheck process was implemented. If the results of the simulation do not agree well with the measurements, the initial conditions and boundary conditions need to be modified to satisfy the real conditions.

2. Infrared ray tracing analysis

The commercial software, TracePro, was used to simulate the infrared ray tracing in the study. TracePro is an

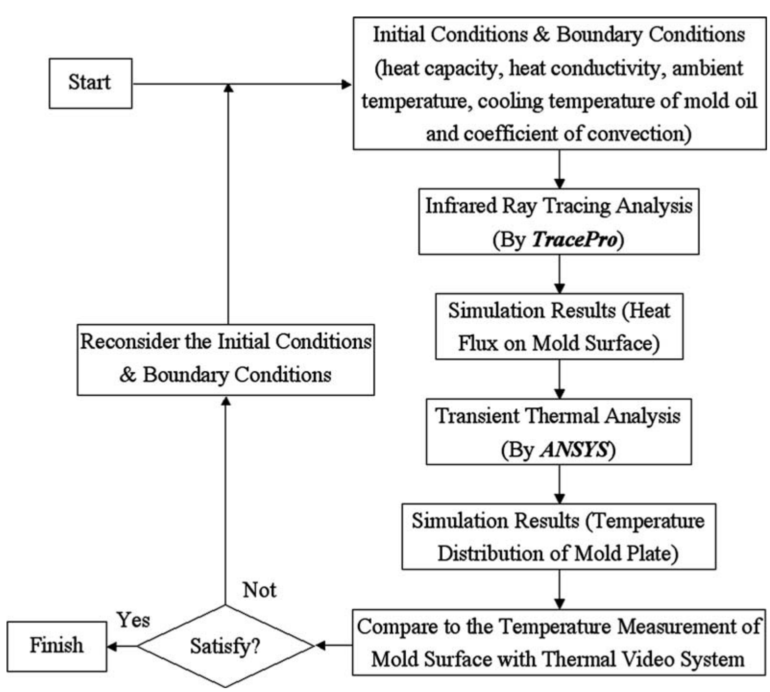


Fig. 1. Flowchart of infrared heating analysis.

optical analysis program. TracePro can perform stray light analysis, illumination analysis, and optical systems analysis. It uses Monte Carlo ray tracing to compute optical flux as it propagates through a model. TracePro accounts for absorption, specular reflection and refraction, scattering and aperture diffraction of light. Results can be examined in spatial irradiance plots, angular radiance plots, contour maps, candela plots, or ray histories in tabular form.

For ray tracing simulation, the model of the infrared tungsten/halogen lamp was established. Four infrared tungsten/halogen lamps (4 kW) are used as the radiative source to heat the mold insert surface. Although the model includes quartz, filament, poles, base and resistance (Fig. 2), the boundary conditions (transmissivity, absorptivity and heat power) were only applied on the quartz and the filament for efficient evaluation. Two types of reflector surface, flat and sphere, were used to estimate the reflective ability for infrared surface heating. The flat reflector with scattered lamps is shown in Fig. 3a. If the flat specular plate is removed, the infrared could irradiate both side of mold (Fig. 3b). The spherical reflector with scattered lamps configuration (Fig. 3c) and centralized lamps configuration (Fig. 3d) were used to simulate the heating ability. The curve equation of the approximate spherical reflector is shown in the following equation:

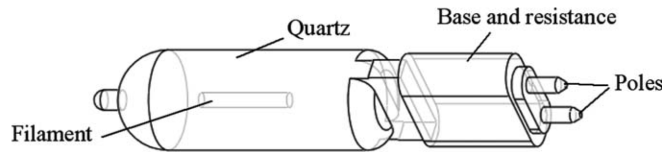


Fig. 2. Model of the infrared tungsten/halogen lamp for simulation.

$$y = \frac{x^2}{4f} + s\frac{x^4}{8R^3} \tag{1}$$

where x and y are the variables of the curve, s is the approximation of the curve, f is the focal length and R is the radius of the curve ($R = 2f$). If the approximation is 1, the curve is an exact circle. Revolving the curve equation forms the 3D model of the approximate spherical reflector.

Power is used as the radiative source in TracePro and it is assumed that each lamp emits full power of 1 kW. Each lamp has 20,000 rays for tracing simulation. The reflector material is aluminum alloy and polished for high reflectivity. The material of injection mold is pre-hardened steel (AISI P20) and the surface of mold plate is grinded. The material properties for the ray tracing simulation are shown in Table 1. The transmissivity of quartz is 0.93 for infrared [16]. The reflector and mold have no transmissivity. The surface roughness of the mold plate and reflector

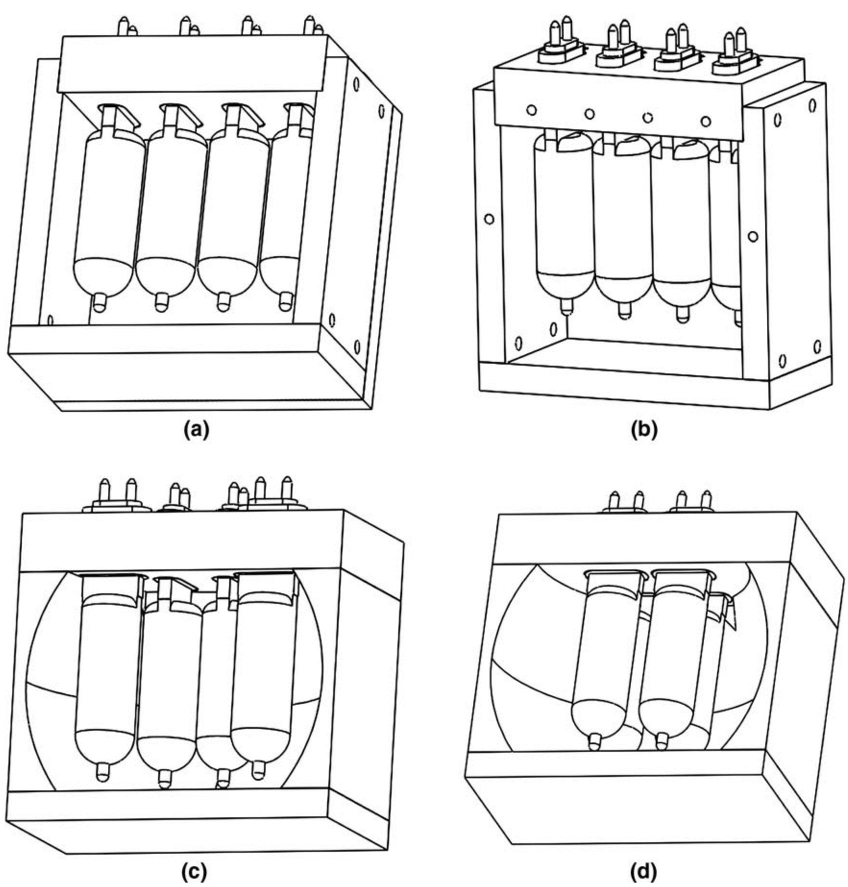


Fig. 3. Types of the reflector and lamp configuration: (a) flat reflector for single irradiation, (b) no flat reflector for double irradiation, (c) spherical reflector and scattered lamp configuration and (d) spherical reflector and centralized lamp configuration.

will affect the absorptivity and reflectivity. To prevent the interference between lamp holder and mold surface, the clearance between reflector and mold plate is 2 mm. Thus, some infrared rays will irradiate out from the clearance. For example, the ray tracing result of double side simulation by TracePro is shown in Fig. 4. The mold plate is defined as a thin plate in the simulation for ray absorption and the area of the mold plate is 180 mm × 180 mm. The irradiance of ray absorption on mold plate can be simulated and generated an irradiance map. The irradiance of the mold plate is the heat flux of absorbed energy. Also, the total energy absorption can be evaluated and listed in the result summary of TracePro.

Table 1
Material properties of the infrared ray tracing in the TracePro simulation [16,17]

	Quartz	Aluminum alloy	Mold steel
Absorptivity	0.07	0.15	0.25
Reflectivity	0	0.85	0.75
Transmissivity	0.93	0	0

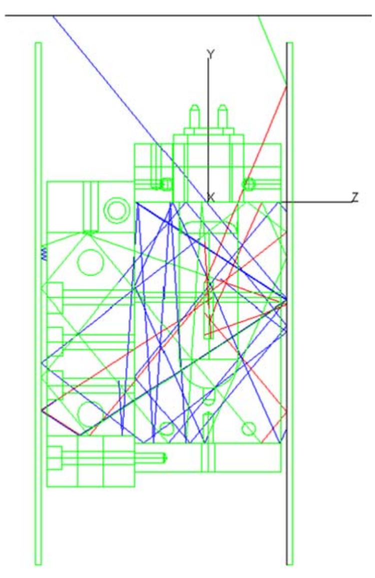


Fig. 4. Example of the double side ray tracing simulation by TracePro.

3. Mold surface temperature simulation

The result of the irradiance simulation can be saved as matrix data and was employed as the heat source for thermal simulation in ANSYS. The irradiance is the absorbed heat flux on the mold surface. In this study, both 2D and 3D thermal analyses were executed to evaluate the mold plate surface temperature. Although the infrared rapid surface heating is a 3D thermal problem, a 2D model was studied for shorter computation time. The number of the irradiance matrix data is 128 × 128 (element size = 1.41 mm). The element size of the 2D thermal simulation is also 1.41 mm. In the simulation, two levels of heating time, 14 s and 19 s (without 1 s filament stable time), were applied to study the thermal condition of the mold plate.

The initial temperature of the mold is 83 °C. The thermal properties of the mold plate are listed in Table 2. The heat transfer mode around the mold plate is air free convection and the coefficient of air free convection is assumed 10 W/m^2 K [15]. During the infrared heating process, the cooling channel is closed and the coefficient of oil free convection is assumed 50 W/m^2 K inside the cooling channel [15].

The 2D model simulates the center section of the mold plate. The area on the mold plate surface is 180 mm × 180 mm and the thickness of the mold plate is 60 mm. The boundary conditions loaded on the mold plate are shown in Fig. 5. The heat flux loaded on the mold surface is the average irradiance from the symmetric center (20 mm bandwidth). The irradiance data on the elements of mold surface was transferred as the heat flux with a batch file of ANSYS. The batch file can be input for simulation in ANSYS. The heat flux is loaded on outer surface of the elements. The total number of elements in the 2D mesh model is around 6000.

Then, a 3D transient simulation was done to predict the temperature distribution on the mold surface. The mesh

Table 2
The thermal properties of the pre-hardened mold steel (AISI P20) in the simulation [16]

Properties	Thermal conductivity (W/m K)	Heat capacity (J/kg K)	Density (kg/m^3)
Value	40	132	7850

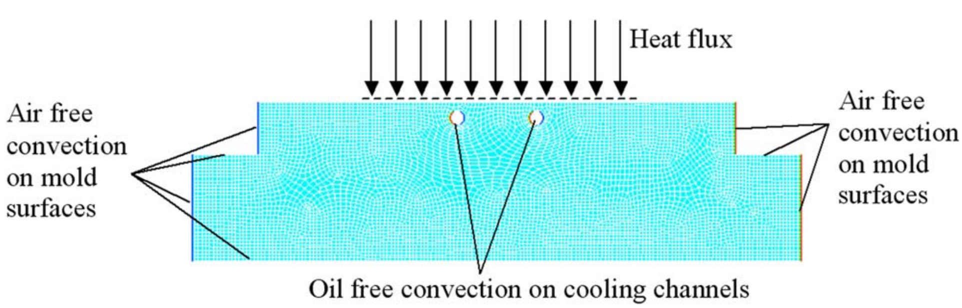


Fig. 5. Mesh model of the 2D mold plate thermal simulation by ANSYS.

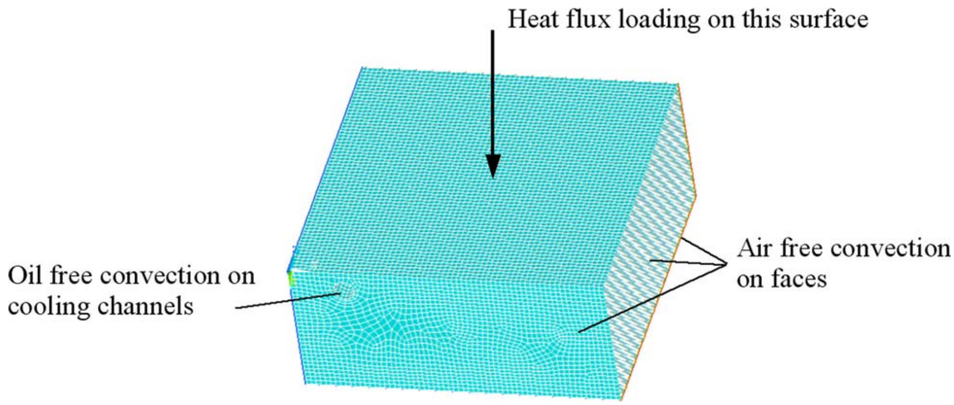


Fig. 6. Mesh model of the 3D mold plate thermal simulation by ANSYS.

model is symmetric at x and y axes. The boundary conditions loaded on the mold plate are shown in Fig. 6. The irradiance matrix data was also transferred as the heat flux with a batch file of ANSYS. The number of element in the 3D mesh model is around 111,000. Although not specified here, the convergence test for both 2D and 3D meshes were executed. The size of the meshes is determined to be proper for the simulation.

4. Measurement of the mold temperature

The schematic of the infrared heating system assembled on the mold plate is shown in Fig. 7. The infrared rapid surface heating system for injection mold is designed to assemble on the mold and a control system is used to operate the motion of the lamp holder. The lamp holder includes reflector, lamps and lamp connectors. The lamp holder is moved by a pneumatic cylinder. The lamp holder connector is fixed with the pneumatic cylinder by lamp holder connector. The cooling plate is used to protect the switch sensors and the rubber piston in the air cylinder from over heating. The lamp connectors are made with phenolic plastics to resist heat and electricity.

In order to verify the thermal condition of the mold surface, a thermal video system, AVIO TVS-600, was used to measure the central temperature of the mold surface. The resolution of the thermal video system is 0.15 °C and the resolution of image is 320×240. Because of the specular property of mold plate, the surface temperature distribution cannot be measured precisely by the thermal video system. Thus, an alternative approach is to use heat-resistant tapes that are glued on the mold surface and then measure the surface temperature of the tapes by thermal video system (point at Fig. 8). The emissivity of the heat-resistant tape is almost 1 and the temperature is verified with thermal couple temperature measurement.

When under stable conditions, the temperature of the mold surface is maintained at 83 ± 1 °C before infrared heating process. The location of the measurement point#1 is near the horizontal central axis and around 10 mm from vertical central axis of the mold plate (Fig. 8). In the experiment, two levels of heating time, 15 s and 20 s, are also applied to study the heating ability of the infrared rapid surface heating system. The heating time includes the stable time of the halogen lamp (~1 s). It is assumed that the power emitted by halogen lamp during the stable time is neglected. Therefore, the power emitted by halogen lamp in 15 s experiment is the same with that in 14 s simulation.

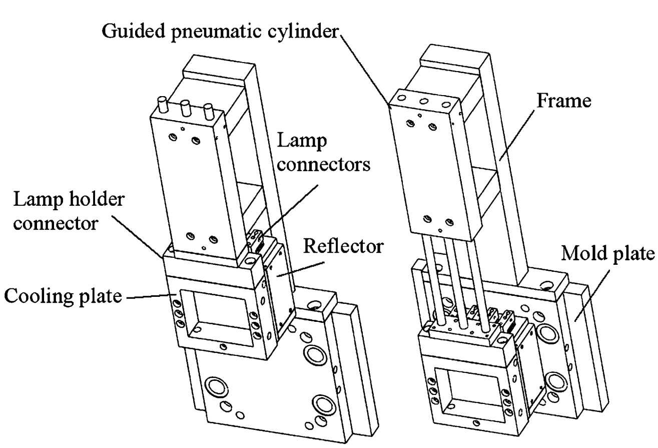


Fig. 7. Schematic of the infrared heating system assembled on the mold.

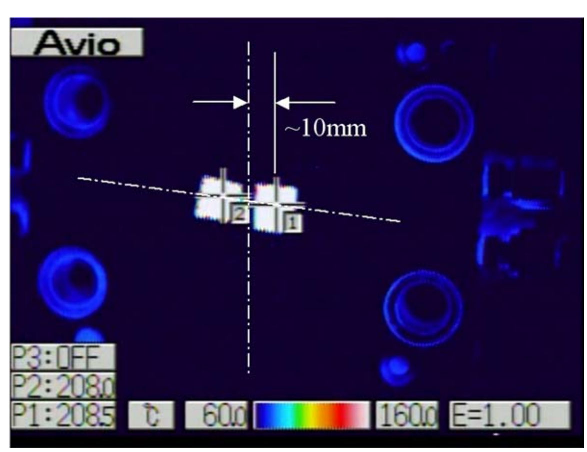


Fig. 8. Surface temperature of stationary mold plate measured by a thermal video system (AVIO TVS-600).

5. Results and discussion

The irradiance map of simulation with flat reflector is shown in Fig. 9. The maximum irradiance is concentrated on the horizontal center axis, which is the location of the filament. The irradiance map of simulation with spherical reflector and centralized lamp configuration is shown in Fig. 10. The irradiance is much more concentrative at the center of the mold plate than that of flat reflector and the value of the maximum irradiance is also larger. If the molded parts are small or at the center of the mold, the concentrated effect of spherical reflector and centralized lamp configuration is better than that of the flat one. According to the simulation of the energy absorption of the mold plate, the approximate optimal parameters of the circular curve for the heating system can be found. Thus, the values of s and f are 1 and 30 mm, respectively. The total amount of absorbed energy of the mold plate is shown in Table 3. Regardless of centralized or scattered lamp configurations, the heating ability of spherical reflector is better than that of the flat one. Because the radiation is separated to both sides of the mold plate in double side irradiation, the absorbed energy on each mold plate is smaller than the others. Thus, the mold surface temperature of the double side irradiation may not exceed the heat deflection temperature of the resin. More lamps or larger power of lamps are needed for the double side irradiation. If the heating area is small or at the mold center, and

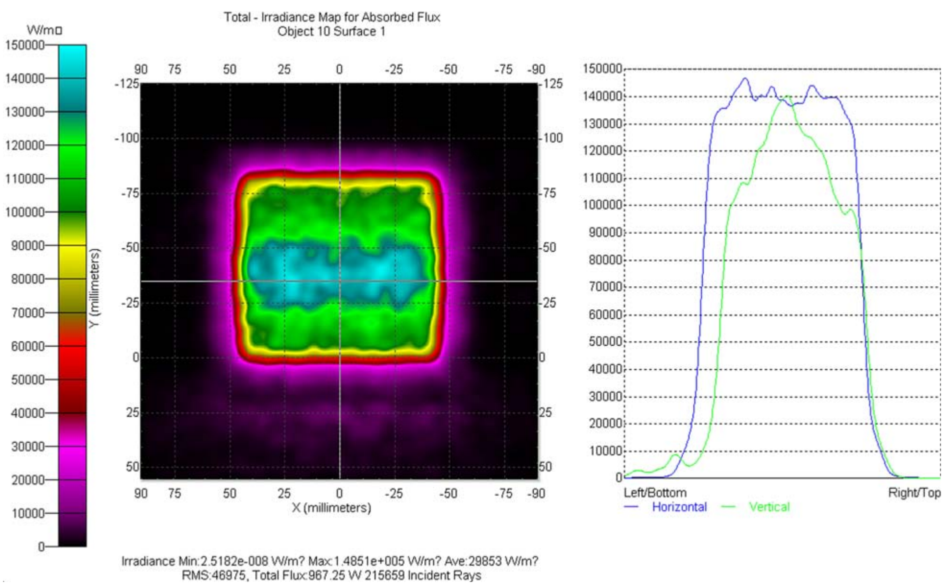


Fig. 9. Irradiance of the mold surface with flat reflector infrared heater simulated by TracePro.

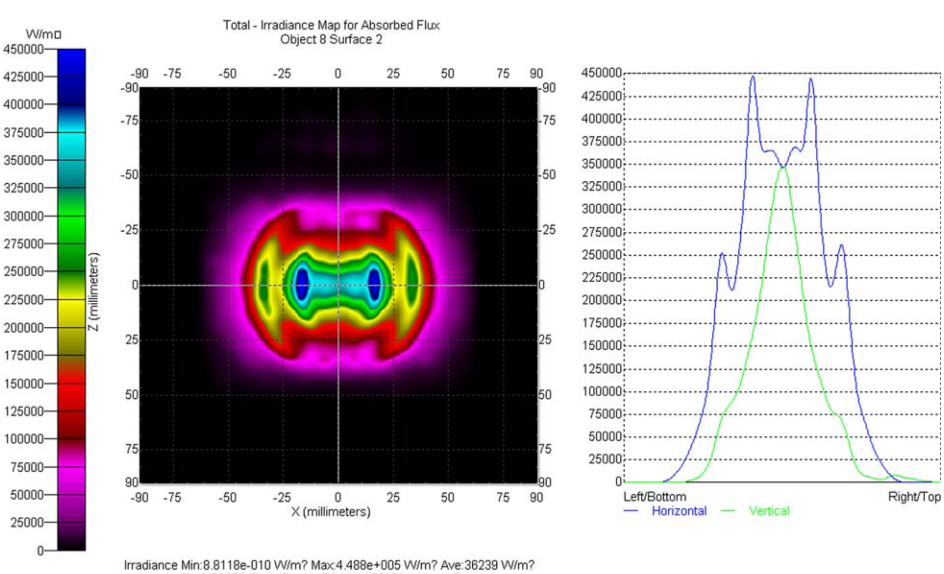


Fig. 10. Irradiance map of the mold surface with spherical reflector infrared heater and centralized lamps configuration simulated by TracePro.

Table 3
Total energy absorbed by the mold plate from simulation

Reflector type	Absorbed energy (W)
Flat	967.25
Double side	716.4/518.02
Spherical scattered	1158
Spherical centralized	1171.1

centralized lamp configuration is better than the scattered one for double side heating.

The central temperature of mold surface from 2D transient simulation is shown in Table 4. Because the spherical reflector can concentrate the infrared on the mold center, the central temperature of the mold plate heated by flat reflector is the lowest. The concentrative effect of centralized lamp configuration is better than scattered one. The central temperature of the mold surface with 20 s heating is 15 ~ 20 °C higher than that with 15 s heating. The central temperature of mold surface from 3D transient simulation is shown in Table 4. The location of the observed point is the same as point#1 in the thermal video measurement experiment. The results of 3D simulation are similar to those of the 2D simulation.

The temperature measurement results are shown in Table 4. From the temperature measurement results, it is

Table 4
Comparison of central temperature at the mold surface by simulation and measurement

	Central temperature of mold surface (°C)	Spherical reflector centralized lamp configuration	Spherical reflector scattered lamp configuration	Flat reflector
15 s heating	Measurement	187.7	182.5	143.7
	2D simulation	199.94(6.5%)	177.94(−2.5%)	145.92(1.5%)
	3D simulation	208.84(11.2%)	189.13(3.6%)	145.06(0.9%)
20 s heating	Measurement	208.5	196.4	157.4
	2D simulation	215.96(3.5%)	192.32(−2.0%)	151.37(−3.8%)
	3D simulation	224.11(7.5%)	199.66(3.2%)	152.75(−2.9%)

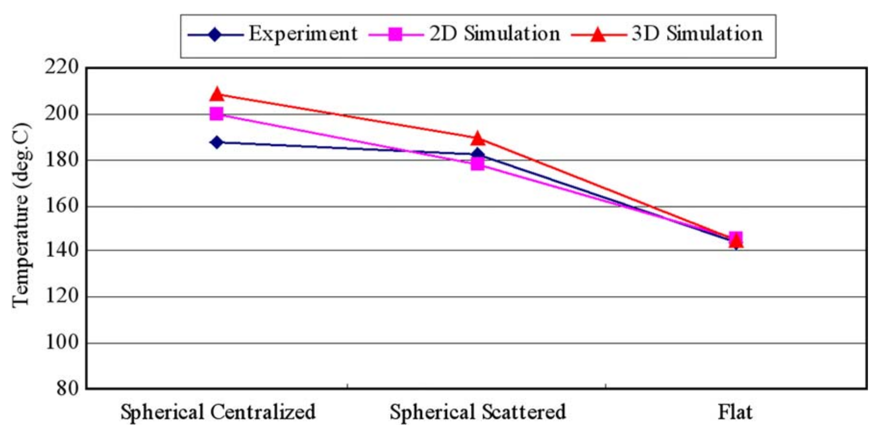


Fig. 11. Temperature comparison of point#1 after 15 s infrared heating.

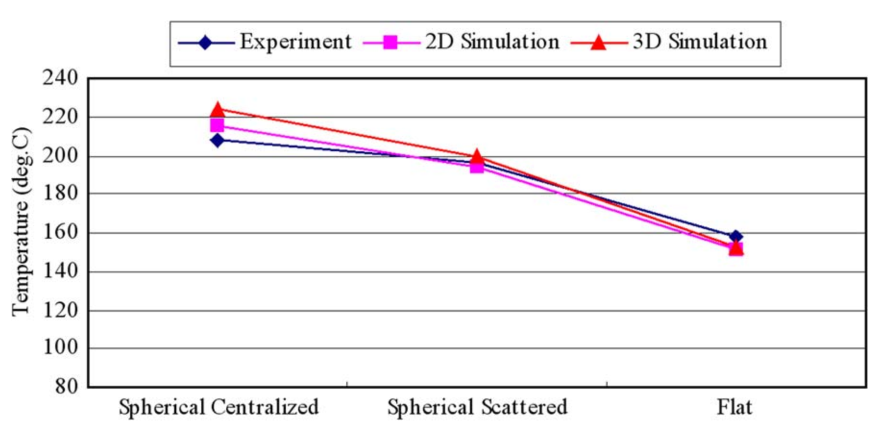
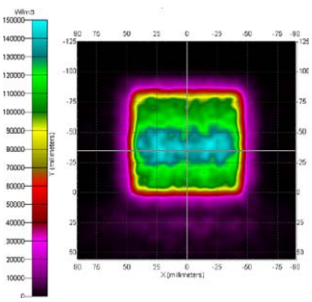
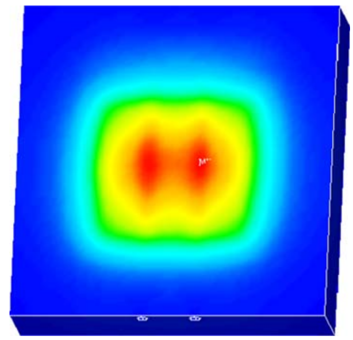
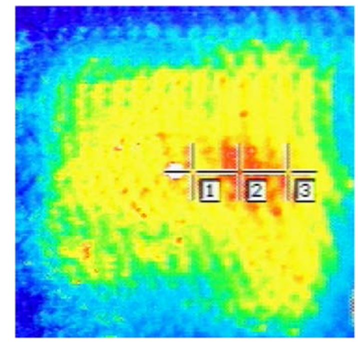
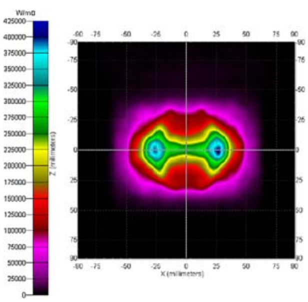
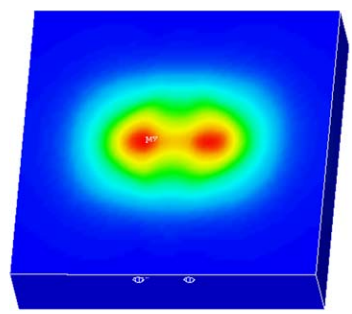
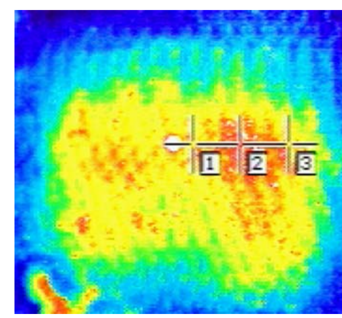
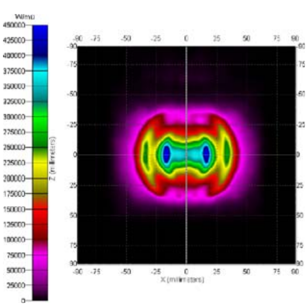
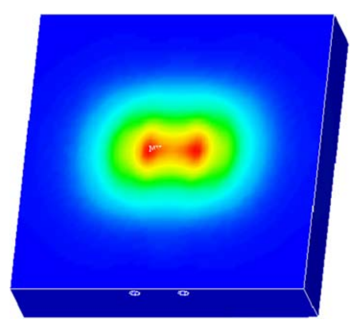
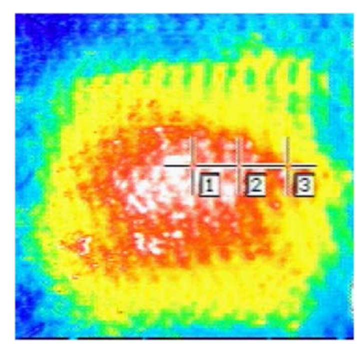


Fig. 12. Temperature comparison of point#1 after 20 s infrared heating.

Table 5
Comparison of irradiance map and temperature distribution of the mold surface

Reflector type and lamp configuration	Heat flux distribution (simulated by TracePro)	Temperature distribution (simulated by ANSYS)	Temperature distribution (measured by thermal video system)
Flat			
Spherical and scattered			
Spherical and centralized			

observed that temperature increase is proportional to heating time. The temperature at the mold insert center heated by spherical centralized type reflector is higher than those of the other two cases. Comparing the results (Figs. 11 and 12), the mold center temperature from simulation and measurement are in good agreement. But, the mold center temperature of 3D simulation heated by spherical centralized type reflector is 16–20 °C higher than the measured. The comparison of irradiance map and temperature distribution of the mold surface is listed in Table 5. The simulated temperature distribution of the mold plate heated by flat reflector is more uniform than those by the others. The concentrative effect of centralized lamp configuration is better than the scattered one. Because of the specular properties of the mold surface, the temperature cannot be measured precisely. Also, it is difficult to measure the temperature distribution precisely due to the non-uniform surface roughness of the mold surface (grinded mark). But, it can be observed that the white color (high temperature) area of the center mold surface heated by spherical centralized type reflector is larger than the others. It is demonstrated that the spherical centralized type reflector has better concentrative effect.

6. Conclusions

The temperature distribution of mold surface heated by infrared rapid heating system is simulated in the study. By combining the ray tracing tool of TracePro and thermal module of ANSYS, the temperature on the mold surface after infrared heating can be evaluated. Besides, this approach can also be applied to find the concentrative effect or the optimal geometry of the reflectors. Due to the specular properties of the mold surface, the temperature distribution cannot be measured by thermal video system precisely. But, the central temperature measurements of the mold surface are very close to the simulation results. It is reasonable to assume that the temperature distribution of the simulation is not too far from the real condition.

For practical applications of injection molding high aspect ratio micro featured or micro parts, the effective surface temperature of mold before injecting resin should be higher than heat deflection temperature. For example, the heat deflection temperature of PP is about 100 °C and PC is about 127 °C. From the simulation, the temperature of mold surface after heating will be 140 °C at least. But, the time need to moving away the reflector and clamping the mold will take about 4–5 s. The surface temperature of the mold plate will decline during the time. The declining rate of the mold temperature is depending on the thermal condition and material properties of the mold and environment. Besides, heating and cooling processes will prolong the cycle time of the injection molding processes. However, the energy consumption of the infrared rapid surface heating system is a lot lower than the existing systems. So, the infrared rapid mold surface heating system is a good option if rapid mold surface heating is needed.

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