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Design and analysis of a spatially shaped laser beam used for temperature field simulation

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Abstract: Laser has controllable space-time characteristics and can be loaded on materials as a heat source in laser manufacturing, laser medical and other fields. In the thermal fatigue test of engine parts, thermal load can also be considered by laser beam. In this paper, a large aperture spatially shaped laser beam with complex and uneven intensity distribution is selected as the heat source for temperature field simulation. Using the method of key nodes selection, the temperature distribution of a few key nodes can reflect the desired temperature field of the whole nodes. Based on finite element model (FEM), through the numerical simulation of the temperature field, optimized intensity distribution of the shaped laser beam is calculated, and a diffractive optics element (DOE) is designed to achieve the shaping effect. The results show that a spatially shaped laser beam can be used for temperature field simulation.

Keywords: Temperature field simulation, Shaped laser beam, DOE, FEM

Introduction

With the continuous expansion of laser application, different application objects often put forward different requirements for laser intensity distribution, such as [1-5], linear beam in laser scanning, flattop beam in laser machining, spots array in laser surface treatment, etc. Due to the limitation of Gaussian intensity distribution of traditional laser beam, it is necessary to use shaping technology to convert it into a shaped one with certain spatial intensity distribution [6]. Spatially shaping technology is actually a process of redistribution of laser radiation. Because of the ability to freely modulate the irradiance and phase profile of laser beam by the surface relief microstructure, diffractive optical elements (DOEs) have been widely used in laser beam shaping technology [7-10]. Based on the spatial shaping technology and DOE, some studies [11-12] have shown that, in thermal fatigue test of engine parts, it is possible to use a shaped laser beam for thermal loading to induce temperature field similar to the actual working condition. The spatial intensity distribution of the shaped laser beam can be modulated according to the temperature value of each position, so as to ensure the accuracy and reliability of thermal fatigue test.

The desired temperature field on the top of a piston is given in this paper. It is not the results of thermocouple measurement, but the simulated results in the process of piston design. Because of the large number of nodes in the simulation data, it is impossible for a shaped laser beam to make the temperature of each node meet the desired one. Therefore, the first step is to select the key nodes to ensure that the temperature distribution of the key nodes (we call it the target temperature field) can

represent the temperature field of the whole nodes. The second step is to optimize the spatial intensity distribution of the shaped laser beam. A finite element model (FEM) of the piston is established and the target temperature field can be simulated by adjusting the intensity and loading regions of the shaped laser beam. Then the phase of a DOE is calculated iteratively according to the input and the spatially shaped output beam. The iterative Fourier-transform algorithm and ST algorithm are utilized in the phase design. The FEM is used to simulate the shaped effect of input beam on DOE after phase modulation. Finally, in the temperature test experiment, the original input laser beam is passed through the DOE, and the temperature results at different positions on the top of the piston is measured. The experimental results show that the measured results are consistent with the simulated results, which proves that the spatially shaped laser beam is feasible for temperature field simulation.

Methods

In this section, we first describe the key nodes selection that need to be considered, in order to simplify the design difficulty and reduce the amount of calculation data. Afterwards, the temperature simulation by FEM and the numerical design approach of the DOE are introduced in detail.

Since the desired temperature field on the top of the piston is the simulated result in piston design process, the default coordinate system can be selected as the coordinate system for finite element calculation. According to the contour map drawn by all temperature nodes, the spacing value of key nodes is determined by the width of each contour line. Taking the coordinate origin as the center, the key nodes are extracted on the x-axis and y-axis with this spacing value, and the nodes with contour changes violently and the nodes with the highest and lowest temperature are also added. On the basis of the temperature value of the extracted key nodes, the contour map is drawn, and compared with the contour map of all given temperature nodes, the areas with large differences between them can be found. The key nodes near these areas must be adjusted until the contour map of key nodes is consistent with the contour map of all given temperature nodes. So far, all the key nodes have been selected, and the target temperature field can represent the desired temperature field.

The temperature field loaded by spatially shaped laser beam is simulated by FEM, and the target temperature field can be obtained by adjusting the intensity and loading regions of the shaped laser beam. Based on the heat equation and Fourier's law of heat conduction [13], the transient temperature field on the piston can be calculated with the given boundary conduction. Because the target temperature field is non-uniform and has a particular distribution, it is necessary to design the shaped laser beam with different intensity loading regions. We can modulate the loading regions and intensity ratio until the simulated temperature results are combined with the target temperature field. After the intensity distribution of the spatially shaped laser beam is obtained, a DOE can be designed to convert the input beam into the shaped one. The DOE is a pure phase element and its phase is calculated based on iterative Fourier-transform algorithm and ST algorithm [14-17]. According to the relationship between the input and output shaped beam distribution [18-19], the phase of the DOE can be calculated. Large scale integration technique is applied to the DOE fabrication [20]. Utilizing the DOE in the temperature test experiment, infrared pyrometers are used to detect temperature values of some positions on the top of the piston. The effectiveness

of the method is verified by comparing the experimental results with the simulation ones.

Results and discussion

The desired temperature field on the top of the piston is given in Figure 1 (a), which is the simulated result during the piston design process. The total number of nodes is more than 3000. We just select 23 nodes as the key nodes, and almost all of them are located in the position of large temperature gradient. The temperature distribution of key nodes is shown in Figure 1 (b). With the method of key nodes selection, the target temperature field has a similar trend and can replace the desired one. Therefore, this method is effective to choose the temperature distribution of a few key nodes to reflect the desired temperature field of the whole nodes on the top of the piston.

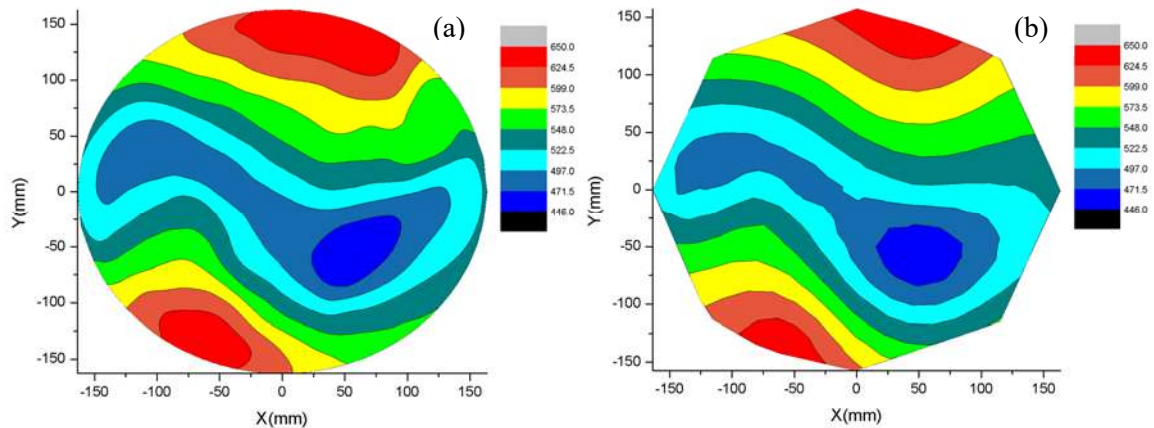


Fig. 1. The temperature fields. (a) Whole nodes; (b) key nodes. (Unit: K)

In order to obtain the target temperature field, the spatial intensity distribution of the shaped laser beam has to be determined. We can calculate the temperature results induced by loaded laser beam based on FEM, and the numerical model of the piston is built. The power of the input laser beam is 10kW and the wavelength is 1064nm. On the basis of the target temperature field, we assume that the spatially shaped distribution is composed of several regions with different intensities. By adjusting the size and intensity of different regions to make the loaded temperature results closer to the target values, an optimized spatially shaped distribution can be obtained, as shown in Figure 2. The top surface of the piston is divided into 7 regions, and no laser irradiation is loaded in region5. The power ratio of each region is $P(\text{Region1}): P(\text{Region2}): P(\text{Region3}): P(\text{Region4}): P(\text{Region6}): P(\text{Region7}) = 33.8: 42.2: 1: 3: 1: 122$, and the relative radii of circular regions from region1 to region 6 are 75mm, 65mm, 25mm, 25mm, 40mm and 25mm. The simulated temperature field loaded by the optimized shaped laser is shown in Figure 3. We can see that the high and low temperature regions are basically consistent with the target ones, and the simulated results with the shaped laser beam have the similar temperature change trend as the desired. There are still temperature differences in some parts of the field, but this method is still available because the temperature influences in a small range have little impact on thermal fatigue test.

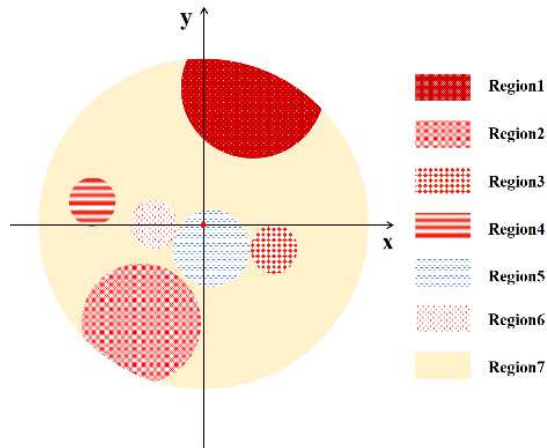


Fig. 2. An optimized spatial shaping distribution.

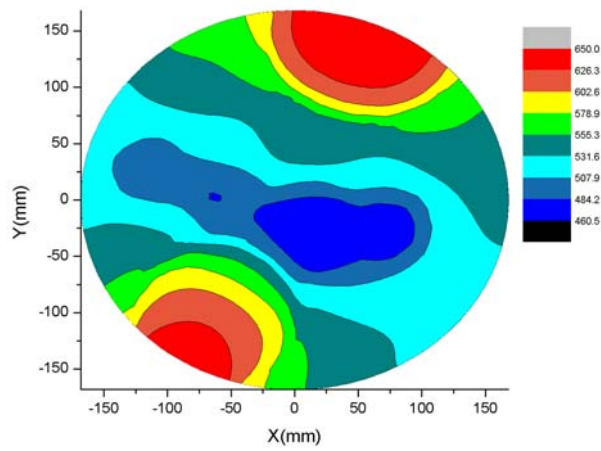


Fig. 3. Simulated temperature field by shaped laser.

The phase of the DOE is calculated based on the iterative Fourier-transform algorithm and ST algorithm which is a kind of modified G-S algorithms. The DOE is divided into several small square cells with sample points of 11800×11800 . The input laser diameter is 47.2mm and the diameter of the whole output shaped beam is 336.4mm. The distance between the input and the output plane is 1.3m. After optimized phase modulation, the simulated output spatially shaped beam is shown in Figure 4. The results show that the simulated shaped effect can meet the design requirements. By quantifying the phase data, the DOE can be fabrication by reactive ion beam etching technology.

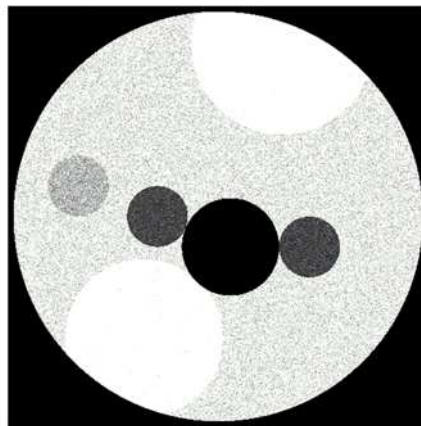


Fig. 4. Simulated output shaped laser beam

In the temperature test experiment, the input laser beam passes through the DOE and the shaped laser beam is formed on the top of the piston. The infrared pyrometers are used to detect temperature values at some points on the top of the piston. The experimental and simulated results are shown in Figure 5. The deviations of 19 points from experimental and simulated values are all less than 5% and the deviations of the other 4 points are between 5% and 7%. From the results, we can find that the experimental temperature values are in good agreement with the simulated ones, which verifies that the shaped laser beam by the DOE can be considered as the heat loading in thermal fatigue test. On this basis, the typical thermal loading conditions [21-22], such as thermal high cycle fatigue and thermal low cycle fatigue, can be performed by controlling the laser loading time or temperature fluctuation range. The research results will provide meaningful technical reference for the evaluation of laser thermal loading and damage.

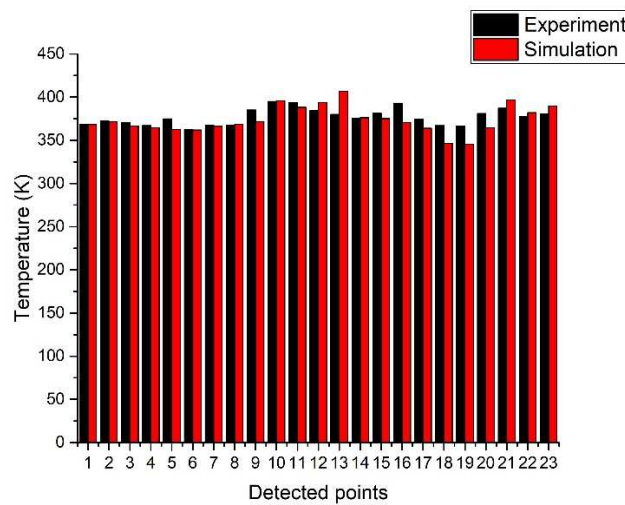


Fig. 5. The experimental and simulated temperature results in detected points

Conclusions

This paper provides a feasible method to simulate a large-scale and complex non-uniform temperature field on the top of a piston. The spatially shaped laser beam is used as the heat source. The intensity distribution of the shaped beam is divided into seven regions, and a DOE is designed to realize the transformation based on FFT and ST algorithm. From the simulation and experimental results, the shaped effect can meet the requirements. The study has a certain reference value for the simulation of temperature field with complex distribution requirements.

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Authors' contributions

All authors made contributions to this work. All authors read and approved the final manuscript.

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Availability of data and materials

All data are available in the present paper.

Competing interests

The authors declare that they have no competing interests.

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Figures

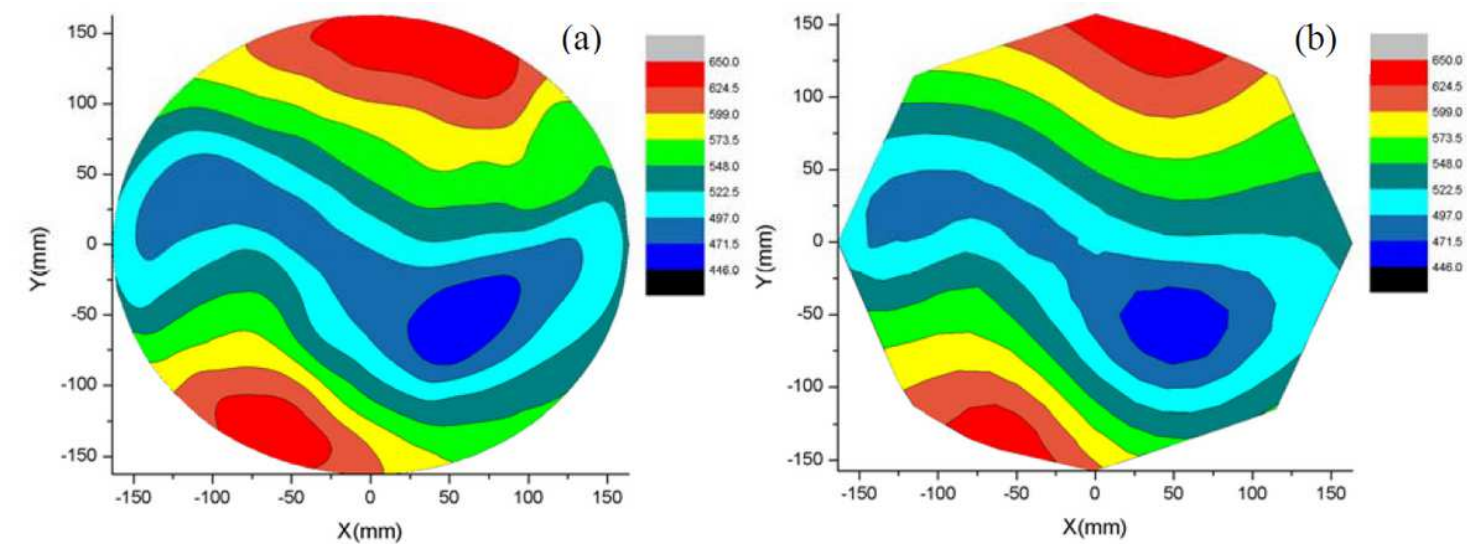


Figure 1

The temperature fields. (a) Whole nodes; (b) key nodes. (Unit: K)

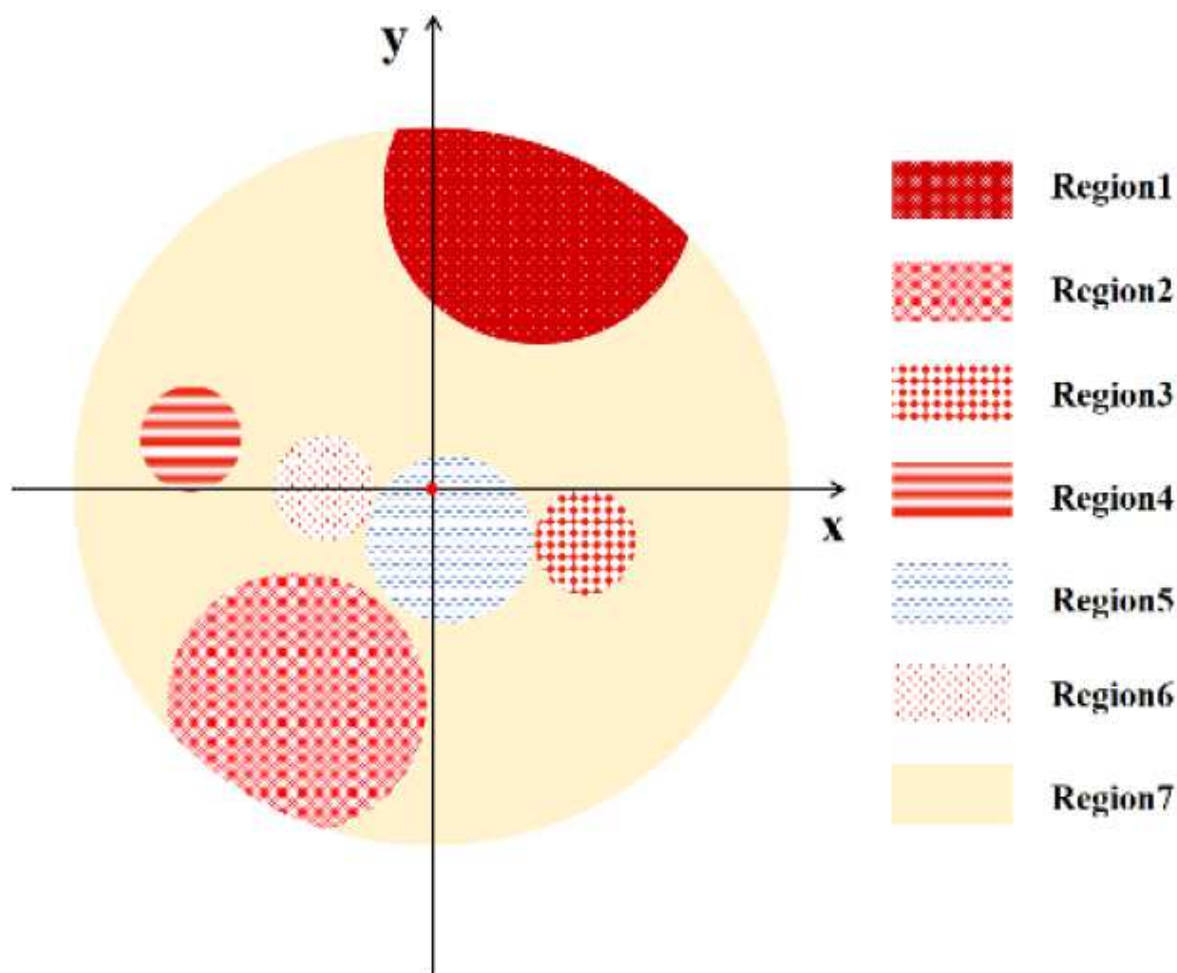


Figure 2

An optimized spatial shaping distribution.

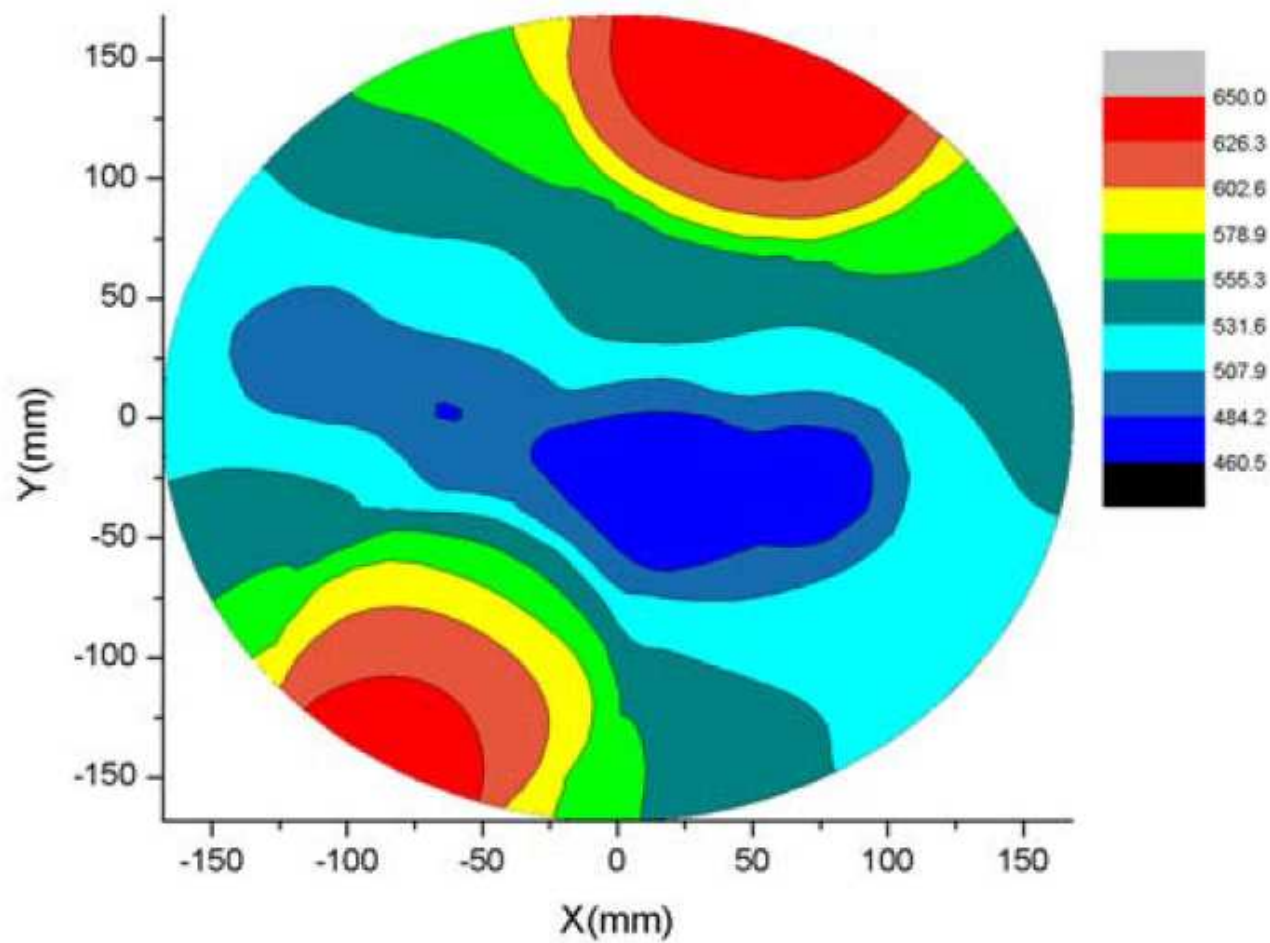


Figure 3

Simulated temperature field by shaped laser.

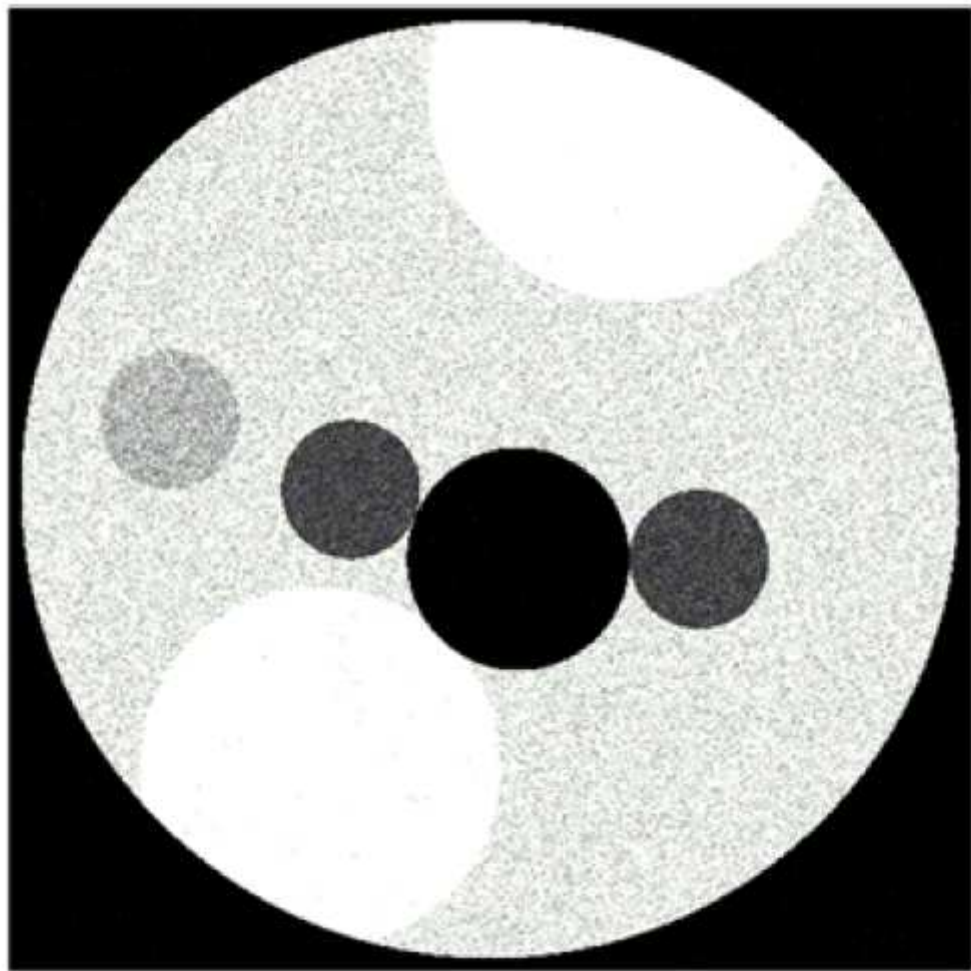


Figure 4

Simulated output shaped laser beam

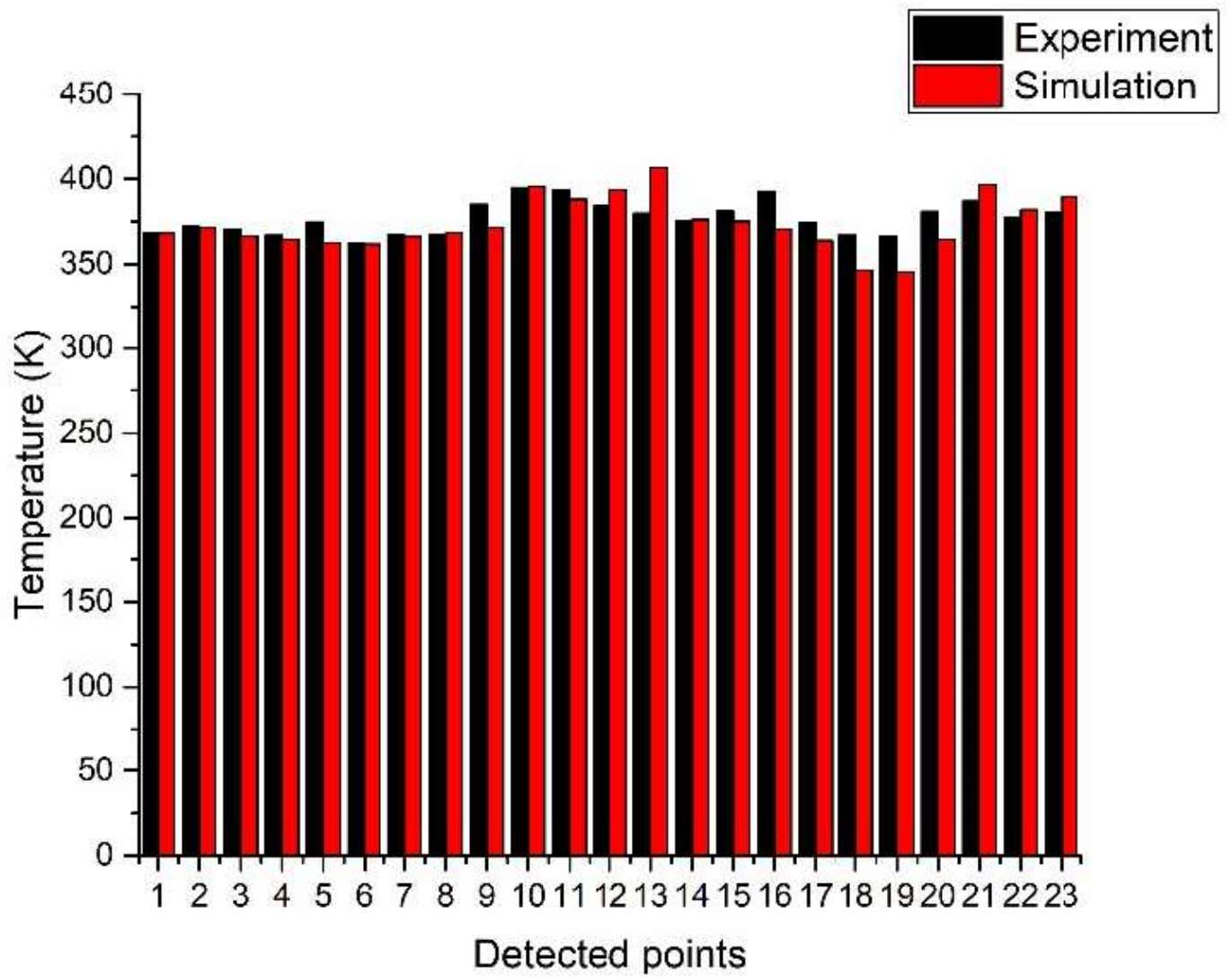


Figure 5

The experimental and simulated temperature results in detected points