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Temperature-uniformity study on transverse flux induction heating applied to rapid PCR

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Abstract. Induction heating has been widely used in industrial and domestic fields due to its rapid heating rate, low power, no pollution and easy control. However, its temperature uniformity isn't good enough to meet the requirements of precise temperature control. The application in the field of nucleic acid amplification instruments (PCR instruments) is basically blank. In response to this situation, a method is provided to improve the temperature uniformity of transverse flux induction heating, which, for the first time, is applied to the study on rapid PCR. The principle of electromagnetic induction heating is analysed, a specific method for calculating the basic parameters of the transverse flux induction coil is introduced, then, different coil structures are designed and analysed by COMSOL Multiphysics according to the determined parameters, simulation analysis and comparison are carried out to obtain an optimal coil structure. The results show that, with other parameters unchanged, the temperature uniformity of the entire heating plane can be up to ±0.5 °C by adjusting the coil structure, which can meet the requirements of precise temperature control, and have a revolutionary impact on the study of rapid PCR.

1. Introduction

PCR (Polymerase Chain Reaction) instrument, as a vital tool in life sciences, plays an important role in many fields such as life science, clinical medicine and precision medicine, food safety, and environmental monitoring [1]. With the continuous development of life sciences and biomedical detection technology and the outbreak of new large-scale infectious diseases (such as H1N1, Ebola, etc.), conventional PCR instruments with long reaction time and high price are unable to meet the requirements, a fast, portable, low cost PCR instrument is urgently needed [2]. At present, the heating methods applied to PCR instrument mainly include peltier heating, water-bath heating and air heating. Peltier heating is currently the most widespread method used in PCR instrument, but due to the limitations of its working principle, it seems impossible to make a breakthrough in heating rate to achieve the standard of rapid PCR. The PCR instrument by water-bath heating requires a large amount of water as a heat source, the temperature gradient is low, and the equipment is cumbersome, it is only used in some large-scale and high-throughput PCR reaction. Air heating can achieve better temperature uniformity and rapid heating rate, making the PCR reaction more efficient, but due to the poor thermal conductivity and specific heat of the air, the larger the sample size is, the more detrimental the air exchange is. Creatively making the transverse flux induction heating technology available for the PCR instrument can make full use of the characteristics of induction heating with low power consumption, such as, fast heating rate, high heating efficiency and satisfactory effect in energy-saving [3], realizing the real rapid PCR.

At present, there are few researches on the application of electromagnetic induction heating to PCR instruments at home and abroad. There is only one PCR instrument based on longitudinal flux induction heating, Mic qPCR cycler, which adopts solenoid coil. According to its manual, 35 PCR cycles can be completed in 25 minutes, which has greatly shortened the PCR reaction time compared to traditional PCR instruments, but considering the extremely fast heating rate of induction heating, there is still a lot of room for improvement in running time of the PCR instrument. What's more, Mic qPCR cycler need make the coil rotate in high speed, which increases the cost. In the present study, most of the research on transverse flux induction heating is related to power modules, strategies on temperature control or flat heating used in industrial heating, which are limited to some certain fields [4]. Some related studies have pointed out that the structural shape of the coil and the distance between the coil and the heating material have a great influence on the heating efficiency, generally, the appropriate coil structure is selected according to the shape and temperature uniformity of the material to be heated [5]. In the case of transverse flux induction heating, distribution of the eddy current on the heating surface is approximately equal to the projection of the coil structure on the surface [6]. The transverse flux induction heating used in this paper is still blank in the development of PCR instrument. It's the biggest difficulty that whether the transverse flux induction heating can achieve the temperature uniformity of the heating block the PCR instrument require.

This paper, composed of the principle analysis, theoretical calculation and simulation optimization of transverse flux induction heating, puts forward a method to design the induction coil which can achieve high temperature uniformity. As a result, the feasibility of applying transverse flux induction heating to the rapid PCR is proved, and a new method for the development of rapid PCR is presented.

2. Principle of induction heating

The theory of induction heating is that high-speed alternating current flowing through a coil generates a high-speed alternating magnetic field getting through a ferromagnetic object nearby, which causes the alternating current (eddy current), making the carriers move randomly in high speed in ferromagnetic object, and collide with each other to generate heat. Transverse flux induction heating is the induction heating that the magnetic flux generated by the coil is perpendicular to the heating surface. Instead of surrounding the heating element, the coil is placed on one or both sides of the heating element, which makes it flexible to place the device, especially suitable for continuous heat treatment and local heating.

When alternating current flows through the coil, an alternating magnetic field is generated around the coil according to Ampere's law, and Equation (1) and (2) is the formula to calculate magnetic flux.

$$\int H \mathrm{d}l = Ni \tag{1}$$

In equation (1), H is the magnetic field intensity, N is the number of coil turns, i symbolizes current.

$$\Phi = \mu HA \tag{2}$$

In equation (2), Φ is the magnetic flux, μ is the magnetic conductivity, A stands for area.

According to Faraday's law of electromagnetic induction, the formula of the instantaneous value e is:

$$e = -N \frac{\mathrm{d}\varphi}{\mathrm{d}t} \tag{3}$$

The eddy current can be calculate by equation (4):

$$I_f = \frac{e}{Z} = \frac{e}{\sqrt{R^2 + X_L^2}} \tag{4}$$

In equation (4), R is the equivalent impedance of the material, X_L is the equivalent reactance of the material. The induced current flow through conductor, converting electric energy to thermal energy, to achieve the aim of heating.

3. Design of the coil

Electromagnetic effect of the induction coil must be considered in designing the coil, which mainly includes skin effect and proximity effect. When alternating current passes through a conductor, the alternating magnetic field generated by alternating current will cause eddy current inside the conductor, resulting in the uneven distribution of current density on the cross section of conductor, the closer to the surface of the conductor, the greater the current density. This phenomenon is called skin effect. With the increase of alternating current frequency, skin effect becomes more obvious. In this paper, the skin effect is weakened by winding the coil with multiple insulated copper wires. Because of skin effect, alternating current reach a certain radial depth starting from the conductor surface, which is called penetration depth. When the wire is round copper:

$$\Delta H = \frac{66.1}{\sqrt{f}} \tag{5}$$

In equation (5), f is the frequency of the current.

When the operating frequency is known, the suitable wire diameter should be chosen according to the principle that the diameter of the wire is less than twice the penetration depth.

The proximity effect refers to the result that two adjacent charged conductors or windings produce alternating magnetic field interacting each other due to different current directions, which affects the change of magnetic flux. The penetration depth will only affect the distribution of eddy current, while proximity effect will change the size of eddy current. Therefore, in the design of induction heating, if it is local heating, the processed object can be placed outside the induction coil to obtain better working characteristics.

To acquire the inductance of the coil, the material of the heating block and the size of temperature variation should be defined first, and then the required working power can be obtained. Then the inductance of the coil can be obtained according to the working voltage and current of the coil. Finally, the number the coil turns can be calculated according to the formula of the inductance of the coil. The formula for calculating the inductance of planar vortex coil is as follows:

$$L = \frac{\mu_0}{8\pi} N^2 d\Psi \tag{6}$$

In the equation (6), μ_0 is the vacuum permeability, N is the number of coil turns, d= $(d_1+d_2)/2$, Ψ is a variable related to $\rho=r/d$, which can be obtained by referring to the table [7].
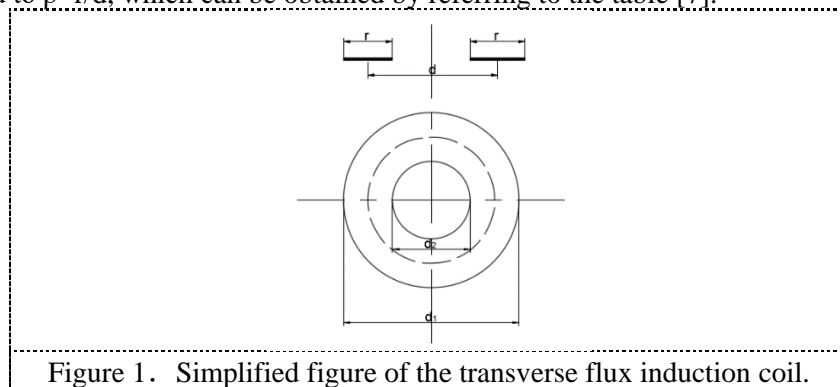

Figure 1．Simplified figure of the transverse flux induction coil.

This paper provides a method for calculating the parameters of transverse flux induction coil. The selection and calculation of the parameters in the process can be determined according to the actual situation.

4. Simulation and optimization

In this paper, the induction heating module in COMSOL Multiphysics is selected to complete the simulation analysis. The basic parameters of induction heating mainly include electromagnetic

excitation, material, and geometric parameters of model. The frequency of 40 KHz is selected in the simulation. When all the parameters are known, the range of heating time is 0.1-2s, the time-dependent temperature of the heating block with different coil structures is analysed and compared. The outer diameter of the coil is slightly larger than that of the heating block. The above parameters (size, gap between coil and heating block and so on) are selected according to the characteristics of rapid PCR.

When the coil is evenly wound that the interval between adjacent coils is the same. The model and simulation results are as follows:

Figure 2. Three-dimensional model of the coil and heating block.

Figure 3. The temperature distribution in the heating surface of the block. The area between O_1 and O_2 is the heating area needing a better temperature uniformity.

Figure 4. The temperature distribution along the radius in the block. Each curve represents a moment, from 0 to 2s.

From figure 3, it can be known that the temperature of the area near centre of the block, with no coil above, is significantly lower than other areas. In addition, it can be concluded that the temperature at the same radius is basically the same, and with the increase of radius, the temperature tends to rise. The isotherm between circular O_1 and circular O_2 is sparse, and the temperature uniformity is much better. According to the characteristics that temperature difference of the whole block is larger and the temperature uniformity is good in some local area, so the area between circular O_1 and circular O_2 is selected as the heating area. Although the temperature homogeneity in the heating area is fine, the temperature difference is still as high as 10 °C when the time is 2s, which does not meet the requirement of temperature uniformity in the PCR reaction. Therefore, it is necessary to improve the coil in order to acquire a satisfactory temperature uniformity.

Continuously adjusting the interval between adjacent coils, analysing and comparing all the methods, an excellent method is obtained. The model and simulation results are as follows:
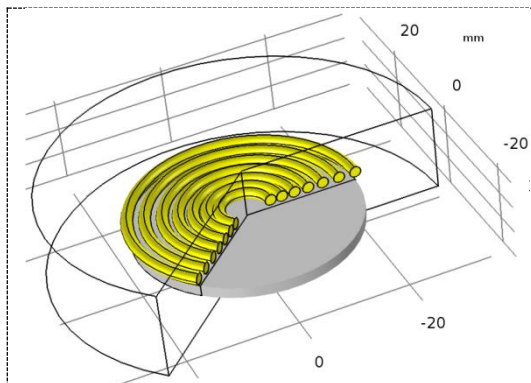
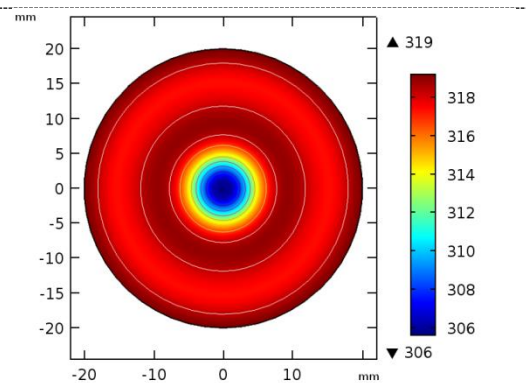Figure 5. Three-dimensional model of the coil and heating block.

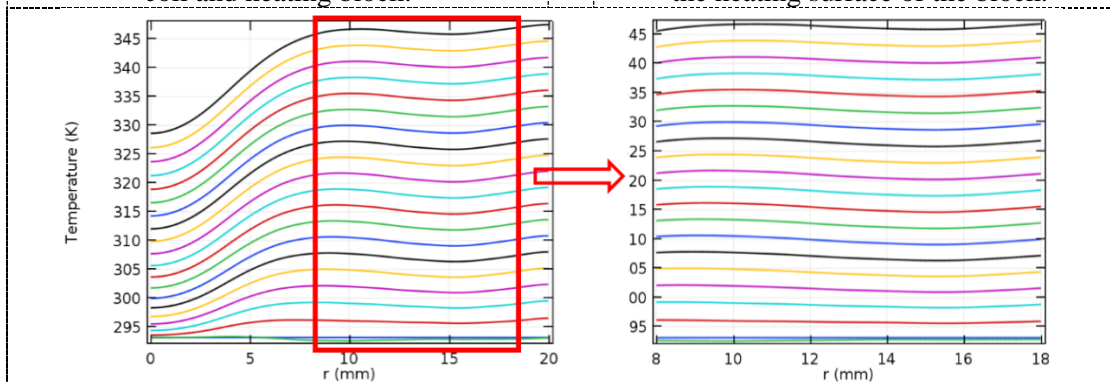Figure 6. The temperature distribution in the heating surface of the block.

Figure 7. The temperature distribution along the radius in the block and the heating area.

From figure 6, the heating area is basically surrounded by two isotherms, which means that the temperature uniformity is fine.

Enlarging the temperature curve of the heating area, it's found that the maximum temperature difference in the heating area is limited to ±0.5℃. The temperature uniformity of the heating area is fine enough to achieve PCR. In addition, figure 7 shows that the heating rate of the block can reach 28℃/s, much faster than conventional PCR. In conclusion, the transverse flux induction heating we provide is quite qualified for rapid PCR with an excellent temperature uniformity.

For comparison, another structure of multi-stranded conductors, of which the section is square, is analysed in this paper.
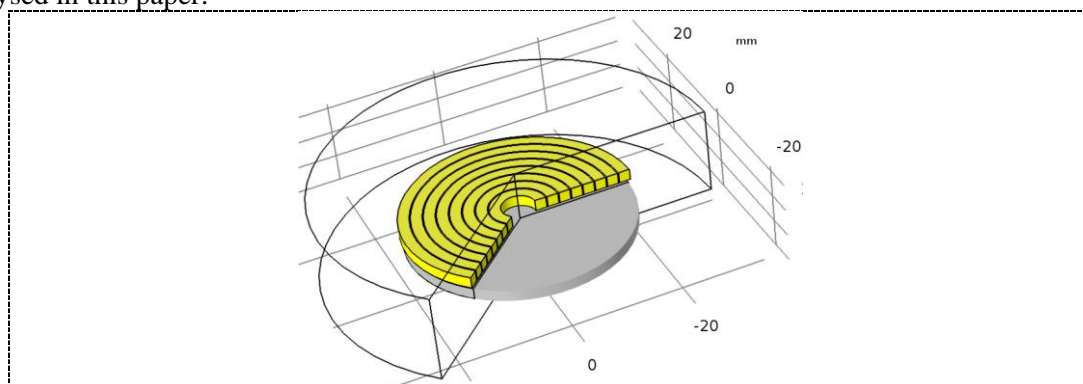

Figure 8. Three-dimensional model of the coil and heating block.

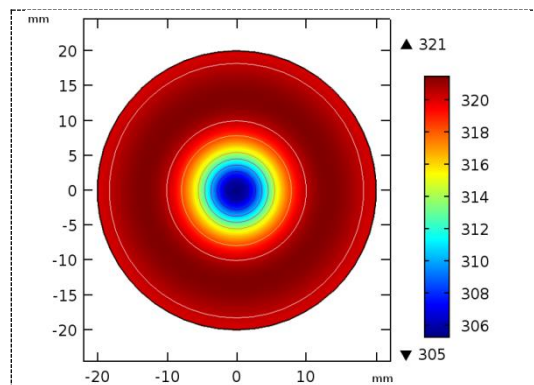When the coil is evenly wound that the interval between adjacent coils is the same：

Figure 9. The temperature distribution in the heating surface of the block.
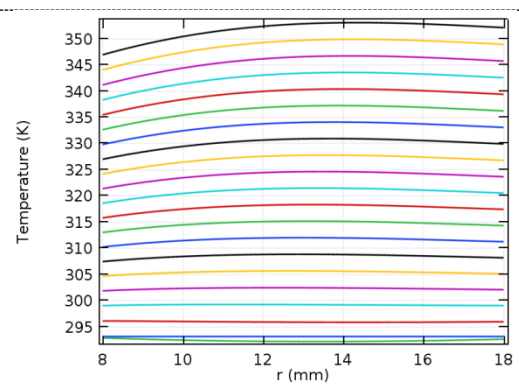

Figure 10. The temperature distribution along the radius in the heating area.
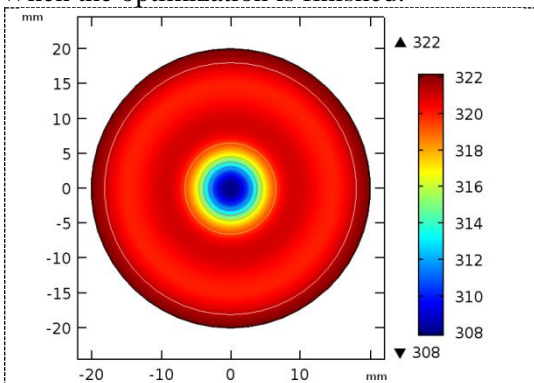
When the optimization is finished:

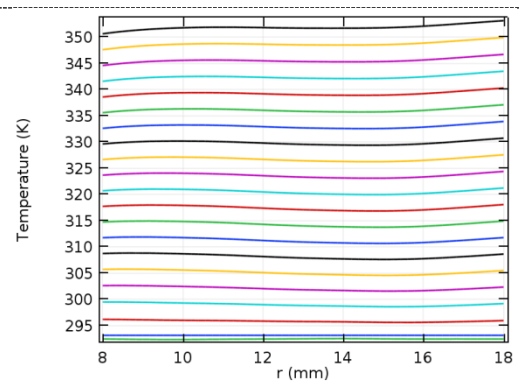Figure 11. The temperature distribution in the heating surface of the block.

Figure 12. The temperature distribution along the radius in the heating area.

After optimization, the temperature uniformity is basically the same as that of the method we provide above, which can also meet the requirements of PCR reaction. However, considering the difficulty of making the square coil, it is difficult to conform to the theoretical model and the cost is high, so this method is not adopted.

5. Conclusions

After comparing and analysing the heating effect of various methods, the best method is the coil which is made up of multi-strand insulated conductors and has a circular section. By this method, applicative temperature uniformity is obtained to achieve rapid PCR. This paper not only proves the feasibility of applying transverse flux induction heating to rapid PCR, but also provides a method to design a coil with satisfactory temperature homogeneity, which is of great significance to the development of rapid PCR and fill the market gap.

Acknowledgments

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