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The design and theoretical analysis of major components of pulse light sterilization equipment

Baiqing Zhang [a*], Bingxin Sun [a], Fengming Ma [b], He Zheng [a]

[a]*Shenyang Agricultural University, Shenyang 110866, China*
[b]*Northeast Forestry University, Haerbin 150040, China*

Abstract

The cold sterilization technique is of great significance for improving food quality and safety. The article comprehensively analyzes the design requirements of pulse light cold sterilization, and determines the major components' design parameter of the sterilization equipment. The equipment could use the pulse xenon lamp as light source, a dual power capacitor pulse circuit, a processing room of circular counter-refacing to gather and seal the light and Single Chip Micyoco to achieve automatic control. The input voltage of the equipment is 800~3000V, the flash duration is 15~20 μs, the lighting frequency and condensation rate can be adjusted, the distance between light and test specimen is 0~120 mm. The design of the equipment facilitates the processing and controlling. The sterilizing tests using pulsed light sterilization equipment show that the equipment design is feasible.

Key words: *pulse light; sterilization; design; analysis*

Introduction

The sterilization technique is an important way for food storage. And developing cold sterilization technique of the pulse light is very significant for the food quality and safety. According to the sterilization technique, the pulse light equipment includes a power unit, an inert gas lamp unit, a processing room and an automatic control unit. The analysis and design of the equipment in this article is based on above units.

* Corresponding author. Tel.: 86-24-88487162; fax: 86-24-88487162.
E-mail address: sybaiqingxl@sina.com

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1. The design principle of the pulse light sterilization equipment

The main function and operation of the whole equipment: under the control of the system, the power unit provides the high voltage pulse energy for the inert gas to generate the pulse light, and the processing room condenses and seals the strong light to achieve the purpose of the sterilization.

The power unit which generates the high voltage pulse provides the energy for the inert gas. The capacitor can be full of the electrical energy in a fraction of a second, and it can release it all in a millionth or thousandth of a second to kill the bacteria. So the inert gas unit can produce the strong light to achieve sterilization. The automatic control unit is used to control the power unit to provide the energy for inert gas lamp accurately. At the same time, it makes the operation of the equipment simple and easy.

Taking the inert gas lamp into account such as the convenience of the purchase, the flash exposure is determined about 20μS. And the input energy is above 800J, but not too high. In the meantime, the size of the lamp should not be too big, or it will add cooling system.

2. The choice of the lamp

2.1. The choice of the lamp

Being used to deal with the test specimen finally, the lamp is the main component for operation. So the whole equipment is designed mainly on the lamp. According to the demands of the pulse light sterilization, the lamp needs to meet the conditions as follow: the strong brightness, the quick flash exposure, and wide application. The pulse xenon lamp has many advantages. It can start quickly and its light spectrum is close to the sunlight and pretty stable. In addition, it can produce the strong light during the very short time and has owned the high brightness, the high efficiency, the simple structure and the wide applicability. And it can be manufactured easily and lighted in the single or repetitive frequency. So we choose the pulse xenon lamp as the light source. Moreover, considering to the convenience of the installment and operation, we also use the tubular pulse xenon lamp. The working voltage (V) namely the breakdown voltage of the lamp is 800~3000V.

2.2. The calculation and selection of the pulse xenon lamp's main parameters

In addiction to the working voltage, the following several main parameters should be paid attention to.

(1) The maximum allowable input energy of the pulse xenon lamp

If the input energy of the pulse xenon lamp exceeds the maximum, it will explode. The value is connected with the structure of the lamp, the pressure of xenon gas, the sealing technology and the discharging duration. For the pure capacitor discharge circuit, the energy is: $E_{\max} = 12ld\sqrt{t}$

E—the energy (J); t—the pulse width (μs); l—the length of arc (cm); d—the inner diameter of the tube.

The maximum allowable input energy could be estimated by the above formula with the given length of the arc l and inner diameter of the tube lamp d. The input energy of the lamp must be less than the 30% of the maximum allowable input energy while working. Otherwise, the lamp will be damaged easily. In this design the input energy is about 20%.

(2)The calculation of the pulse power

The average power of the pulse light is the ratio of the output of every single pulse energy E to the pulse repetition period T; the peak power of the pulse light (P_p) is the power of a single pulse in the duration, i.e. the ratio of the single pulse output energy *E* to the pulse width *r* and it is the maximum of the light pulse output power.

For the rectangular, triangular pulse, the relation of the P and P_p is $\bar{P}/P_p = r/T$. Obviously, when the lamp power is constant, the pulse light intensity is positively correlated with the pulse width. So for the sterilization, the light intensity 10W of the pulse light that the flash exposure is 10s is the same effect as the 1000000W pulse lamp that irradiates 1 μ S. So the pulse light intensity be can changed by changing the pulse width.

(3) The maximum working frequency of the lamp

When the resistor is charging, the charging time constant is RC (it is the pulse width, i.e., the time constant of the capacitor discharge circuit). Generally, the capacitor is full after 3RC (90% full load energy). And the interval of the twice flash time is $t_{charge} = 3RC = 3(V - V_{\min}/I)C$. When $V_{\min} \ll V$, $t_{charge} = 3RC \approx 3VC/I$, and $E = 1/2\,CV^2$, so the maximum flash frequency is

$$f = 1/t_{change} = IV/6E$$

V — the working voltage, I — the working current, C — the capacitance. The formula is applicable for the flash frequency which is not too high.

The effect that the lamp's deionization process on the maximum working frequency of the lamp is not considered in the above discussion. In fact, when the time of the deionization process gets long, the working frequency will get little. The maximum flash frequency formula can only be used when the time of the deionization process is less than 3RC.

2.3. The trigger mode of the pulse lamp

There are two patterns for the trigger mode of the lamp: outer trigger (also called parallel trigger) and inner trigger (also called series trigger). The circuits are shown in figure 1 and 2.

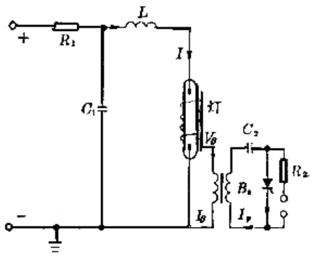

Figure1 outer trigger

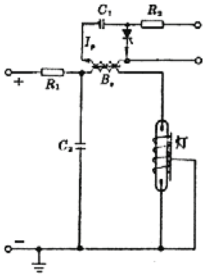

Figure2 inner trigger

When the lamp is lighted, the controlled silicon will receive the trigger signal and conduct the circuit. The capacitor C_2 can discharge through the controlled silicon and the pulse transformer B_3 . The pulse transformer B_3 can trigger the pulse lamp as soon as it accepts the high voltage pulse.

When the outer trigger is used, the ionization zone will be appeared simultaneously in the two electrodes and the electric arc will move from the electrodes to the pipe center. The process is very fast, if the lamp that the inner diameter is 6.3 mm and length is 76 mm, when the arc moves from the both ends to the center, the time it used is less than 25 ns.

The inner trigger's ionization process is faster than the outer trigger's. And the ionization seems to happen simultaneously in every place of the tube. This is because the electric potential of the trigger wire and the electrode is equal and the trigger signal adds from the other electrode. If the same lamp selected as above, the length of the arc from appearing to being fully formed is only 15 nanometers. In addition, inner trigger is more reliable than outer trigger, especially when the working frequency is higher. But the peak of the electric current of the inner trigger's ionization process is very large, and it will be harmful for the lamp's life.

3. The design of the power unit

The power unit provides the energy for the pulse xenon lamp to be lighted and operates as what the design scheme demands. The power unit should produce an electric pulse which lasts 20μS and the energy that is approximate 800J. And the frequency is about once per six seconds. The electric source is the city electricity.

The capacitor adopts discharge circuit for the pulse xenon lamp to supply the energy. The specific plan is as follows:

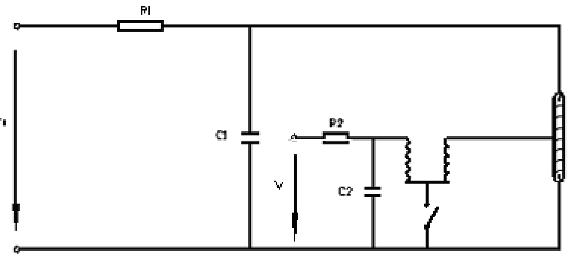

Figure 3 the circuit of producing the pulse light

The circuit of producing the pulse light is shown in figure 3. According to the demand of lighting the pulse xenon lamp, the circuit has to output two voltages: the trigger voltage and the working voltage. So the circuit designed in figure 3 is composed of the main circuit (i.e. working circuit) and the trigger circuit. And it is different from the regular pulse circuit. And the main circuit and the trigger circuit are separate and independent. For the main circuit, the direct current power supply (supply voltage V_0) charges the energy storage capacitor C_1 to be up to working voltage V_C by the charging resistor R. The working voltage V_C is lower than the breakdown voltage V_B and higher than the firing voltage V_Z. For the trigger circuit, a separate direct current power supply is set to charge the energy storage capacitor C_2. The voltage of the capacitor C_2 is magnified dozens of times by high voltage coil. And it can produce trigger voltage large enough to break the lamp down. The trigger wire is around the tube of the pulse lamp. So when the lamp is working, the high pressure in the trigger wire will make the tube generate the spark line. The spark line can reduce the inner resistance of the lamp greatly. And with the help of the spark line, a lot of the energy which the capacitor C_1 has been stored in can discharge in a very short of the time through the pulse lamp. At the same time, the strong intense light will be seen.

3.1. The design of the circuit of the pulse light

The main circuit is shown in figure 4. After the autotransformer, the supply voltage that is 220V should be adjusted for the different voltage to supply the others. And the voltage is up to the desired voltage by the step-up transformer. The bridge rectifier will change the AC to the DC. And the pulse capacitor will be charged after passing the current-limiting resistor. In the meantime, the current passes the both ends of the xenon lamp and produces the trigger signal by the trigger circuit. The instantaneous high voltage which comes from the trigger circuit can make the inert gas in the pulse lamp ionized. The pulse capacitor can discharge to make the pulse lamp produce the intense light. The light will achieve the purpose of the sterilization.

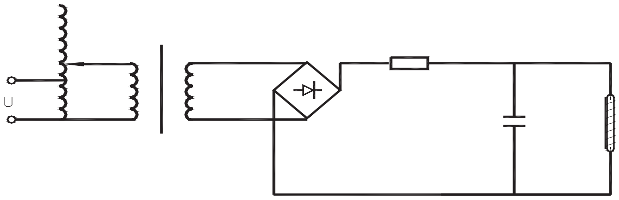

Figure 4 Main circuit

(2)The design of the capacitor discharge circuit

According to the calculation and the data of the pulse xenon which the factory supplies, if the flash duration is 20 μ S that the capacitance should be 10 μf and the working voltage is less than 5000V. The pulse capacitor which is produced by the Shanghai is 10 μf 、20kV in the experiment.

The charge resistor R in the circuit has two functions. First of all, it can limit the charging current which comes from the power supply. So we can increase R to decrease the charging current, that is, we can use the littler power supply to obtain the larger outer of the light. Second, it can prevent the lamp from discharging continuously after the flash. But not all of the charge resistors can do it. If the R is too little and the charge process is too fast, the voltage of the capacitor will have been higher before the lamp tube deionizes and the continuous glow discharge will happen. The design adopts the ceramic resistor that the capacitance is 50 $k\Omega$ and basically, it meets the requirements.

The duration of the flash (the pulse width)

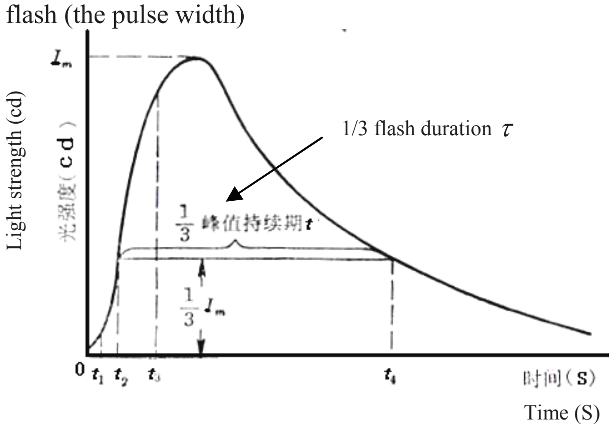

Figure 5 the curve of light strength-time

The typical curve of the pulse light strength changing with the time is shown in figure 5. The I_m is the peak of the light intensity, the t_2 and the t_4 are the time corresponding to 1/3 I_m on the curve. The light intensity of the tail of the curve is very weak，so we take $\tau = t_4 - t_2$ as the effective duration (or flash duration) of the pulse light. The t_1 and t_3 stand for the time corresponding to the points of the 0.1 I_m and 0.9 I_m on the curve respectively. Usually, we define $t_3 - t_1$ as the leading edge of the pulse light. The pulse width namely RC is the time constant of the capacitor discharge circuit, the R is the resistance when the lamp is working. So the pulse width is changing with the capacitance.

In the circuit, both the pulse width and the light flow are variables closely related. The capacitance C is increased with the light flow increase. And it will also lead to the increase of the pulse width. So by controlling the light flow we can control the pulse width. Learning through literature, the pulse width that is 20μS is more common, so in this design 20μS is used.

(3)The trigger circuit

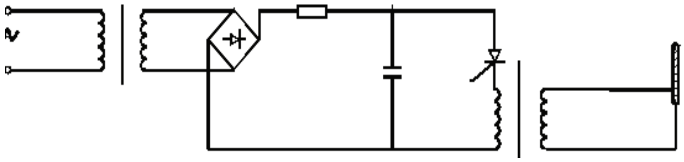

Figure 6 trigger circuit

The figure 6 shows the trigger circuit. After the transformer, the supply voltage that is 220V is enhanced up to 500V. And it passes the bridge rectifier to change into DC. The capacitor will be charged after passing the current-limiting resistor. For control circuit, it can be controlled by the controlled silicon, and the trigger signal can make the controlled silicon connect, the high voltage coil discharges by the capacitor at the primary side, and send the high voltage pulse to the secondary side. When the high voltage reaches 15000V, it can touch the xenon lamp tube wall to help the xenon lamp to achieve the purpose of the sterilization with the main circuit.

There are two methods for the circuit control. One way is that we need to keep the capacitance constant and control the input energy by changing the voltage. So the pulse width can't be changed. In this case, if the pulse width is controlled in a very little rang, we only need a very little capacitance. Another way is that the charge voltage is changed while the input energy is constant. But it must keep a very high value to meet the distribution demand of the spectrum of the lamp.

The trigger circuit is very simple and cheap; the main circuit adopts auto discharge way and is not controlled. The main circuit discharges as the lamp is broken down by the trigger. And the discharge capacitor will discharge automatically until the electricity uses up and the lamp dies out. Because the capacitor voltage effects on the lamp directly, if it is larger than or close to the trigger voltage of the lamp itself, the lamp will be self-flash without the trigger voltage. In that case, it is adverse for the circuit control. With the voltage changing, the time of the capacitor discharge namely the pulse width also changes at the same time. But if the time only changes not bigger than 3μS, it can still be accepted.

When adopting the latter method, we can put additionally an electronic switch (that is IGBT) and a synchronous trigger in the main circuit in the above scheme. Because of the existence of the switch, the lamp and the discharge are separate. When the circuit does not work, there is no voltage for the lamp. In this case, it can avoid the self-flash of the lamp. Within a certain range that the capacitance allows, the pulse width can be changed by controlling the discharge time.

4. The design of the processing room

The processing room plays a role in gathering the light that the lamp emits as soon as possible. It can enhance the intensity (or light strength) of the light exposure upon the test specimen. On the other hand, the processing room can also protect the testers. Because of the high intensity by the pulse light, if the lamp is uncovered in the open air, it will hurt eyes largely, so a sealing processing room to prevent the pulse light from leaking is needed. In addition, there should be also a place to lay the electrical components.

Taken the intermittent sterilization room as an example, it mainly consists of three parts: the reflecting light surface of the lampshade, the specimen support platform, the out shell.

4.1. The reflecting light surface of the lampshade

Considering the demands of the optical focus, there are three kinds of lampshade to choose. They are the cylindrical, the parabolic and the parabolic surface. The cylindrical reflecting light surface is described in the below figure. Its advantages are regular shape, easy manufacturing, higher light utilization rate and light intensity.

As for semicircle cross section, when there is a luminous body (the lamp) in it, there must be a strongest point of focusing light if the luminous body is in the center line of the semicircular inner. See picture below.

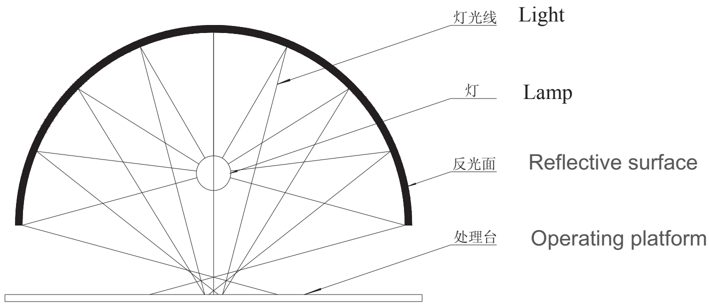

Figure7 surface of cylinder reflecting light

In order to keep the high glossiness of reflecting surface, we can use the stainless steel plate to manufacture the cylinder reflecting light surface. The glossiness of inner surface can be enhanced by polishing, coating, veneering and so on.

The distance between the reflecting light surface and the lamp should be adjustable to adapt the change of the distance between specimen and the lamp.

4.2. The design of the support platform of the specimen

The distance between the specimen and the lamp can be adjusted by controlling the platform up and down. The structure of the support platform should be simple and adjusted easily. At the same time, it must guarantee the effect of sterilization. Moreover, the platform should be smooth and the height of the platform should be adjustable.

4.3. The integral structure of the processing room

The processing room is a cuboid, its length and width should adapt to the size of the lampshade. The volume of the processing room's out shell should be as small as possible. In addition, the mirror can be stick to the inner surface of the processing room to improve the reflecting effects.

Because of the difference of the design concept and level, application environments, the design for major components of pulse light sterilization equipment may be different. Although the design and preliminary analysis above may also have some shortcomings and deficiencies, it can play a certain role in the development of the pulse light technology and equipment.

5. Summary

Experiments show that using the equipment designed as above a remarkable effect of the sterilization is achieved. It can kill 99.9% bacteria, molds and yeasts when the flash time is more than 16. More information will be obtained through the first author's related papers.

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