Lighting cooling device based on thermoacoustic effect

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Abstract. The device is designed based on thermoacoustic effect, through the sound waves to achieve cooling heat dissipation of lighting equipment. The device is arranged on the main heating part of the lighting equipment. External sound waves enter the device through the resonance absorption module, and be integrated into stable acoustic frequency. Based on the thermoacoustic effect, under the effect of sound waves, the stack near one end of the sound waves form the hot end, from one end of the sound waves form the cold end, heat transfer from the hot end of the cold end to constantly. In this process, the lighting equipment heating part of the heat through the device, so as to achieve the purpose of heat dissipation.

1. Introduction
Theatrical performances and stage performances are becoming more and more important parts of people's lives. According to the survey, more than 2,000 theaters have been built and put into use in China, including more than 1,000 professional theaters. Each theater holds more than 46 performances per year on average. With the increase of stage performance, a large number of various lighting devices are used. In order to achieve better performance effects, performance organizers will use various kinds of lights, such as spotlight, soft light, return light, pad light and foot light. These lighting equipment are generally high-power LED, lighting intensity is high. However, the high-power LED lamp will generate huge amount of heat under the high-intensity operation for a long time. If the heat cannot dissipate in time, it will greatly reduce the service life of the lamp itself and even cause safety accidents. On June 27, 2015, a dust explosion occurred in Taiwan's new north amusement park caused by the excessive temperature of the stage lights. A total of 474 tourists were sent to hospital. There are hundreds of such cases every year, ranging from burning objects to causing personal property losses to massive fires and casualties. Therefore, how to realize the stage lighting equipment in a timely manner to cool is a question worth considering.

All kinds of stage lighting equipment sold on the market now mainly use two ways of cooling: active cooling and passive cooling. Active cooling is mainly achieved by setting a PWM fan inside the lighting device. And another kind of cooling method is passive cooling, mainly by changing the appearance of the lamp shell, creating convective air, or sadding aluminum radiator heat conduction out, to achieve the purpose of cooling. In the actual use of these two methods, cooling efficiency is not high. In addition, when the fan dissipates heat, the fan will generate a large noise of cutting wind, which will affect the audience's viewing experience.
This device design based on the thermoacoustic effect, can use sound waves to achieve within the stage of the heat dissipation of stage lighting equipment, while guarantee the efficiency, and reduce energy consumption.

2. Implementation plan
The overall structure of the device is shown in the figure below. The device is composed of resonance sound absorption module, laminated module, heat exchange module and heat dissipation module.

3. Module design

3.1. Resonance sound absorption module
The main function of this module is to absorb and rectify the sound waves from the outside world and convert them into sound waves with stable frequency, which is realized by resonance absorption structure. The module as a whole is a spherical object with holes in the wall, the size of which is much smaller than the wavelength of sound wave, causing the kinetic energy of air vibration to concentrate on the movement of air in the neck of the hole. Eventually, a certain frequency of sound waves passes through the hole and enters the device. The rectified sound waves pass through the resonant tube into the laminated module.
3.2. Laminated module
Lamination is an important part of thermoacoustic refrigeration, which is mainly responsible for the exchange of heat between the hot end and the cold end. Under the action of driving sound pressure, the gas particles in the stack vibrate slightly near their equilibrium position. When the gas in the resonant tube is subjected to the action of sound pressure, adiabatic compression and expansion are generated, the air mass at the hot end of the plate stack is compressed by standing wave, the temperature rises, and heat is released to the plate stack. At the other end of the thermoacoustic plate stack, due to the adiabatic expansion of the standing wave low-pressure phase, the temperature of the air mass is lower than that of the local plate stack. The air mass absorbs heat from the plate stack and forms the cold end. The air mass moves back and forth. In each cycle of the sound wave, the air mass transfers heat from the cold end to the hot end through the plates, maintaining the temperature difference.
3.3. Heat exchange module
The module consists of a heat exchange plate and a cold-end heat exchange, whose function is to exchange heat between the cold end of the device and the main heating part of the lighting equipment. The heat exchange plate contacts the heating end for direct heat exchange, so that the heat from the heating end of the lighting equipment is transferred to the cold end heat exchange of the device. The heat of the cold end heat exchange is transferred to the hot end heat exchange through the circulation of sound wave.

3.4. Heat dissipation module.
The module consists of a hot end heat exchanger and an aluminum heat exchange plate, whose function is to dissipate heat from the hot end. The heat transfer module transfers heat through the stack to the hot end, which requires constant external heat dissipation. First of all, the hot end is surrounded by aluminum alloy wafers, and the heat is transferred to the shell through heat transfer. The shell part
is made of high-thermal plastic with good thermal conductivity, which is convenient to bring the heat to the air, so that the hot end of the resonant tube and the cold end maintain a certain temperature difference, so as to maximize the cooling efficiency.

Figure 5. Heat dissipation module

4. Feasibility analysis
Referring to the application of thermoacoustic refrigeration in theatre LED cooling, the first step is to understand its comprehensive performance parameters, namely:

\[
COP = \frac{Q_{\text{load}}}{W_e}
\]  

(1)

Wherein, \(Q_{\text{load}}\) is the cold end heat exchange payload, and \(W_e\) is the external input electrical work. In this system, \(Q_{\text{load}}\) should be the effective heat taken away by the thermal turbulence caused by sound work. \(W_e\) should be the effective sound power collected by the resonant tube.

Based on this, the comprehensive performance parameters COP can be expressed as:

\[
COP = \eta_{\text{ec}} \eta_{\text{se}} \varepsilon COP_S
\]

(2)

\[
\eta_{\text{ec}} = \frac{W_e}{W_{\text{ec}}}, \eta_{\text{se}} = \frac{W_S}{W_{ac}}, COP_S = \frac{Q_S}{W_S}, \varepsilon = \frac{Q_{\text{load}}}{Q_S}
\]

(3)

Where \(W_e, W_{ac}\) and \(W_S\) are the input electrical power, generated electrical power and effective sound power, and \(Q_S\) and \(Q_{\text{load}}\) are the maximum load and payload of the cold-end heat exchange.

To calculate the temperature and the relationship between sound pressure in resonance tube, the ideal gas state equation.

\[
P = \rho R_t T
\]

(4)

Where \(P, \rho\) and \(T\) are the pressure, density and temperature of the gas respectively, \(R_t = R / M\) and R are the gas constants with molecular weight in grams, 8.314·mol⁻¹·k⁴ and M are the molecular weight of the gas. The change in \(P, \rho,\) and \(T\) is:
\[ \frac{\Delta P}{P_m} = \frac{\Delta \rho}{\rho_m} + \frac{\Delta T}{T_m} \]  

(5)

The numerator is the change, and the denominator is the average. In an adiabatic process, \( \gamma \) is the conduction constant or specific heat ratio. Here is 5.193 J/g·K

\[ \frac{\Delta P}{P_m} = \gamma \frac{\Delta \rho}{\rho_m} \]  

(6)

Cancel out \( \Delta \rho / \rho_m \), you get:

\[ \frac{\Delta T}{T_m} = \frac{\gamma - 1}{\gamma} \frac{\Delta P}{P_m} \]  

(7)

If the sound pressure level is 94dB, with helium gas at 45\(^\circ\) C as the transmission medium, the sound speed can reach 349m/s

\[ c = (331.45 + 0.61t / ^\circ\text{C}) \text{ m/s}^{-1} \]  

(8)

So you get \( \Delta T = 0.3475 ^\circ\text{C} \), which is the temperature that you control just for the sound adiabatic binding of the air mass. The power of cooling from 80\(^\circ\) C per unit gas is 1.67w.

Sound and heat gradients form compressors, and the heat gradients taken away can be represented as follows:

\[ \rho c_p \left( \frac{\partial T}{\partial t} + \mu \frac{\partial T}{\partial x} \right) = \rho c_p \frac{\gamma - 1}{\gamma} T_m \frac{\partial}{\partial \mu} + K \nabla^2 T \]  

(9)

The attenuation coefficient of sound:

\[ \delta_k = 8.6787 \ln x + 6.0016 \]  

(10)

So we get:

\[ T_i = \left( \frac{\gamma - 1}{\gamma} T_m \frac{1}{P_m} - \nabla T \frac{m}{\omega} \mu \right) \left\{ \frac{\cosh \left[ \frac{(1+j)\delta_k}{\delta_k} \right]}{\cosh \left[ \frac{(1+j)\delta_k}{\delta_k} \right]} \right\} \]  

(11)

Two parts provides of 100 w heat produced in the process, nearly 20 w refrigeration efficiency. Considering heat the air cooling heat dissipation efficiency, think every 100 w heat, can supply 15 w heat dissipation effect.
5. Benefit Analysis

Based on thermoacoustic effect, the device USES sound waves to form a stable temperature difference in the device to conduct heat out and achieve zero energy consumption. However, the heat dissipation mode adopted by existing lighting equipment is mainly aluminum substrate, aluminum profile, and electric fan, which has a simple structure. The general power is between 1W and 7W, and the average power is about 5W, with the heat dissipation efficiency between 15% and 25%.

From energy point of view, with a single 4 hours of performance, for example, around 100 lamp that is about all kinds of lights, cooling the amount of electricity used in the traditional fan for:

\[ W = n \times P \times t \]  

(12)

Where, \( n \) represents the number of lighting equipment, \( P \) represents the power of lighting equipment, and \( t \) represents the working time, and \( W = 10 \text{kWh} \) is obtained. While using the device for heat dissipation, the main use of sound energy of the outside world, do not need to use electricity.

From the efficiency point of view, the device's heat dissipation efficiency can reach about 30%, higher than the traditional fan cooling method. It can be seen that this device can save some energy.

6. Conclusion

The device is designed based on thermoacoustic refrigeration technology. Compared with fan cooling and other active cooling methods, the device can achieve zero energy consumption while ensuring cooling efficiency. Compared with using aluminum plate thermal conductivity such passive cooling way, the device can improve the efficiency of heat dissipation. Therefore, this device has a broad application prospect.

This device is designed to solve the heat dissipation problem of lighting equipment, so it can be applied to the high-power lighting equipment of most active stage.

Considering the particularity of the operating conditions of the device, after appropriate modification, it can be applied to the cooling of high-power devices in other noisy places, such as stadiums and construction sites.

References

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