Research on Heat Dissipation Enhancement of Venturi Effect Based on Synthetic Jet Technology

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Abstract. Convection is the main way of cooling and heat dissipation of mechanical devices. Because of its easy realization and high heat efficiency, convection is widely used in various electronic integrated devices or other purely mechanized devices. However, for some occasions with narrow space and high thermal radiation frequency, convective heat dissipation is often difficult to achieve good results. In this paper, the synthetic jet mode of dual mode double cavity resonance is studied, and combined with the Venturi tube, the flow of synthetic jet is supplemented by the Venturi effect to enhance the convection frequency and flow rate. Through the CFD optimization design and experimental verification, the Venturi tube outlet flow can be increased by 16.7%, and it has wide application occasions and good heat dissipation benefits.

1. Introduction

Convective heat dissipation is a heat dissipation method that relies on gas flow for heat exchange, belonging to active heat dissipation. It mainly relies on external energy or devices to generate convective gas, and exchange heat with the target heat dissipation object to achieve heat dissipation. Convective heat dissipation is currently mainly used in electronic component occasion and some mechanical occasion where heat can’t be dissipated by coolant, such as chassis body cooling fans and various types of fans. However, since the active convection heat dissipation energy conversion mode is single, the working duration is longer and the power consumption is higher, and it is not applicable to some occasions requiring a large amount of heat dissipation time. The existing low-power consumption, high-frequency single-membrane single-cavity synthetic jet actuator can generate discontinuous jet flow. The device has the advantages of light weight, small size, and generating fluid vector under the circumstances of less power consumption and no additional gas source supplementation, having a wide range of applications. The Venturi structure, which is widely used for flow expansion, can concentrate and speed up the fluid, and its structure is simple, the coupling of structural parameters is higher, and it is easy to design. However, the relevant design of Venturi to expand the convective heat dissipation fluid for increasing the heat dissipation efficiency has not appeared in the present research. There is still a vacancy in the heat dissipation method combining the Venturi tube and the synthetic jet.

This paper mainly studies the combined structure of the synthetic jet actuator-Venturi tube to supplement and control the discontinuous jet, so that the smaller airflow generated by the actuator can generate large flow and high frequency jet at the exit of the Venturi. The airflow satisfying the convective heat dissipation condition is generated under the circumstances of low power consumption and no additional air source supplementation, and the combined structure of the two is optimized by
means of basic parameter simulation and experimental verification to obtain more comprehensive heat dissipation efficiency analysis data.

2. Calculation model selection

2.1. Airflow Mathematical Model
According to the calculation formula of Reynolds number:

$$Re = \frac{\rho vd}{\mu}$$ (1)

According to the use conditions of the device, $\rho$ is an air density of 1.293 kg/m$^3$, $v$ is 2 m/s, $d$ is an inlet diameter of 60 mm, and $\mu$ is the air viscosity coefficient of 1.81 10$^{-5}$ Pas at 20 °C.

The calculation can obtain the Reynolds number of about 10667>4000, and when the other cross-section values are substituted into the formula, and the Re is greater than 4000. It can be known that the flow of the model is completely turbulent, and the gas type is incompressible, and the influence of molecular viscosity can be neglected. Therefore, the standard model is used for the air flow problem in the venturi. The model is mainly composed of the turbulent kinetic energy differential equation $k$ and the pulsating kinetic energy dissipation rate differential equation $\varepsilon$:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i}[(\sigma_k \beta_k) \frac{\partial k}{\partial x_i}] + \gamma_{t} \frac{\partial u_i}{\partial x_i} \frac{\partial u_i}{\partial x_i} - \rho \varepsilon$$ (2)

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i}[(\sigma_{\varepsilon} \beta_{\varepsilon}) \frac{\partial \varepsilon}{\partial x_i}] + \gamma_{t} \frac{c_p}{k} \eta_{t} \frac{\partial u_i}{\partial x_i} \frac{\partial u_i}{\partial x_i} - c_{\gamma_{t}} \rho \frac{\varepsilon^2}{k}$$ (3)

When using the $k-\varepsilon$ model to solve the turbulence problem, the governing equations include the continuity equation, the momentum equation, the energy equation and the $k, \varepsilon$ equation and $\eta_t$ calculation method, in which the calculation formula of $\eta_t$ is:

$$\eta_t = c_{\mu}^{'} \frac{1}{\varepsilon} = \frac{1}{c_{\mu}^{'} \rho k^2 l} = \frac{c_{\mu}^{'} \rho k^2 l}{c_{\mu}^{'} k^2}$$ (4)

2.2. Venturi tube mathematical model
As the taper increases and the shrinkage ratio decreases, the gas clogging phenomenon is caused, on the contrary it is not suitable for the gas to flow through the throat section, and the throat section diameter should not be less than 18 cm in order to allow the turbulent flow to be blown out around after passing through the throat section. The effect of turbulence on heat dissipation is three times better than laminar flow, so make sure the gas flow in the venturi tube is always turbulent flow, according to the Reynolds number calculation formula:

$$Re = \frac{\rho vd}{\mu}$$ (5)

The value is taken at the throat section, $\rho$ is the air density of 1.293 kg/m$^3$, $v$ is 16 m/s, and $\mu$ is air the viscosity coefficient of 1.81 10$^{-5}$Pas s.at 20 °C. In the case of Re>4000, d is a minimum of 3 mm. The Reynolds number and the outlet diameter are mutually determined by d>18 mm.

The 90% resistance loss in the Venturi tube comes from the divergent tube. Compared with the straight-faced surface type Venturi tube, the pressure field distribution in the outlet curved surface Venturi tube is relatively more uniform, which can reduce the resistance loss of the Venturi tube by more than 40%. At the same time, in order to better match the convective heat transfer of the radiator-fin, the outlet of the venturi is designed as a two-way outlet, and a part of the air is sprayed from the
intermediate outlet to the inner flow passage of the radiator-fin, thereby forcibly convecting the hot air in the flow passage and the outside air, thereby the heat dissipation method in the flow channel is converted from the heat conduction of the air to the heat convection of the air, so that the heat can be carried away by the cold air relatively quickly. Another part of the air is sprayed from the annular outlet to directly act on the radiator-fin wall surface, so that the laminar layer at the radiator fin wall surface is thinned, and the thermal resistance between the wall surface and the convective air is reduced, thereby greatly improving the heat transfer efficiency.

In order to make the maximum area effect of the gas ejected from the annular outlet on the fin, the hyperbola is the curve most suitable for the exit type curved surface type. General formula is:

\[
\frac{y^2}{a^2} - \frac{x^2}{b^2} = 1(a > 0, b > 0)
\]

(6)

3. Simulation

3.1. Numerical simulation of Venturi airflow

In order to analyze the influence of various parameters on the fluid quality in the Venturi, the CFD software (fluent) is used to simulate the air flow in the Venturi flow path, and the air intake is used as the pointing variable to determine an optimized parameter for maximizing the introduction of cold air from the outside for the Venturi.

3.1.1. Optimization algorithm for intake air volume. The contraction ratio of the venturi and the taper of the tapered portion have a large influence on the amount of intake air in the adsorption chamber. Generally speaking, as the taper of the tapered portion increases and the contraction ratio of the throat section decreases, the air flow rate increases. The air flow rate is increased, and the pressure difference for the contact part between the throat section and the tapered portion is increased, so that the gas introduced from the outside of the adsorption chamber is increased. However, as the taper increases and the shrinkage ratio decreases, the pressure loss along the path increases, which in turn affects the flow of gas through the throat section. In order to obtain the optimal design with the maximum intake air volume, the following experiment has been designed for this project.

| level | Contraction ratio | taper/° | Nozzle size/mm |
|-------|------------------|---------|----------------|
| 1     | 20/60            | 50°     | 2              |
| 2     | 25/60            | 60°     | 4              |
| 3     | 30/60            | 70°     | 6              |
| 4     | 35/60            | 80°     | 8              |

Table 1. A slightly more complex table with a narrow caption.

Figure 1. Venturi velocity profile.

Figure 2. Intake increment variation curve graph under different influencing factors.
It selects some representative points from the comprehensive experiment to carry out experiments according to the characteristics of orthogonality, “uniform dispersion and uniform comparability”. It is a high efficiency, fast and economical experimental design approach. The experimental design idea of this project is: after theoretical analysis and reference to the venturi related research to determine the three affecting factors which are the air intake and the contraction ratio of the Venturi, the taper of the tapered portion and the air inlet of the adsorption chamber, These three factors set up four levels of equal horizontal orthogonal experiments, as shown in Table1. Each set of models are to be imported into Fluent for flow field analysis and numerical simulation as shown in Figure 1. The obtained equal horizontal orthogonal experimental data is shown in statistical Figure 2.

What can be seen from the orthogonal test and the result analysis is that when the adsorption chamber nozzle size is 2mm, the shrinkage tube taper is 50°, and the throat section shrinkage ratio is 25/60, the intake air amount reaches the maximum value, as the taper continues to increase or the shrinkage ratio continues to decrease, the amount of intake air exhibits a decreasing trend. Therefore, the shrinkage ratio and the taper are set to 20/56 and 70°.

3.1.2. Optimization design of divergent pipe and outlet. 90% of the resistance loss in the Venturi tube comes from the divergent tube. The curved surface divergent tube is more uniform than the straight type, which can reduce the resistance loss by more than 40%. At the same time, in order to better match the convective heat transfer of the radiator fin, the outlet of the Venturi is designed as a two-way outlet, and a part of the turbulent flow is sprayed from the intermediate outlet to the inner flow passage of the fin, so that the hot air in the flow passage is forcibly convected with the outside air. The heat dissipation efficiency is improved. Another part of the turbulent flow is directly sprayed from the annular outlet with a direct action on the fin wall, which makes the laminar layer at the fin wall surface thinner, reduces the thermal resistance between the wall surface and the convective air, thereby greatly improving the heat transfer efficiency.

Table 2. Comparison of curved surface type and linear type divergent tubes.

| Divergent Tube type | Air output/m³/s   | Outlet velocity/m/s |
|---------------------|-------------------|----------------------|
| Curved surface type | 1.4399932e-09     | 0.56081800           |
| Linear type         | 1.3980139e-09     | 0.41550493           |
4. Venturi tube-heat dissipation mechanism of synthetic jet

The main research content of this work is to study the heat dissipation mechanism of Venturi-synthetic jet with a new type of high-power LED lamp as the matrix. This work proposes an improved design from two aspects: changing fluid state and increasing air intake.

Figure 5. Overall flow chart.

The overall working flow chart of the device is shown in Figure 5. The synthetic jet is used to change the fluid state, and the Venturi is used to increase the gas output. The two work together to increase the convective heat transfer coefficient and accelerate the heat between the fin and the surrounding air. In turn, the junction temperature is lowered. Compared with the conventional device, the device makes the laminar layer boundary thinner, the heat transfer coefficient increases, and the junction temperature decreases, thereby achieving the effect of prolonging the service life of the LED and improving the luminous efficiency.

4.1. Synthetic jet

The synthetic jet actuator was originally designed as a single-membrane, single-cavity structure that utilized only one-sided air change in the vibrating membrane. In order to improve the energy utilization rate and jet flow frequency, this project proposes the double-membrane double-cavity structure design. Under the premise of making full use of the double-sided air change of the vibrating membrane, the double-membrane structure can increase the volume utilization of the gas under the same volume. The jet flow intensity is increased; the double-cavity structure can make full use of the bilateral air change of the vibrating membrane in the same time, so that the turbulent jet frequency is doubled.

Figure 6. Schematic diagram of synthetic jet actuator structure, Schematic diagram of synthetic jet actuator slot

The structure of the double-membrane double-cavity synthetic jet actuator is shown in Figure 6. The internal space of the synthetic jet actuator is divided into inner and outer double cavities by a slot structure, and the green wire frame represents the vibration membrane. A double cavity is formed between the two membranes and between the membrane and the sealed case. The constant voltage circuit is processed by the circuit to form a sine wave, and the coil is energized to generate magnetism, so that the membrane periodically reciprocates.

1) Internal and external double cavity design. The slot is used to block the air circulation, and the portion between the outside of the membrane and the outer casing is closed as an outer cavity to connect with the outer cavity outlet; the inner portion of the membrane forms an inner cavity with another portion of the outer casing, and connects with the inner cavity outlet.
2) Vibration structure design. The coil is fixedly connected to the membrane, and the permanent magnet is fixed to the center casing. Due to the electromagnetic effect, changing the magnitude of the current causes the magnetic field of the coil to change, and generates attraction and repulsion interaction with the permanent magnet, thereby realizing the up and down vibration of the membrane to form turbulent flow.

![Figure 7. Working flow chart of double membrane double cavity synthetic jet](image)

The workflow is shown in Figure 7:
1) The first stage: the coil current is enhanced, and opposites attract with permanent magnet, the upper and lower vibrating membrane are compressed into the inner cavity, the inner cavity exhausts, and the outer cavity inhales;
2) The second stage: the movement of the first stage is continued, the vibrating membrane reaches the bottom end, and the inner cavity reaches the compression limit;
3) The third stage: the coil current is weakened, and the same polarity is repelled by the permanent magnet. The upper and lower vibrating membrane are expanded to the outer cavity, so the inner cavity inhales, and the outer cavity exhausts;
4) The fourth stage: the third stage of the movement continues, the vibrating membrane reaches the top end, the inner cavity reaches the expansion limit, moving in cycles, and the membrane reciprocates, eventually causing the bottom notch to form a synthetic jet nozzle group.

4.2. Venturi tube

The structure of the Venturi tube is shown in Figure 8. The turbulence formed by the synthetic jet enters the Venturi inlet and passes through the throat section with a small cross section (L2 section). As the cross section decreases, the pressure intensity of the turbulent flow increases and the flow rate also increases. A vacuum degree is generated in the adsorption cavity, so that outside air is drawn into the pipeline, and enters the divergent tube (L3 segment) along with the turbulent flow, eventually increasing the flow at the outlet. In the figure, $\alpha$ is the taper of the Venturi, the shrinkage ratio is $d/D$, the nozzle size is $L$, the length of the reducer is $L_1$, the length of the throat segment is $L_2$, and the length of the divergent pipe is $L_3$.

![Figure 8. Venturi tube structure design drawing](image)

According to the throat segment's shrinkage ratio of 25/60, the Venturi inlet diameter is 60mm, the adsorption cavity’s inlet diameter is 2mm and wall thickness is 2mm. It can be determined that the starting end diameter of the divergent pipe's curved surface type is 33 mm. which is shown in the drawing 8.

Since the overall diameter of the Venturi is 100 mm, the diameter of the Venturi outlet is set to 80 mm without affecting the area of the jet action and ensuring that the slope for each point of the curve is as small as possible. The coordinate system is established with the circle center of the beginning end for the divergent pipe as the origin. By substituting the coordinates M(0, 16.5) and N(25, 40) into the general formula, the hyperbolic equation can be obtained as:
Connect M and N points to obtain a straight line with a slope $K$ of 0.9. Make a reference line tangent to the hyperbola and parallel to the MN. The tangent point is taken as K. The slope for the shelf at the middle exit is consistent with the reference line, so that the mutation rate of the gas in the divergent tube is always smaller than that of the linear type divergent tube, so that the pressure loss of the divergent tube can be further reduced. The beginning end points of the intermediate outlet are on the same plumb line with the tangent point. According to the interworking situation of diameter at the intermediate outlet and the fins, the outlet diameter can be obtained as 18cm.

5. Appendices

The development and use of LED and its luminous efficiency are affected by the heat dissipation conditions. A reasonable heat dissipation device can effectively improve the various use parameters of the LED lamp and increase its service life. Based on the existing research, the existing passive heat dissipation methods have certain limitations and low efficiency. The dual-mode dual-cavity synthetic jet actuators proposed in this project have higher jet flow intensity and the space utilization of the heat dissipating fluid compared with the traditional jets. They will have a more significant heat dissipation effect when applied to the luminaire. At the same time, the CFD technology has been used to design and optimize the structure before the experiment, and the optimal solution of the venturi related parameters is to be found when the synthetic jet effect is the strongest generated in the dual-mode double-cavity structure, and the use efficiency of the heat sink is to be improved.

6. References

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