Research on ventilation cooling devices with low-energy consumption characteristics_1

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Abstract

Due to the problem of air conditioning shortage in summer, homeless people and poor residents are threatened by high temperature, a low-energy ventilation cooling device (LEVCD) is designed to prevent heatstroke and improve the living environment. The abandoned plastic bottles, as a core ventilation cooling accessory, were used to construct the LEVCD. The flow and ventilation cooling characteristics of the LEVCD were investigated. The representative image was fabricated to discuss ventilation cooling performance by examining temperature, pressure, and velocity nephograms. The fluid dynamics characteristics, such as the jet action and throttling effect, were analyzed. The temperature drop efficiency index is presented to examine the ventilation cooling characteristics of the LEVCD. The results show that the abandoned plastic bottles were recycled, which can effectively reduce environmental pollution. The ventilation cooling function is mainly induced by jet action. The ventilation cooling effect increases with the increase in inlet airflow velocity. The temperature drop efficiency increase with the increase in ambient temperature.

Keywords: Ventilation cooling; Throttling effect; Jet action; Temperature drop efficiency

1. Introduction

People spend most of their lives indoors, so maintaining the comfort of indoor artificial environment is very important (Akorede et al., 2014). However, the energy shortage and global temperature rise have affected the stable power supply and high electricity price (Olukan et al., 2022). Energy and environmental issues seriously restrict people's demand for life quality, especially in areas with power shortages, high temperatures, and droughts (Kumareswaran et al., 2021). To address the above issues, the new energy-saving ventilation cooling technology is extremely urgent. Natural ventilation is a traditional ventilation cooling method to reduce indoor temperature, and reduce the risk of heatstroke in power shortage areas, but the cooling effect is very limited (Gilvaei et al., 2022). How to adopt the limited electrical energy to improve the living environment is a very meaningful research gap.

1.1. Natural ventilation technology

Natural ventilation and cooling can improve the indoor living environment, the research topic has aroused interest in the scientific community. Yu et al. (2015) designed a novel heating ventilating and air conditioning (HVAC) combined with a natural ventilation device. Subsequently, the radiant heat transfer characteristics of the thermally activated building systems were discussed.. Lee et al. (2017) presented a multipoint measurement method to calibrate the outdoor ambient temperature by using polyvinyl chloride pipe. The natural ventilation was used to evaluate the ventilation cooling of residential buildings, and the improvement of the measurement accuracy was proved. Bady et al. (2011) focused on indoor natural ventilation of high-density urban cubic building surfaces. The four typical building patterns of wind tunnel models in a 1:100 scale was carried out. The wind direction and building configuration induced natural ventilation.

Yin et al. (2016) established a novel airflow distribution mode with square column attached ventilation, and the visualization research was employed in isothermal conditions. Artmann et al. (2010) examined a building design to assess night-time ventilation cooling in different conditions. In low airflow operating condition, the displacement ventilation is much more effective than mixed ventilation. The air jet is significantly affected by high airflow. The studied building design contains the advantages of mixing air and displacement ventilation, and the ventilation cooling has helpful in engineering applications.

1.2. Throttling ventilation cooling technology

A typical throttling process cooling characteristics of buildings can be analyzed by the DeST simulation software. The relationship between exhaust temperature and ventilation time are studied. The pressure, temperature, and velocity will be affected by the typical throttling cooling characteristic. (Yang et al., 2017). Chen et al. (2013) discussed the airflow temperature of impinging jet action. The important influence factors of air circulation were analyzed. The local thermal comfort will be altered by impinging jet action ventilation. Numerical simulation of the throttling ventilation cooling were conducted using the Ansys software by Zhang (2007). The throttling ventilation cooling characteristics were affected by the size and length of the throttle orifice. The throttling ventilation coolingof impinging jet action can be used as a new ventilation-cooling technology. Chen et al., (2012) investigated the influences of diffuser geometric structure on the throttling ventilation cooling characteristics of the indoors. The average temperature and flow field indoors is affected by isothermal turbulence.

1.3. Numerical simulation of ventilation cooling

Numerical calculation is applied as a computer-aided research approach of experimental test and has been popularize by the scientific community. Therefore, the CFD as an important analysis tools is used to evaluate the ventilation cooling characteristics of buildings (Wang 2021; Lam et al., 2021). Zhang et al. (2017) analyzed the thermal environment of the large-span greenhouse. The temperature variation regularity of the greenhouse chamber with natural ventilation was revealed. In summer, Ren et al. (2015) numerically investigated the temperature characteristic of the large-span greenhouse with different ventilation conditions and prediction models. The ventilation cooling characteristics of the greenhouse chamber were discussed. The influencing factors of flow impinging jet action were investigated, and the ventilation cooling influence of the wet curtain fan system is the best. To achieve a comfortable indoor environment, Ji et al. (2019) presented a night ventilation cooling system. The studied system can achieve low-energy consumption based on air jet action, and achieve enhanced convective heat transfer and air recirculation based on high turbulent air.

Chen et al. (2015) numerically analyzed the ventilation characteristic of the office environment with different airflow schemes. The wall confluent jet and impinging jet action of the system can provide a comfortable indoor environment. Chen et al. (2019) numerically tested the effects of outdoor temperature on grain quality by using ventilation cooling. The external thermal environment and configuration of circular wall air ducts can affect the temperature cooling and storage timeof the grain. The ventilation cooling of the communication base station was investigated by Wu et al. (2017), the ventilation cooling system combined with air conditioner cooling and chimney ventilation is designed. The efficient control strategy of intensive air convection is adapted for the purpose of energy-saving. The system with chimney ventilation can reduce 50% energy consumption compared with conventional air conditioners. Although the energy consumption of traditional natural ventilation is low, the cooling effect is not significant.

In summer, the high temperature and power shortage threaten the life safety of poverty-stricken residents. To improve their living environment, and avoid to run a risk of getting heatstroke, a novel low-energy ventilation cooling device (LEVCD) with low operating cost is designed. In a power shortage residential building without air-conditioning, the LEVCD can effectively achieve ventilation cooling effect and reduce the risk of heatstroke. The main assembly of the LEVCD is core ventilation cooling accessory, the abandoned plastic bottles are used instead of core ventilation cooling accessory, which can not only reduce equipment costs but also improve environmental quality. The recycle of the plastic bottles is a kind of wisdom to balance waste management and disposal costs. In this paper, the ventilation cooling characteristics of the LEVCD are investigated, and its feasibility of engineering application is explored.

2. Experimental analysis

The LEVCD is used to achieve the purpose of ventilation cooling. Its working principle is as follows: Due to the sudden change of throat region, the air flows through the core ventilation cooling accessory, the energy can not be exchanged within a short time, the velocity increases, but the pressure and the temperature decrease. The performance studies of the LEVCD is completed by experimental tests, the built experimental chamber is used to replace indoor space, the airflow and temperature characteristics of the studied experimental chamber are analyzed by adjusting the inlet wind velocity, inlet temperature, and the throttling cross-section.

2.1. Experimental apparatus

The experimental system of the LEVCD is mainly composed of an experimental chamber, a ventilation door, cooling fans, and plastic bottles. The experimental chamber is assembled by acrylic plates, its geometric dimension is 1000 × 1000 × 1000mm, and is used to replace indoor space. The ventilation holes are uniformly arranged in the ventilation door, and the hole diameter is slightly larger than the mouth diameter of a plastic bottle. The plastic bottles are designed as the core ventilation cooling accessory of the LEVCD, which are embedded in acrylic plates and achieve the function of ventilation cooling. The plastic bottle is used as a substitute for a convergent nozzle. There are different diameters between the bottom and the mouth of a plastic bottle. The bottom of the plastic bottle is cut off, and the mouth of the plastic bottle keeps its original shape. The diameters of the bottom and the mouth are 64mm and 32mm, respectively. The arrangement of plastic bottles is sorted in 6 rows × 6 columns. The bottle mouths are arranged towards the experimental chamber, and the bottle bottoms are arranged towards the outdoors of the experimental chamber. Considering the stability of experimental tests, the experimental apparatus of the LEVCD is installed indoors.

To simulate the natural wind, nine 24V cooling fans are used to replace the natural wind. The different inlet airflow velocities and temperatures of the experimental chamber are discussed. The experimental chamber is covered with insulating cotton to prevent heat transfer with natural environment and obtain reliable measurement results. The rectifier device is designed in front of the experimental chamber, which is used to make the airflow steadily blow into plastic bottles. The low-energy ventilation cooling device (LEVCD) is displayed in Fig. 1, and the geometrical parameters of the LEVCD apparatus are listed in Table 1.

(a) Experimental chamber. (b) Ventilation door.

Fig. 1. The low-energy ventilation cooling device.

Table 1

Geometrical parameters of the LEVCD.

2.2. Experimental testing

The experimental chamber is regarded as an indoor space. The outside of the experimental chamber is regarded as the natural environment. Because the temperature in the experimental chamber is difficult to reach absolute stability, so the average temperature of the experimental chamber need to be calculated. The five measuring points are selected to calculate the average temperature. The locations of testing points of the experimental chamber are shown in Fig. 2.

Fig. 2. Locations of testing points.

The wind velocities of cooling fans are adjusted by changing the supply voltages. The anemometers are used to measure the wind velocities, the average inlet wind velocity is calculated by the multiple inlet measuring positions. The inlet temperatures are measured at different locations by an infrared thermometer, then the average value of the temperature is determined. The temperature values of the 5 measuring points of the experimental chamber are measured by PT100 high-precision thermometer and recorded every 3 minutes. To improve the measurement accuracy, the above measurement processes should be repeated at least 10 times.

Table 2

The detailed parameters of the testing instruments.

Table 3

The detailed coordinate of measuring points.

The voltage values of cooling fans are adjusted to change the inlet wind velocities, and the corresponding temperature values can be accurately obtained at different inlet wind velocities. The throttling cross-section of the core ventilation cooling accessory is used to assess the change of temperature drop, so the ventilation cooling performance can be accurately analyzed. The detailed parameters of the testing instruments are listed in Table 2, and the specific positions of the measurement points with the experimental chamber are summarized in Table 3.

3. Numerical simulation of low-energy ventilation cooling device

3.1. Geometric structure

The 3D geometric model of the LEVCD is constructed by NX12.0 software. To ensure the simulation conditions and the experimental conditions are identical, the structure parameters of the 3D geometric model are set the same as those of experimental chamber with the ratio 1:1. According to the operational mechanism, the LEVCD is simplified and retained core ventilation cooling accessory. The core ventilation cooling accessory adopts variable cross-section bottles with a bottle mouth diameter of 32mm and a bottle mouth height of 20mm. A rectifier component is designed and placed at the inlet of the core ventilation cooling accessory, which is used to stabilize the wind velocity and simulation results.

3.2. Grid Sensitivity

The grids of the LEVCD are generated by ICEM software, the grid quality will affect the accuracy of the numerical calculation. The discrete grids of the whole computational region use tetrahedral unstructured because of the complex geometry structure of the LEVCD. To support the accuracy of numerical calculation, the grids of core ventilation cooling accessory and adjacent regions are encrypted. The grid programs, such as 0.6×10^6, 2×10^6, 3×10^6, and 4.3×10^6, are examined to estimate grid sensitivity and independence. The grid quantity of the 0.6×10^6 grid program calculates divergence. The grid quantity of the 4.3×10^6 grid program performs optimum, the deviation of temperature drop efficiency of the 2×10^6, 3×10^6, and 4.3×10^6 grid programs are 3.3%, 3.7%, and 3.48%. The calculation accuracy, calculation time, and calculation deviations are comprehensively considered, so the number of the 2×10^6 grid program can meet the requirements of quality accuracy and quantity. The overall grid and local refinement grid of the LEVCD are shown in Fig. 3.

(a) Overall grid (b) Refinement grid.

Fig. 3. The overall grid and refinement grid of the LEVCD.

3.3. Numerical methods

Numerical calculation played a prominent role in analyzing the ventilation cooling of a heating ventilating and air conditioning (HVAC) equipment. The Ansys Fluent 18.2 computational software is employed to analyze the LEVCD system. The Numerical methods and application conditions are as followings: The ideal air is selected as a working fluid. A second-order upwind scheme is recommended to deal with the conservation terms. The standard k–ε turbulence model is adopted to improve the calculation accuracy, because the flow patterns of the core ventilation cooling accessory is a complex turbulence. The QUICK algorithm is used to discretize convective terms. The SIMPLE algorithm is recommend to consider the coupling influences of pressure fields and velocity fields. The calculation boundary conditions and assumptions are set as follows: The velocity inlet boundary and pressure outlet boundary are applied, and the absolute pressure is used. The boundary condition of wall temperature uses adiabatic boundary condition. The indoor pollutant factors are negligible. The heat dissipation and viscous dissipation terms are negligible. The ideal air of the experimental chamber is considered incompressible, and air leakage is negligible. The air flows are fully developed and turbulent and the air is under steady state.

The inlet temperatures of the six testing points are set to be the same and their values are 22.95 °C. The inlet velocity of the point 1, point 2, point 3, point 4, point 5, and point 6 are 2.40m·s^{-1}, 2.60m·s^{-1}, 2.75m·s^{-1}, 2.95m·s^{-1}, 3.05m·s^{-1}, and 3.15m·s^{-1}

respectively. The ambient temperature values of the six testing points are also identical, and their values are 22.95 °C. The main convergence condition of residual result of energy term is less than 10^{-6}, and the remaining convergence conditions of residual results of mass term, momentum term, and other variable terms are less than 10^{-4}.

4. Results discussion

Due to the joule heat generated by the cooling fan, which will affect the accuracy of the measurement temperatures, so the joule heat need to be individually measured. To ensure the accuracy of the temperature measurement, corresponding to the same working conditions of the LEVCD, the joule heat of the cooling fan must be individually tested and deducted.

The temperature drop efficiency η of the LEVCD can be calculated by equation (2).

$$\Delta T = T_0 - T' \tag{1}$$

$$\eta = \frac{\Delta T}{T_0} \times 100 \tag{2}$$

Where T' represents the average temperatureof the experiment chamber excluding the the joule heat of the cooling fan. T_0 represents the initial temperature of the experiment chamber. ΔT represents the temperature drop of the experiment chamber.

4.1. Experimental analysis

The initial temperatures within the experimental chamber are 23.45°C, 22.97°C, and 22.92°C, respectively, which represent the three groups experimental curves, and are shown in Fig. 4. For all the studied schemes, the temperature drop efficiency of the LEVCD increases with increased inlet wind velocity, and the temperature drop efficiency also increases with increasing average temperature of the experimental chamber. Nevertheless, the increment of Exp1 is significantly higher than those of the other two experimental groups, and the increments are from 1.39% to 3.41%. Assuming the indoor temperature exceeds 40°C, we boldly predict that the temperature drop efficiency can reach 10% to 15% with the inlet velocity of 8 m/s.

Fig. 4. The temperature drop efficiency of the LEVCD.

4.2. Numerical simulation analysis

To obtain the mechanisms of flow and ventilation cooling characteristics of the LEVCD, the representative section located at X=530mm is constructed in Fig. 5. The average inlet wind velocity is v_{in}=2.4m/s, the average inlet temperature is T_{in}=22.95 °C (X=530 section). In Fig. 5(a), the local pressure characteristics are depicted, the airflow flows from a high-pressure area to a low-pressure area. For the core ventilation cooling accessory, the pressure suddenly decreases, and the pressure reaches the lowest value. Within the experimental chamber, the pressure slowly extends to the entire space along the airflow direction.

(a) Pressure nephogram

(b) Velocity nephogram

(c) Temperature nephogram.

Fig. 5. Nephogram parameters of the LEVCD.

The velocity nephogram at X=530 section of the LEVCD is shown in Fig. 5(b). The airflow velocity drasticly changes when the air passes through the core ventilation cooling accessory. When the airflow enters the bottom of the core ventilation cooling accessory, the airflow velocity begins to slowly increase. The airflow velocity gradually increases with the decrease of throttling cross-section area. The airflow velocity can reach the maximum value, when the airflow arrives at the outlet of the core ventilation cooling accessory. There are transition regions, which are located between the core ventilation cooling accessory and experimental chamber. In this regions, the airflow velocity changes dramatically. After that, the airflow diffuses throughout the entire experimental chamber and forms a high-speed airflow region.

As shown in Fig. 5(c), the airflow temperature decreases along the direction of the airflow. The airflow temperature drops to a lowest value when flows through the outlet of the core ventilation cooling accessory. The low-temperature region mainly exists in the inlet of the experimental chamber. A comprehensive analysis of airflow temperature and velocity characteristics, there is an obvious ventilation cooling phenomenon caused by the core ventilation cooling accessory. The temperature of airflow is lower than that of the surrounding areas, which is used to explain the ventilation cooling function. The LEVCD can play an important role in the ventilation cooling effect.

In Fig. 5, the local pressure, velocity, and temperature nephograms of the LEVCD are detailed described. The lowest temperature, lowest pressure and highest airflow velocity regions are coupled at the cross-section of the core ventilation cooling accessory, which can be used to explain why the airflow temperature can be decreased. When the high velocity jet action accompanied with low-temperature airflow is jetted into the experimental chamber, the ventilation cooling will be finally achieved.

4.3. Uncertainty analysis

The calculation accuracy of numerical simulation is affected by geometric structure, grid quality, turbulence models, control equations, boundary conditions, assumptions, and so on. The measurement accuracy of experimental test is affected by instrument accuracy, measurement error, and so on. Therefore, it is necessary to analyze the errors between numerical simulation results and experimental measurements.

To verify the reliability of numerical simulation, the representative parameters are selected to simulate and compare. The specific parameters of numerical simulation are set to be the same as those of experimental test,and the initial average temperature of the experimental chamber is T_0=22.95 ℃. The deviation curves between the experimental test and numerical simulation are illustrated in Fig. 6. The trend of simulation results is highly consistent with that of the experimental tests. The maximum deviation and average deviation are 8.78% and 4.03%, respectively. Therefore, the calculation model and methods of the the LEVCD can be proven that the simulation results are reliable and reasonable. The studied results can be used as one of the preliminary analysis to investigate the ventilation cooling characteristics of the LEVCD.

Fig. 6. Uncertainty analysis of temperature drop efficiency

5. Conclusions

(1) A comparative discussion of ventilation cooling characteristics is implemented of the LEVCD. The changing law from the simulation analyses is similar to those from the experimental tests. The average deviation between the numerical results and experimental tests is only 4.03%.

(2) The mechanism of ventilation cooling is depicted. The nephograms characteristics of velocity, pressure, and temperature are described. The ventilation cooling can be reasonably explained by the throttling effect of the core ventilation cooling accessory, where the low-temperature region is mainly concentrated at the inlet regions of the experimental chamber accompanied by high-speed jet action and lowest pressure.

(3) The ventilation cooling characteristics of the LEVCD has a practical engineering application value. The temperature drop efficiency decreases with the decrease in the inlet airflow velocity, but it increases with increasing the ambient temperature of the experimental chamber.

Acknowledgments

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Nomenclature

T	——	The average temperature of the experimental chamber, K
T_0	——	The initial average temperature of the experimental chamber, K
T_{in}	——	Average inlet temperature, K
ΔT	——	Temperature variation, K
v_{in}	——	Average inlet wind velocity of the experimental chamber, $m \cdot s^{-1}$

Greek symbols

η	——	Temperature drop efficiency, %

Abbreviations

HVAC	——	Heating ventilation and air conditioning
LEVCD	——	Low-energy ventilation cooling device
Exp	——	Experiment value
Sim	——	Simulation value

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Figure legends

Fig. 1. The low-energy ventilation cooling device.

Fig. 2. The location of testing points

Fig. 3. The overall and refinement grid of the LEVCD.

Fig. 4. The temperature drop efficiency of the LEVCD.

Fig. 5. Nephogram parameters of the LEVCD.

Fig. 6. Uncertainty analysis of temperature drop efficiency

(a) Experimental chamber. (b) Ventilation door.

Fig. 1. The low-energy ventilation cooling device.

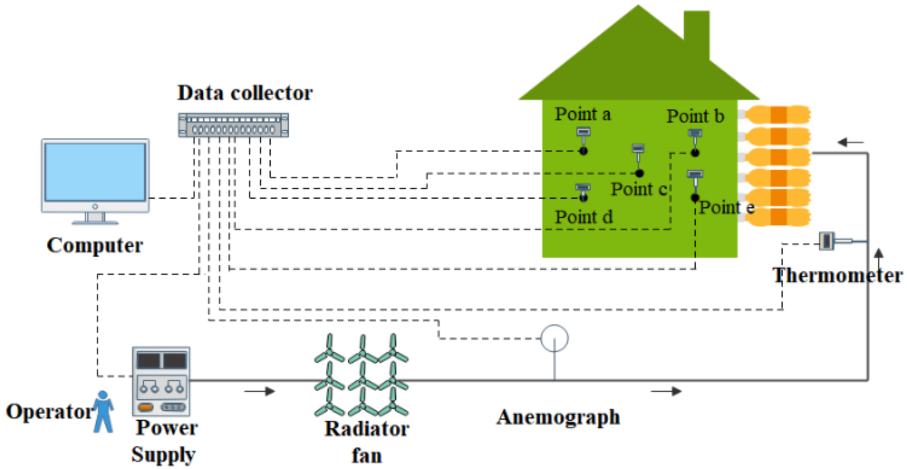
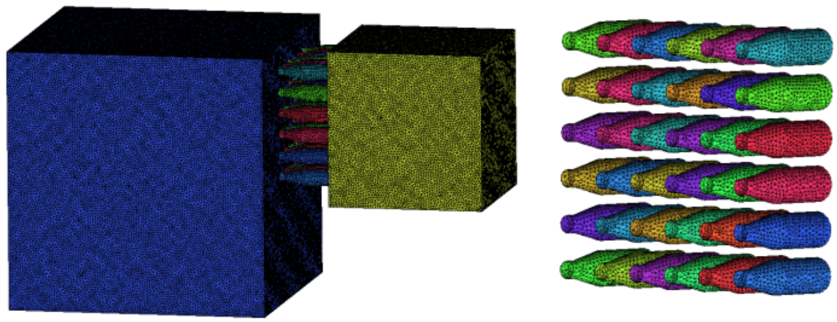


Fig. 2. The location of testing points.



(a) Overall grid (b) Refinement grid.

Fig. 3. The overall grid and refinement grid of the LEVCD.

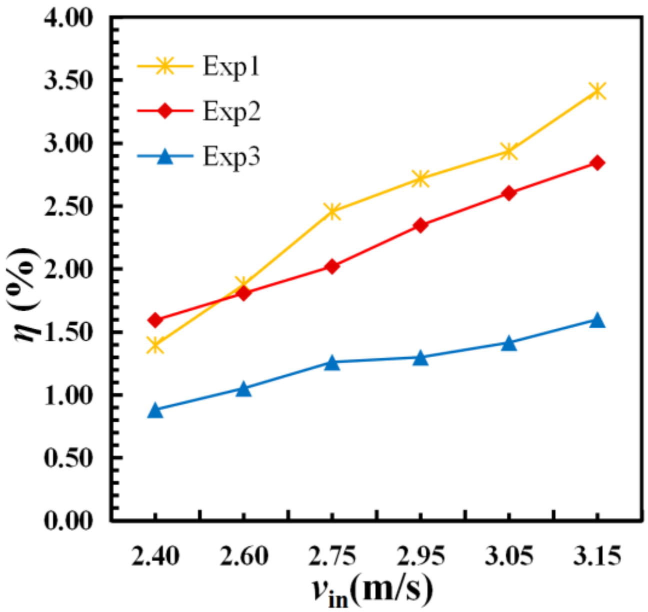
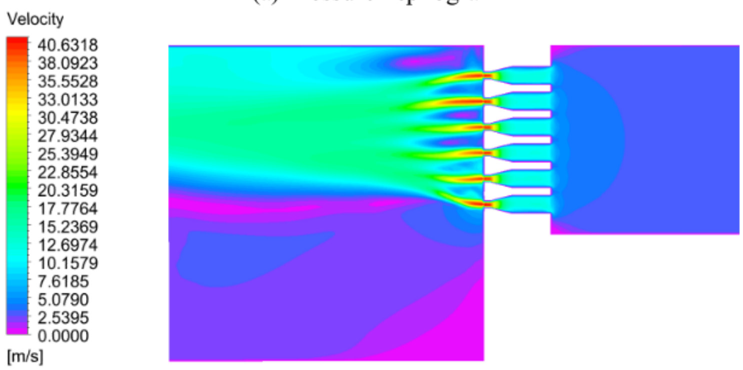
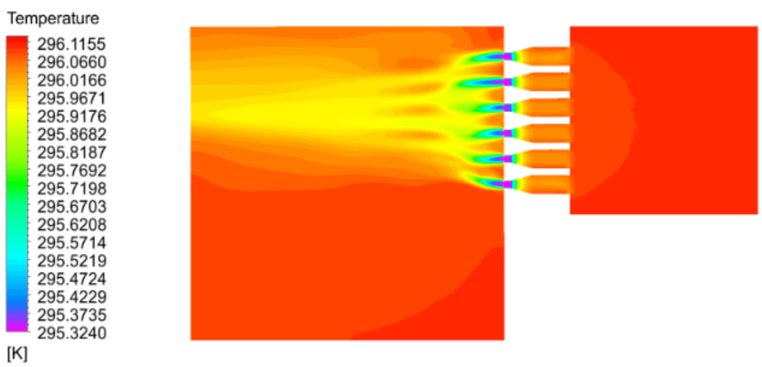


Fig. 4. The temperature drop efficiency of the LEVCD.

(a) Pressure nephogram



(b) Velocity nephogram



(c) Temperature nephogram.

Fig. 5. Nephogram parameters of the LEVCD.

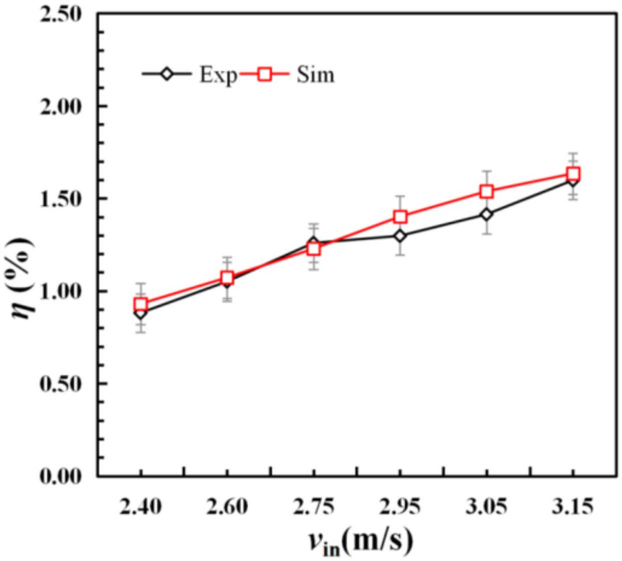


Fig. 6. Uncertainty analysis of temperature drop efficiency.

Table legends

Table 1 Geometrical parameters of the LEVCD.

Table 2 The detailed parameters of the testing instruments.

Table 3 The detailed coordinate of measuring points.

Table 1

Geometrical parameters of the LEVCD.

Item	Unit	Size
Experimental chamber	mm	1000×1000×1000
Ventilation door	mm	300×700
Mouth diameter of core ventilation cooling accessory	mm	32
The bottom diameter of the core ventilation cooling accessory	mm	64
Cooling fan	mm	120×120×25

Table 2

The detailed parameters of the testing instruments.

Item	Unit	Range	Precision	Resolution
Pt100 thermometer 8821	℃	-100~300	±0.15	0.01
Hand held anemometer	m/s	0.40~30.0	±2%	0.01
Infrared thermometer	℃	-50~580	1.5%	0.1
Cooling fan	V	0~24	/	/

Table 3

The detailed coordinate of measuring points.

Item	X / mm	Y / mm	Z / mm
Measuring point 1	465	370	740
Measuring point 2	530	160	720
Measuring point 3	500	500	500
Measuring point 4	460	910	580
Measuring point 5	700	980	580

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