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Designing an Experimental Device for Swinging Excitation Spray Cooling

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Abstract: In this paper, we introduce the design principle of the oscillating excited spray cooling experimental device. We then designed an oscillating excited spray cooling experimental device. By using the device, the swaying motion can be realized through the control system, and the motion of the droplet under different vibration frequencies can be observed. By measuring the liquid flow rate and pressure, the changes in liquid flow rate, pressure, and temperature with time under different vibration frequencies were studied. The trajectory of the droplet and the temperature distribution of the droplet under different vibration frequencies could be observed. The device has a simple structure, is easy to control, and can achieve continuous observation of the spray cooling process.

Keywords: Oscillating excitation spray cooling; Experimental device design

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1. Introduction

In the traditional cooling method, the coolant, in the form of a liquid or gas, forms water droplets by evaporation or condensation on the surface being cooled and takes away heat in the evaporation or condensation process. Therefore, the traditional cooling method is to achieve cooling by spraying water droplets onto the cooled surface, and the cooling process belongs to the heat and mass transfer process. With the development of micro-electro-mechanical systems (MEMS), microelectronics, semiconductors, and various high-tech products, the heat dissipation capacity of electronic components is increasingly required. Spray cooling is an effective heat dissipation method that has been widely used in aerospace, military electronics, power electronics, communications, and microelectronics. Therefore, it is of great significance to study the spray cooling technology [1]. We designed a set of experimental devices for spray cooling based on swing excitation. The device can observe and study the movement of atomized droplets under different vibration frequencies.

2. Experimental equipment

The experimental device is composed of a control system, measurement system, ultrasonic vibration system, cooling system, and swing platform.

2.1. Control system

The experimental device adopts full digital control and uses a single-chip microcomputer to control each device. When the system works, the single-chip microcomputer receives the instructions of the upper computer, controls the ultrasonic generator to generate vibration signals, and drives the high-power LED light tube after processing by amplifying and filtering circuits [2]. At the same time, the single-chip microcomputer can also receive the instructions of the upper computer to control the stepper motor to move the nozzle, so as to observe and study the movement of the spray droplets under different vibration frequencies.

2.2. Measurement system

The device includes three parts: sensor array, data acquisition module, and host computer software. The sensor array is used to measure the movement of spray droplets under different vibration frequencies, and the data acquisition module processes the received data and stores it on the host computer, which can be displayed, measured, and saved in real time through the host computer software. The upper computer software can store and analyze the experimental data and monitor the experimental process in real time.

2.3. Ultrasonic vibration system

The device uses a high-power ultrasonic generator to generate high-frequency oscillating signals, and after circuit processing such as amplification and filtering, drives the LED light tube to illuminate the spray [3]. At the same time, the ultrasonic vibration system can also move the nozzle through the stepping motor.

2.4. Cooling system

The device uses a high-power air-cooled fan to cool the spray. The top of the spray cooling device consists of an intake grille to cool the spray droplets through the airflow.

2.5. Swinging platform

The platform is used to adjust the position of each device, ensuring precise control during operation while also serving as a supplementary measurement system. This experimental device can concurrently execute both the functions of an ultrasonic vibration system and a cooling system [4]. The movement of atomized droplets on the cooling surface under different vibration frequencies can be realized by controlling the moving speed of the rocking platform.

3. Design principles

In chemical production, spray cooling is widely used in the research of high-efficiency heat exchangers, fluid transport in chemical plants, industrial waste heat recovery, and so on. Current research on spray cooling processes mainly focuses on the heat exchange mechanism. However, because spray cooling is a complex heat transfer process, the cooling efficiency is different under different temperature distributions. Therefore, it is necessary to further study the heat exchange mechanism. The heat exchange process involves heat transfer, mass transfer, and other processes, and heat transfer is the key aspect of the whole process [5]. In the heat exchange process, the heat transfer coefficient between the working medium and the coolant is related to the flow rate of the system, the temperature and pressure of the liquid, and the heat transfer coefficient between the liquid and the coolant. During the spray cooling process, heat transfer occurs due to the thermal conduction between the droplets and the environment. When the temperature of the working medium inside the system is lower than the ambient temperature, heat transfer will occur. Therefore, the thermal conduction in the spray cooling system is the main cause of heat loss and heat exchange efficiency reduction. It is particularly important to study the heat conduction phenomenon in the spray cooling process [6]. The experimental device is mainly composed of a rocking excitation system, liquid flow measurement system, liquid pressure measurement system, temperature measurement system, and so on. Among them, the oscillating excitation system is used to simulate the vibration state of the working medium in the process of spray cooling, so that the working medium can vibrate. The liquid flow measurement system is used to measure liquid flow, while the pressure measurement system is used to monitor liquid pressure in real time.

4. Overall structure

The main function of the vibration excitation system is to atomize the liquid medium. During the experiment, the liquid medium is synchronized with the vibration frequency to create a rocking excitation, resulting in the liquid medium oscillating at different frequencies. This oscillation is continuously monitored and controlled by the control system. The experimental device ensures that the vibration frequency remains consistent with the oscillation frequency of the liquid medium, thus enhancing the precision of the vibration excitation while meeting the requirements of the experiment [7]. By measuring the flow rate and pressure of the liquid medium, the change in the motion state of the droplet under different vibration frequencies can be obtained. Through the analysis of the pressure and flow data, the motion states of the droplet under different vibration frequencies were obtained, and the motion laws of the droplet under different vibration frequencies were studied. In order to prevent the liquid medium from being disturbed, an acceleration sensor is introduced. The acceleration sensor offers high sensitivity, a large dynamic range, and strong anti-interference ability, which can eliminate the influence of liquid medium interference on the measurements and realize the continuous measurement of the droplet motion state. The vibration excitation system can be divided into two parts: the vibration control system and the data acquisition system. The vibration control system mainly matches the liquid medium with the vibration frequency, so that the vibration frequency is consistent with the oscillation frequency of the liquid medium, so as to adjust the oscillation speed of the liquid medium [8]. The control system mainly controls the rocking excitation motion and adjusts the vibration frequency according to the experimental needs. The experimental device is simple, easy to control, provides accurate measurements, and allows continuous observation of the droplet motion state. In order to realize the continuous observation of the motion state of the liquid medium, a sensor system that can continuously measure the vibration velocity of the liquid medium is installed on the experimental device. The system is composed of an acceleration sensor, a signal conditioning circuit, a data acquisition card, and a computer.

5. Experimental platform design

The test bench includes a nozzle, a driving device, a measuring device, and a control system (**Figure 1**). The nozzle is installed on top of the test bench, and the nozzle can be moved and tilted to achieve different excitation angles. The drive device generates low-frequency alternating current through the electromagnetic coil, drives the oil pump to produce high-pressure oil, and the pressure value is collected by the pressure sensor [9]. The measuring device mainly includes three parts: signal conditioning, acquisition circuit, and control system. The signal conditioning part mainly amplifies and filters the collected pressure signal. The acquisition circuit is mainly composed of an A/D converter and a control circuit, which converts the vibration frequency into an electrical signal and inputs it into the control system. The control system then adjusts the vibration frequency according to the collected data. The control system is mainly composed of a programmable logic controller (PLC) and a touch screen, which allows the setting of vibration frequency, vibration intensity, flow rate, and other parameters. The PLC allows real-time monitoring of the system, and the touch screen displays the change of each parameter. A glass plate is installed in the middle of the test bench to observe the movement of the droplets. The vibration frequency is adjusted by the control system to make the droplet move at different speeds and reach a stable state [10]. At the same time, different vibration intensities can be set to observe the movement of droplets under different vibration intensities. The driving device can swing up and down, left and right, and front and back through the PLC, so as to achieve different excitation frequencies. The movement of atomized droplets under different vibration frequencies is then observed. The touch screen can be used to monitor the movement state of atomized droplets in real time, and the change of each parameter of the experimental platform can be controlled through the touch screen. When the vibration frequency was 20 Hz, the atomized droplets moved at a high speed. When the vibration frequency was 10 Hz, the atomized droplets moved at a moderate speed. When the vibration frequency was 100 Hz, the atomized droplets moved at a low speed. When the vibration frequency was 500 Hz, the atomized droplets moved at a low speed. When the vibration frequency was 1000 Hz, the atomized droplets moved at a high speed. Therefore, different vibration intensities can be set according to different vibration frequencies.

Figure 1. Physical drawing of the spray cooling system

6. Measurement system design

The experimental device designed in this paper is mainly composed of three parts: a rocking device, a flow-measuring device, and a temperature-measuring device. Among them, the flow measuring device was the YC-B-1 flow measuring instrument purchased from Mettler Toledo, Germany; the temperature controller was purchased from an American company, INTERACTIVE [11]. By adjusting the temperature control switch, the temperature controller controls the flow controller, converts the current signal output by the temperature sensor into an electrical signal, converts it into an optical signal by the photoelectric converter, and converts the optical signal into a digital signal by using A/D converter. Finally, the data is processed by computer. During the experiment, the oscillating device vibrated at a frequency of 6 times per second to change the pressure and flow generated by the liquid flow, and the flow and pressure were measured on the liquid surface. The liquid flow, pressure, and temperature were collected using a data acquisition system. The YC-B-1 flow measuring instrument was used to measure liquid flow, pressure, and temperature with an accuracy of ±5%. The working principle of the YC-B-1 flow meter is that when the liquid flows through the flow meter, the pressure change generated in the liquid flowing through the sensor will cause changes in the output voltage of the sensor, and the voltage will then pass through the voltage converter, and finally convert it into a current signal [12]. After the current signal passes through the A/D converter, the analog-to-digital conversion is performed, and the digital signal is obtained after the conversion. The temperature controller used in this experiment is simple, convenient, and reliable, with a measurement range of -30°C–+125°C. The accuracy is ±2%. The sampling frequency is 10 Hz.

7. Analysis of experimental results

The experimental device was installed in the laboratory and the spray cooling experiment was carried out. The change of surface superheat with the heating power of 500W and the spray height were measured, as shown in **Figure 2**. During the experiment, the fluctuation of heating power led to the instability of liquid flow inside the nozzle and the uneven heat flux in the system, which led to the deviation between experimental data and theoretical data [13]. The main reasons for the deviation of the experimental results are the instability of the thermal fluid and liquid flow and the temperature difference between the hot fluid and the nozzle. The non-uniform heat flux led to temperature variations across the heat transfer surface. In the spray cooling system, fluctuations in heating power resulted in uneven distribution of the hot fluid within the nozzle. Consequently, the temperature of the hot fluid in the system became non-uniform, impacting cooling performance. To ensure the precision of experimental results, it is crucial to maintain a uniform distribution of hot fluid inside the nozzle [14]. Due to the fluctuation of heating power, the liquid flow became unstable. Due to the instability of liquid flow, there was a local high-density area (liquid column) inside the nozzle. These high-density regions increased with the increase of heating power, and the maximum value appeared when the heating power reached a certain value. In this case, the hot fluid in a locally dense region cooled rapidly due to the increase in the height of the liquid column. Due to the uneven heat flux, the superheat in local high-density areas increased rapidly [15]. In this case, a large number of bubbles or droplets formed in the hot fluid, decreasing the efficiency of heat transfer. Lastly, the temperature of the system hot fluid inside the nozzle was lower than the area with low heat flux, but outside the nozzle, it was higher than the area with high heat flux [16]. In this case, the heat transfer efficiency decreased due to the temperature difference between the system's hot fluid and the nozzle.

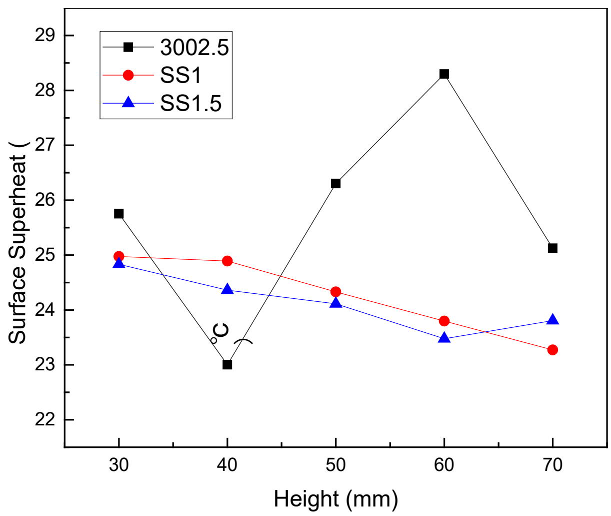

Figure 2. The surface heat transfer coefficient at the heating power of 500W varies with the spray height

8. Conclusion

A rocking excited spray cooling experimental device was designed, which includes a rocking platform, a vibration system, a liquid control system, and so on. The oscillating motion was realized by the control system, and the motion of the droplet under different vibration frequencies was observed. By measuring the liquid flow rate and pressure, the changes in liquid flow rate, pressure, and temperature with time under different vibration frequencies were studied. It is possible to observe the movement track of the droplet and the temperature distribution of the droplet under different vibration frequencies [17]. The experimental device can realize continuous observation of the spray cooling process, observe the movement trajectory of liquid droplets under different vibration frequencies, and find the temperature distribution of liquid mist under different vibration frequencies [18]. The experimental device can realize continuous observation of spray cooling process and is an important tool for spray cooling research. The experimental device is installed in the horizontal pipe. A comparative study between spray cooling in the pipe and cooling in the pipe was carried out to measure the temperature distribution in the pipe [19]. It is found that compared with the spray cooling in the pipe, the air outside the pipe is easier to enter the pipe, resulting in higher pressure in the pipe. Compared with spray cooling outside the tube, the air outside the tube is easier to enter the tube, resulting in lower pressure inside the tube. Under the same conditions, the unit mass flow rate of spray cooling inside the pipe was lower than that of spray cooling outside the pipe. Under the same conditions, the unit mass flow rate and liquid temperature of spray cooling in the pipe were higher than that of spray cooling outside the pipe. The liquid temperature during spray cooling inside the pipe was higher than that during spray cooling outside the pipe [20].

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Disclosure statement

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References

[1] Liu S, Ruan L, Kang Y, 2018, Experimental Research and Numerical Analysis of Atomization Characteristics at Spray Cooling Axis. Science Technology and Engineering, 18(24): 225–229.

[2] Zhou N, Feng H, Xu H, et al. 2021, Experimental Study on Heat Transfer Performance of R134a Closed Spray Cooling. Journal of Refrigeration, 42(03): 152–158.

[3] Chen Z, Cheng Y, Tan H, et al., 2019, Spray Cooling Performance of Spray Rotary Cooler. Iron and Steel, 55(05): 116–123.

[4] Li L, Liu N, Huang Q, 2015, Research Progress of Inclined Spray Cooling. Refrigeration Technology, 35(04): 52–56 + 60.

[5] Wang G, Wang C, Jiang P, et al., 2020, Experimental Study on Low-Pressure Flash Spray Cooling of R134a. Chinese Journal of Engineering Thermophysics, 41(10): 2549–2553.

[6] Liu R, Zhang L, Zhang X, 2018, Application of Spray Cooling Technology in Aerospace Field. Vacuum and Cryogenics, 24(05): 353–357.

[7] Wang R, Chen B, Wang J, et al., 2018, Experimental Study on Transient Spray Cooling and Superheat Effect of

R1234yf. Acta Chemologica Sinica, 69(02): 595–601.
[8] Zhang L, Zhong J, Jiang S, et al., 2018, Design and Research of Spray Cooled Cold Plate. Electronic Mechanical Engineering, 34(01): 23–27. (in Chinese)
[9] Liu S, Ruan L, Li Z, 2018, Research on Influencing Factors of Atomization Characteristics in Spray Cooling System. Cryogenic Engineering, 224(04): 68–74.
[10] Zhou N, Wang Y, Jiang Y, et al., 2016, Experimental Correlation Study of Airborne Spray Cooling Without Boiling Zone. Journal of Aerospace Power, 31(05): 1113–1120.
[11] Wang W, Ren K, Niu J, et al., 2022, Numerical Study on Cooling Characteristics of Dry Ice Spray with Array Nozzle. Cryogenics and Superconductivity, 50(04): 58–64 + 94.
[12] Huang L, Wang S, Wang Y, et al., 2019, Experimental Study on Critical Heat Transfer Characteristics of Spray Cooling. Refrigeration and Air Conditioning, 20(03): 54–59.
[13] Miao Y, 2019, Development of Spray Cooling Experimental Device and Study on Cooling Characteristics of Porous Foam, dissertation, Harbin Institute of Technology.
[14] Du K, 2020, Experimental Research on Pulse Spray Cooling Under Low Pressure, dissertation, Nanjing University of Aeronautics and Astronautics.
[15] Liang Y, Liu N, 2017, Experimental Research Progress of Pulsed Spray Cooling. Electronic Components and Materials, 36(04): 21–26.
[16] Zou T, 2021, Experimental research on the Cooling of Liquid Nitrogen Spray Heat Transfer, dissertation, Harbin Institute of Technology.
[17] Xue R, Ruan Y, Lai H, et al., 2019, Numerical Simulation of Liquid Nitrogen Spray Cooling in Large Space in Low-Temperature Wind Tunnel. Cryogenic Engineering, 227(01): 35–40.
[18] Zhu T, Liu N, Liang Y, et al., 2019, Effect of Dip Angle and Surfactant on Properties of Pulsed Spray Cooling. Chemical Engineering, 49(11): 31–36.
[19] Xin H, Chen B, Zhou Z, 2020, Experimental Study on Influence of Parameters of Heat Transfer Characteristics of Pulsed Spray Cooling. Chinese Journal of Engineering Thermophysics, 41(09): 2220–2224.
[20] Yang C, Zhang H, Liu J, 2019, Experimental Study on Uniformity of Spray Cooling with Open Single Nozzle. High Power Laser and Particle Beams, 32(07): 23–28.