

Article

Experimental Study on Pressure Oscillations of Direct-Contact Condensation between Saturated Steam and Droplets at Sub-Atmospheric Pressure

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Abstract: In this paper, under the background of low-temperature steam waste heat recovery technology, the pressure oscillation characteristics of direct-contact condensation between continuously falling droplets and saturated steam at sub-atmosphere pressure were studied. An experimental device of pressure oscillation based on an acceleration oscillation sensor was established to investigate the influence of vapor pressure and fluid velocity on the oscillation characteristics of direct-contact condensation. The results showed that as the absolute pressure increases, the peak value of oscillation decreases gradually and the time-domain periodic waveform becomes fluctuating. When the liquid flow rate is low, the condensation oscillation shows a single-peak waveform and the dominant frequency moves towards a higher frequency. When the liquid velocity increases gradually, the RMS (root mean square) of pressure oscillation remains unchanged at first and then decreases obviously. The dominant frequency of oscillation decreases from 23.68 Hz to 7.16 Hz continuously, and the amplitude of oscillation decreases in a parabolic pattern. The auto power spectrum showed that the frequencies with higher energy become unconcentrated and show fluctuation characteristics. The amplitude of the dominant frequency is about $0.0004 \text{ (m/s}^2\text{)}^2$, while that of the other peak frequencies is about $0.00010\text{--}0.00015 \text{ (m/s}^2\text{)}^2$. In practical applications, excessive flow velocity and reduced vacuum degree should be avoided to prevent low-frequency vibration, which may lead to fatigue damage or even failure of the equipment due to resonance. In addition, the direct-contact condensation state can be inferred from the vibration signal to reduce environmental noise.

Keywords: pressure oscillation; direct-contact condensation; the auto power spectrum; droplets; saturated steam



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1. Introduction

Industrial waste heat mainly refers to the waste heat, wastewater, waste gas, and other low-grade energy discharged by the thermal energy conversion equipment of industrial enterprises in the production process [1]. Industrial waste heat resources account for about 17% to 67% of the total fuel consumption, of which about 60% can be recycled waste heat resources. Exhaust steam is a typical low-grade waste heat resource in fossil fuel power stations and nuclear power plants. After the use of high-temperature and high-pressure steam in the thermal system, a large amount of low-grade residual steam is generated in various parts at the end of the material and energy cycle [2]. The energy utilization rate of steam thermal power generation is only of about 40%, and most of the lost energy exists in the form of exhaust steam. The recovery and utilization of exhaust steam are of great significance for energy conservation, emission reduction, and improving energy utilization efficiency. A possible solution to reduce the loss of waste heat is the use of cogeneration

(CHP), where low-temperature heat can be used in district heating systems for industrial processes and buildings heating, as well as the use of combined gas–steam cycle (CCGT) power plants. The mixed exhaust steam direct-contact condensation technology uses the atomizing spray device or water jet nozzle to atomize the subcooled water to form droplets, which are in direct contact with the exhaust steam, so that the steam condenses on the surface of the subcooled droplets, thereby absorbing heat and recovering the exhaust steam. This technology has been applied to steam recovery in power plants, rectification and absorption unit operation, ethylene quench cooling, nuclear power plant emergency core cooling, and other fields, with the advantages of high heat transfer efficiency, simple equipment structure, low resistance, no prominent scaling problem, and low cost [3–5].

During direct-contact condensation, the equipment tends to vibrate due to factors such as pressure reduction caused by condensation, fluid flow, and pressure fluctuations caused by gas–liquid two-phase flow turbulence [6]. Oscillation will cause damage to the equipment. On the one hand, when the pressure oscillation frequency is low, the related equipment will have resonance, which may lead to fatigue damage or even failure of the system [7]. On the other hand, in some military fields, oscillation and noise can affect the stealth performance of equipment [8]. Therefore, the study of oscillation characteristics during condensation is of great significance.

At present, the research on the oscillation characteristics of the condensing process mainly focuses on two aspects; one is the direct-contact condensing pressure oscillation of steam immersed in subcooled water, and the other is the oscillation of the tube bundle condenser. When high-temperature and -pressure steam is injected into subcooled water, pressure oscillation is one of the main research directions. To distinguish the regions with different condensation characteristics, many scholars divided the condensation region into several sub-regions and obtained some condensation characteristics of each region [9–13]. In the study of condensation oscillation characteristics, the frequency and waveform of pressure oscillation become important entry points. Kozeki investigated the extent to which the oscillation frequency of condensing pressure is affected by steam flow, water temperature, and air content [14]. Saitoh observed the surge phenomenon at a small steam flow through experiments and studied the instantaneous negative pressure in a tube and the law of water counterflow in a tube [15]. Qingchuan Yang conducted experimental studies on the condensation state and pressure oscillation characteristics of low-mass flow steam jet condensation. The results showed that the average amplitude of pressure oscillation increases at first and decreases with the increase in water temperature. He obtained a dimensionless correlation to predict the Strouhal number for the frequency of pressure oscillations [16]. Wang Keguogang studied the oscillation and oscillation frequency of steam condensation in subcooled water, and the results showed that the condensation oscillation frequency increased with the increase in subcooling degree, and the condensation oscillation was more likely to occur under lower system pressure [17]. Yuelei Cong found that the main frequency of pressure oscillation decreases with the increase in air mass fraction, steam mass flow rate, and subcooled water temperature [18]. Li studied typical flow patterns, temperature oscillations, and pressure oscillations as steam condenses in a T-junction [19]. The results showed that the maximum amplitude of pressure oscillation decreases and the frequency of pressure oscillation increases with the increase in subcooled water temperature [20]. Hong's research showed that the random error of the pressure oscillation frequency can be reduced and the domain frequency can be easily obtained by a fast Fourier transform (FFT) [21]. In addition, the intensity characteristics of condensation oscillation are often characterized by the peak intensity and time-mean intensity of pressure oscillation. Aya and Jie Wang experimentally studied the variation in the peak and time-mean value of oscillation with the water subcooling degree and steam mass flow rate [22,23]. Lo Frano investigated the oscillation caused by steam condensation at sub-atmospheric pressure, showing that the amplitude of the dynamic oscillation (pressure pulse) depends on the steam flow and the temperature of the pool [24]. Qiu investigated the intensity and frequency of pressure oscillations in sonic and supersonic steam jets. They established a

correlation between the dimensionless root mean square (RMS) amplitudes for predicting pressure oscillations and found that the frequency decreases with increasing temperature and vapor mass flux [25].

The elastic tube bundle oscillation induced by the internal fluid is a new research direction for the application of passive enhanced heat transfer technology in the study of tube bundle condenser oscillation. The oscillation of the tube bundle is caused by the transverse flow of the medium through the tube bundle. There are three main causes: Karman vortex excited oscillation, turbulent buffeting, and fluid elastic instability [26]. The analysis of the oscillation response of elastic tube bundles induced by shell flow is of great significance for further research on strengthening the heat transfer mechanism, improving tube bundle structure, and realizing reasonable excitation and effective control of oscillation [27,28]. Jiadong Ji used the sequential solution method based on two-way fluid–structure coupling analysis to study the oscillation response of single and multi-row elastic tube bundles induced by shell flow. The results showed that when the flow velocity of shell flow and pipe flow was constant, the main and harmonic frequencies of oscillation in each direction of the monitoring point of the elastic tube bundle were the same, and the oscillation was mainly manifested as in-plane oscillation [29].

In summary, in the mixed direct-contact condensation process of exhaust steam, there is not sufficient work on the pressure oscillation characteristics of condensation between moving droplets and steam, nor on the oscillation response caused by the two-phase flow of droplets and steam. Therefore, this article establishes a pressure oscillation experimental device based on an acceleration oscillation sensor for the direct-contact condensation process between continuously falling droplets and saturated steam at sub-atmospheric pressure, and studies the effects of droplet flow rate and operating pressure on the oscillation characteristics. The results of this study can provide a certain basis for the investigation of the condensation oscillation mechanism of direct contact between steam and moving liquid droplets, and provide new references for the design and operation of direct-contact heat exchangers.

2. Experimental Apparatus and Procedure

The droplet–steam direct-contact condensation system mainly consists of the direct-contact condenser, steam and droplet generation system, and oscillation data acquisition system. The schematic diagram of the experimental setup is shown in Figure 1.

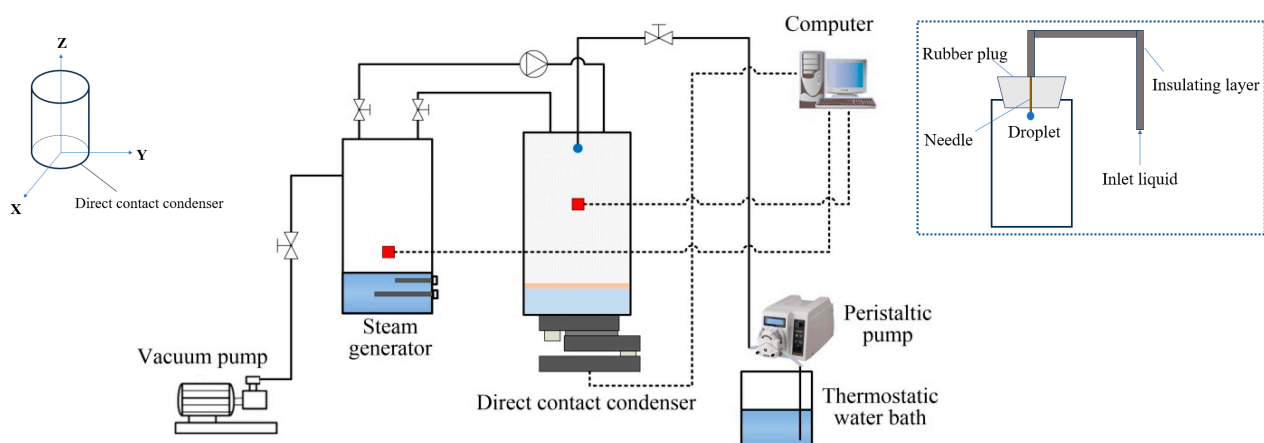


Figure 1. Scheme of experimental apparatus.

The direct-contact condenser is a cylindrical vacuum container, in which steam and liquid droplets are in direct contact, mass transfer of the gas phase from the high-pressure to the low-pressure phase occurs, and the gas phase condenses on the liquid surface. Saturated steam is provided by the steam-generating device. First, the non-condensable gas in the whole experimental device is drained with a vacuum pump, and the vacuum degree is up

to 0.099 MPa. Then, the deionized water is heated by a heating rod to generate saturated steam under the corresponding vacuum degree. The pressure of the steam is precisely controlled by a thermal resistor ($\pm 0.15\text{ }^{\circ}\text{C}$, 0.2% FS, Pt100, Omega Co., Ltd., Norwalk, CT, USA) and temperature controller (AI-508A, UDIAN Co., Ltd., Zhejiang, China). When the steam is in a steady state, it is pumped into the condenser and continuously circulates at a low speed. Needles of different sizes are installed at the inlet to allow the fluid to enter the steam environment in the form of droplets. The temperature and velocity of the droplets are controlled by the thermostatic water tank (DC-2006, Ningbo Scientz Biotechnology Co., Ltd., Zhejiang, China) and the high-precision peristaltic pump (LabN1, Shenchen Pump Co., Ltd., Shanghai, China). The range and uncertainty of each parameter are shown in Table 1.

Table 1. Experimental parameters.

Parameter	Parameter Symbol	Value	Error
Pressure, kPa	P	14–21	$\pm 0.2\%$
Inlet mass flow rate, mL/min	V	20.067/30.054/35.047/40.040/45.034	$\pm 0.1\%$
Droplet temperature, $^{\circ}\text{C}$	T_i	25	$\pm 0.05\%$
Oscillation amplitude, m/s^2	A		$\pm 5\%$

The oscillation data acquisition system is composed of the acceleration sensor, data acquisition equipment (LMS SCADAS, Siemens PLM, Plano, TX, USA), analysis software (Simcenter SCADAS Mobile and Simcenter LMS Test. Lab, version number: 2021.1), and computer. The red dots in the figure are pressure measurements. The resolution of the IEPE piezoelectric accelerometer is 0.0005 g, the sampling rate is 5120 Hz, and the sampling time is 1786 s. It must be ensured that the IEPE piezoelectric accelerometer, data acquisition equipment, and cables are in normal working condition and connected to a DC power supply. At the beginning of the heat transfer process, the data acquisition equipment was started to import the data into the analysis software (Simcenter.TestLab.2021.1).

The duration of a single experiment is approximately 30 min, starting from 0% to 100% of the material mass percentage in the direct-contact condenser. To evaluate the reliability and accuracy of the experimental results, the experiment was repeated three times under the same operating conditions. The pressure oscillation peak, first main frequency, and the RMS value had a good reproducibility, and the maximum difference in the experimental results did not exceed 30%. We carried out two experiments for $P = 14\text{ kPa}$ and $V = 20.067\text{ mL/min}$, and the results are shown in Figure 2.

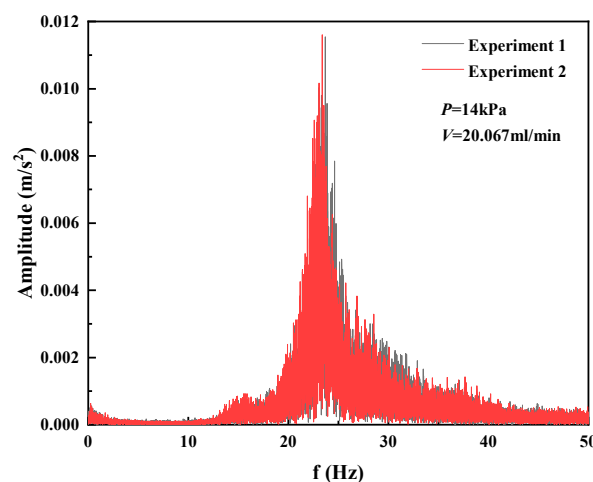


Figure 2. The reproducibility of the experiment.

3. Results and Discussion

3.1. The RMS of the Pressure Oscillation

The strength and energy of the oscillation signal of the direct-contact condenser in X, Y, and Z directions are measured and calculated by the root mean square (RMS) of the pressure oscillation:

$$X_{rms} = \sqrt{\frac{1}{n} \sum_{i=1}^n x^2(t_i)} = \sqrt{\frac{x_1^2 + x_2^2 + \cdots + x_n^2}{n}} \quad (1)$$

where X_{rms} is the RMS value; and $x(t_i)$ is the original sequence.

The RMS of the pressure oscillation along the X-Y-Z axis of the direct-contact condenser under different inlet water mass flow rates and pressures is shown in Tables 2 and 3, respectively. It can be seen that the RMS value of the pressure oscillation in the Z-direction is generally larger under different working conditions, indicating that the condenser has the maximum energy in the Z-direction. The maximum RMS value reaches 0.08 m/s^2 . Considering that the failure of the direct-contact condenser is often determined by the maximum oscillation condition, the Z-direction is selected as the main direction for data analysis and research.

Table 2. The RMS of the pressure oscillation along the X-Y-Z axis (m/s^2) under different inlet mass flow rates.

	<i>V</i> , mL/min				
	20.067	30.054	35.047	40.040	45.034
X	0.05	0.04	0.03	0.03	0.04
Y	0.02	0.04	0.02	0.02	0.02
Z	0.08	0.08	0.06	0.05	0.04

Table 3. The RMS of the pressure oscillation along the X-Y-Z axis (m/s^2) under different pressures.

	<i>P</i> , kPa				
	14	16	19	20	21
X	0.05	0.05	0.04	0.04	0.03
Y	0.02	0.03	0.03	0.02	0.02
Z	0.08	0.06	0.05	0.04	0.04

3.2. The Time-Domain Characteristics of the Pressure Oscillation

When droplets enter the condenser, transient condensation occurs at the gas–liquid interface with continuously circulating negative pressure steam and gradually reaches dynamic equilibrium. The unstable interface causes condensation oscillation in the flow field. The interface behavior varies under different condensation states, resulting in different condensation oscillations. To study the pressure oscillation characteristics under different states, the oscillation waveform under condensation conditions was analyzed at an inlet flow rate of 20.067 mL/min and an absolute pressure of 14 kPa .

The oscillation signal of steam and liquid droplets during the direct-contact condensation process is shown in Figure 3. Figure 3a shows the general waveform of condensation oscillation throughout the entire process, and Figure 3b shows the oscillation waveform in a short period. It can be seen that when transient condensation occurs, the peak pressure oscillation exhibits pulsating fluctuations.

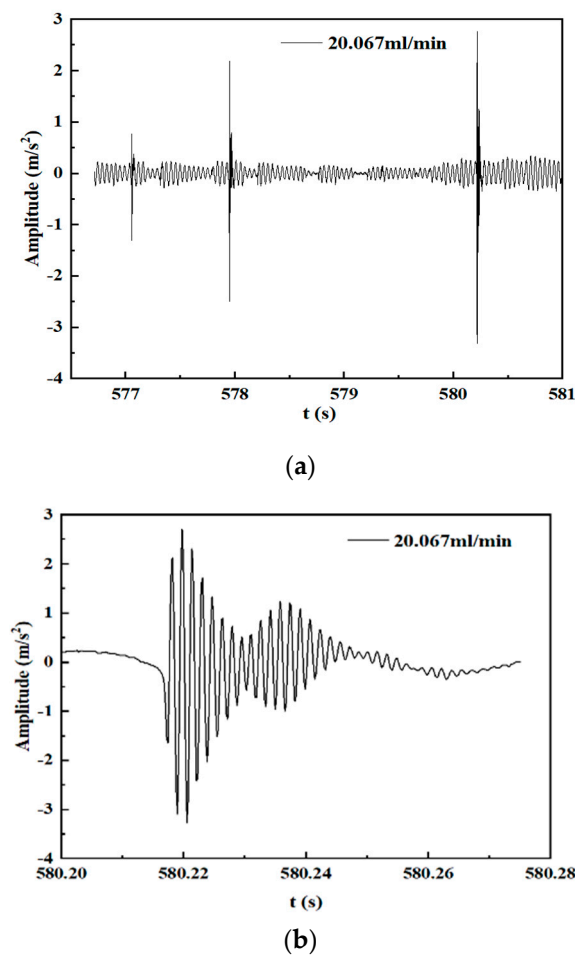


Figure 3. Oscillation signal over a longer time range (a) and a short period (b).

To further investigate the pressure oscillation characteristics of direct-contact condensation over time, a time-domain analysis method was adopted to analyze the oscillation signals of the material mass percentage inside the container from 25% to 30% during the condensation process, which is shown in Figure 4. It can be seen that as the absolute pressure increases from 14 kPa to 21 kPa, the peak value of the time-domain oscillation signal gradually decreases. When the absolute pressure is 14 kPa, the peak value is 2.73 m/s², while when the absolute pressure is 19 kPa, the peak value decreases to 1.43 m/s². When the absolute pressure continues to increase to 20 kPa, the oscillation signal no longer shows significant peak changes in the time domain, and the high-energy oscillations in the condensation process disappear. One reason for this phenomenon is that as the absolute pressure increases, the inlet flow rate and droplet diameter slightly increase, especially for small-diameter droplets. The increase in droplet volume relative to the heat transfer surface of droplets is greater, and the thermal equilibrium process of droplets from the outside to the inside will slow down, resulting in a decrease in condensation efficiency [30]. On the other hand, as the pressure increases, the dew point of the steam increases, the heat transfer driving force decreases, and the heat and mass transfer resistance increases, which leads to the lowest condensation rate of the steam after the rapid condensation stage. At the same time, under vacuum conditions, the steam density decreases and the steam velocity increases, resulting in a decrease in heat and mass transfer resistance between the two gas–liquid phases [31]. Therefore, the direct-contact condensation efficiency increases with the increase in vacuum degree, and condensation pulse oscillation is more likely to occur.

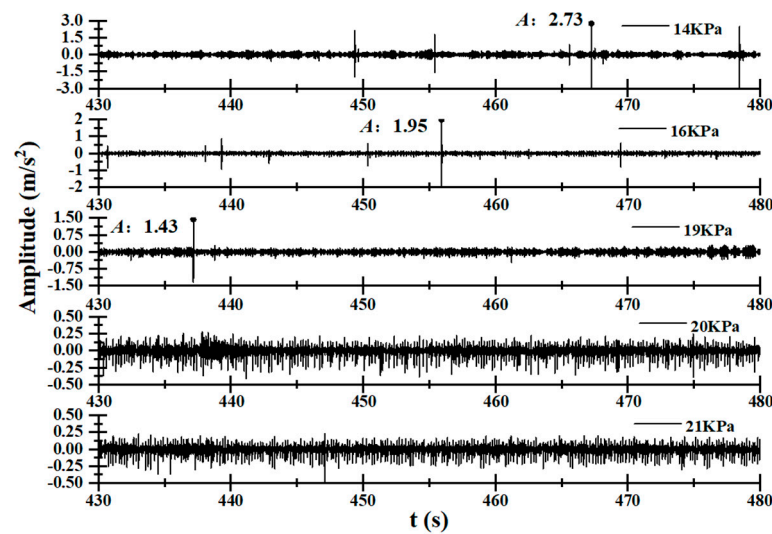


Figure 4. Oscillation signal in the time domain at different absolute pressures.

To study the oscillation characteristics of the direct-contact condensation process under different inlet flow rates, the time-domain analysis method was also adopted to analyze the oscillation signals of the material mass percentage inside the container from 53% to 56% during the condensation process, which is shown in Figure 5. It can be seen that when the absolute pressure is 14 kPa, the peak of the condensation oscillation signal mainly occurs at low mass flow rates. As the flow rate continues to increase, there is no significant peak change, and the amplitude of the peak gradually decreases. This is because, at low mass flow rates, the optimal condensation distance decreases as the liquid mass flow rate increases [30]. As the flow rate of the liquid phase continues to increase, the optimal condensation distance increases. The droplets are stretched into short liquid columns at the outlet, reducing the contact area between low-pressure saturated steam and fresh condensate liquid surface in direct contact with the condensation container, resulting in a significant decrease in the heat transfer efficiency of the steam. Therefore, at low mass flow rates, the condensation efficiency is higher and the oscillation signal is stronger. In addition, an increase in the liquid flow rate will enhance the energy consumption of the system, resulting in a decrease in the total energy of the oscillation system.

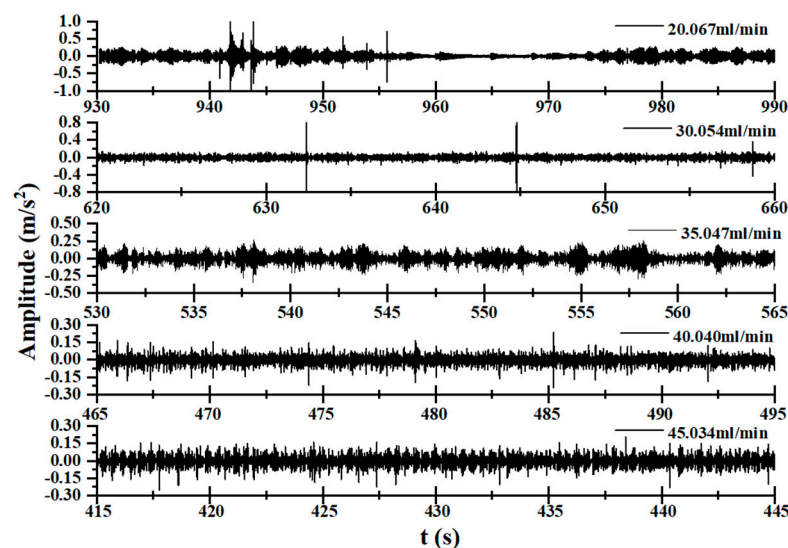


Figure 5. Oscillation signal in the time domain under different inlet mass flow rates.

To determine the periodic variation pattern of the time-domain signal, a stationary segment of the oscillation signal is taken for analysis. As shown in Figure 6, the maximum amplitude is 0.100 m/s^2 at 14 kPa, 0.088 m/s^2 at 16 kPa, 0.081 m/s^2 at 19 kPa, 0.072 m/s^2 at 20 kPa, and 0.063 m/s^2 at 21 kPa. It can be seen that the amplitude gradually decreases with the absolute pressure increases, which is consistent with the phenomenon observed earlier. When the pressure increases by 50%, the maximum amplitude decreases by 37%. The amplitude decreasing speed from slow to fast indicates that the oscillation is more obviously affected by pressure as the pressure increases. In addition, from the periodic characteristics of the oscillation signal, the waveform becomes chaotic and the periodicity weakens, indicating that as the absolute pressure increases, the condensation oscillation changes from only one main frequency to multiple frequencies with high energy. Comparing Figure 5 with Figure 3, it can be seen that as the condensation inside the container gradually increases during the condensation process, the time-domain characteristics of the oscillation waveform show a transition from a clear peak to a stable state, and finally the condensation system converges to a stable state.

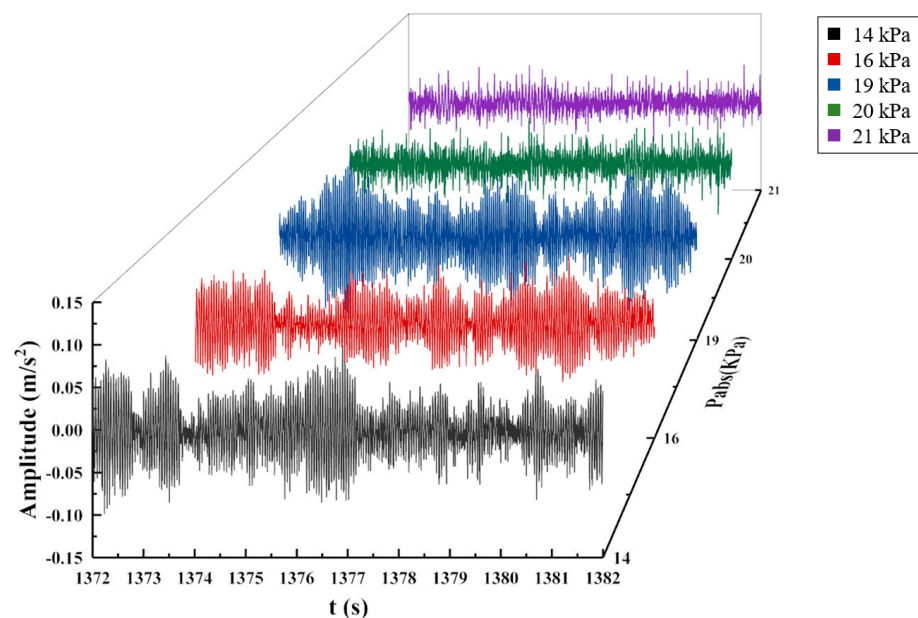


Figure 6. Periodic fluctuation in oscillation signal under different absolute pressures.

3.3. The Frequency-Domain Characteristics of the Pressure Oscillation

To obtain the frequency-domain characteristics of the pressure oscillation signal during the direct-contact condensation process, a spectral analysis was conducted on the pressure oscillation in the Z-direction of the direct-contact condenser. The results are shown in Figure 7, where different colors represent the energy contributions of different frequencies. As shown in the figure, in the range of 0–50 Hz, the energy of different frequencies of the Z-direction oscillation signal exhibits different characteristics at different droplet velocities. As the inlet flow rate increases, the energy contribution in the frequency range of 20–30 Hz decreases, while the energy contribution in the frequency range of 5–20 Hz increases.

To analyze the oscillation characteristics of the direct-contact condensation process under different inlet flow rates in detail, the peak value, peak frequency, and acceleration RMS value of the oscillation signal were further studied. Fourier transform on the Z-direction pressure oscillation signal in direct contact with the condensing container was performed to convert the signal from the time domain to the frequency domain.

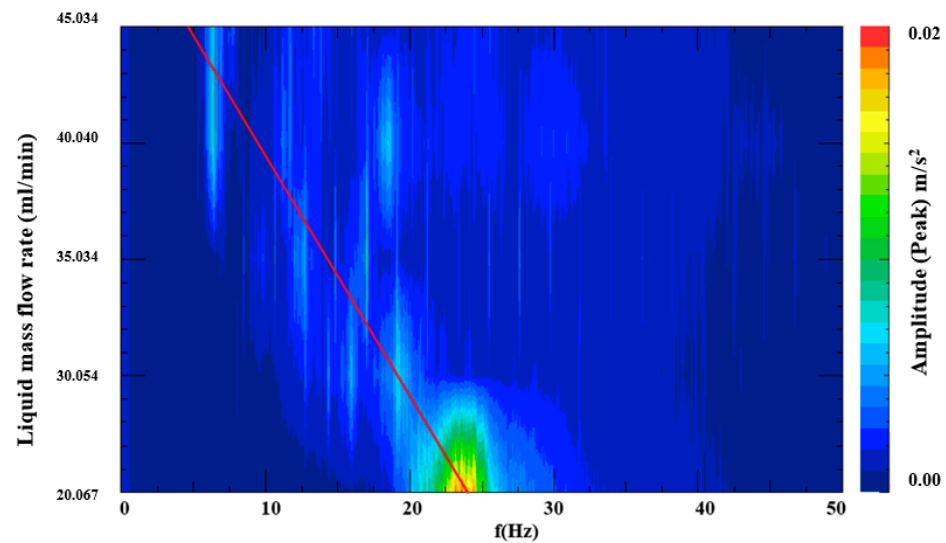


Figure 7. Waterfall diagram of acceleration spectrum in Z-direction under different inlet flow rates.

To improve the convenience of actual operation, the fast Fourier transform (FFT) analysis method was used to process the signal, and the results are shown in Figure 8. It can be seen that 0–50 Hz is the interval with the largest change in oscillation frequency during steam condensation. The analysis results show that the RMS value of acceleration does not change significantly when the inlet flow rate is small, which is 0.08 m/s^2 . When the inlet flow rate continued to increase to 45.034 mL/min , it significantly decreased to 0.04 m/s^2 . Meanwhile, as the inlet flow rate increased from 20.067 mL/min to 45.034 mL/min , the peak frequency continued to decrease from 23.68 Hz to 7.16 Hz , while the peak value decreased from 0.0115 m/s^2 to 0.0059 m/s^2 .

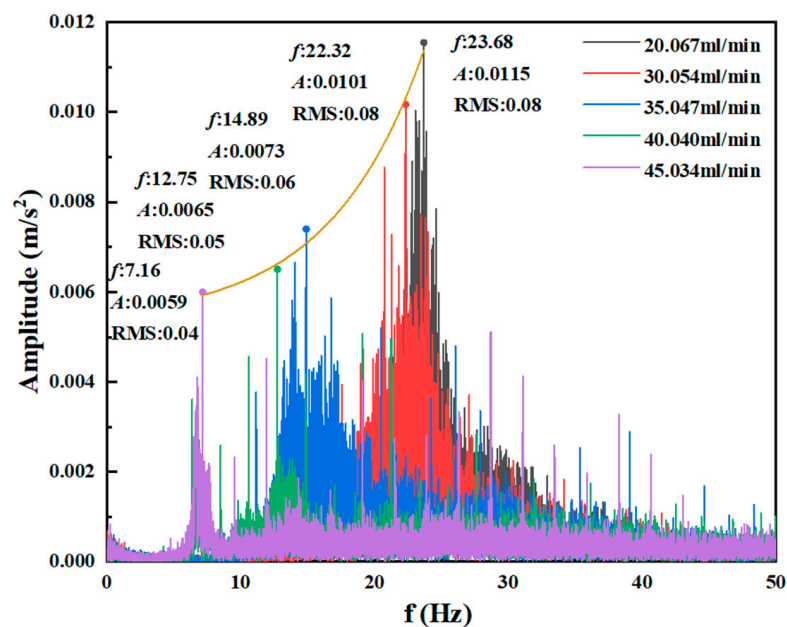


Figure 8. Oscillation signal in the frequency domain under different inlet flow rates.

The overall frequency-domain signals within 0–50 Hz at low and high flow rates are compared as shown in Figure 8. It can be seen that at a low mass flow rate, the high energy frequency of droplet oscillation is more concentrated and has a larger amplitude. As the droplet velocity increases, the frequency domain with high energy is no longer concentrated, and the energy gradually decreases, making the oscillation phenomenon more complex. At a low mass flow rate, the peak frequency moves towards higher fre-

quencies as the condensation efficiency increases with a decrease in flow rate, resulting in a rapid condensation process. Meanwhile, as the steam condensation rate increases, the condensation interface becomes more unstable, and the flow field amplitude increases.

To further analyze the characteristics of the oscillation signal spectrum under different inlet flow rates under constant absolute pressure, the auto power spectrum of the FFT-transformed pressure oscillation frequency-domain signal is calculated, which determines the dominant frequency in the oscillation system and divides the strong and weak frequencies. According to Parseval's theorem, the total energy of the time-domain signal is equal to the total energy of the frequency-domain signal, and the auto power spectrum can be calculated from the spectrum obtained by the Fourier transform of the random signal.

When the absolute pressure is constant, the auto power spectrum of the acceleration oscillation signal in the range of 0–50 Hz at different inlet flow rates is shown in Figure 9. Comparing Figures 7 and 9, it is found that the trend of the auto power spectrum in the Z-direction of the direct-contact condenser is consistent with the frequency-domain plot. The dominant frequencies of oscillation can be obtained under different droplet velocities. From Figure 9, it can be observed that at low mass flow rates, as the inlet flow rate increases within the range of 20.067–30.054 mL/min, the main frequency of oscillation remains 23.04 Hz. However, as the droplet velocity continues to increase to 45.034 mL/min, the main frequency of oscillation gradually decreases to 7.68 Hz. Meanwhile, the energy contributed by the main frequency of oscillation decreases continuously with the increase in droplet velocity.

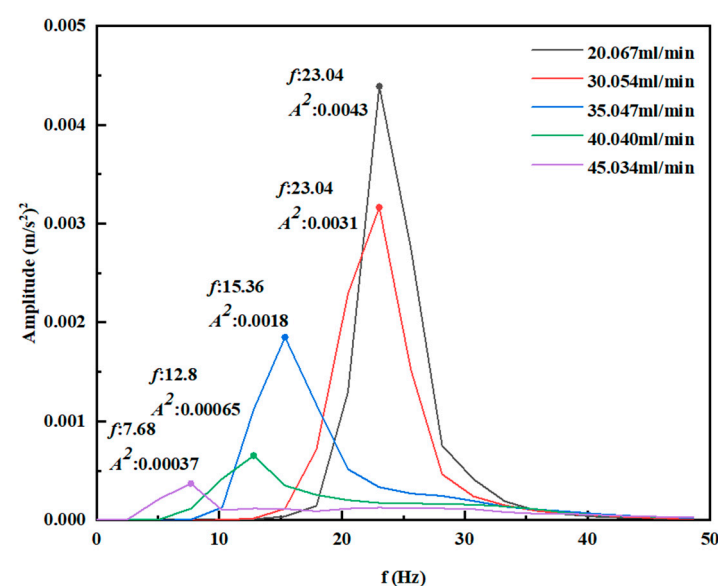


Figure 9. The auto power spectrum of the pressure oscillation signal under different inlet flow rates.

The overall change in the auto power spectrum within 0–50 Hz is shown in Figure 10. With the increase in drop velocity, the main frequency of oscillation becomes unstable, and the auto power spectrum changes from only a single peak to multiple peaks. The image shows fluctuation characteristics, which indicates that the oscillation energy is no longer concentrated, which is consistent with the phenomenon observed in the above frequency-domain signals. The amplitude of the dominant frequency in the figure is about 0.0004 (m/s^2)², and the amplitude of the other main frequencies is about 0.00010–0.00015 (m/s^2)². Since the natural frequency of the direct-contact condenser is low, the lower the main frequency, the greater the possibility of resonance with the condenser. It can be seen that other dominant frequencies occur only under certain conditions, but not all conditions. If the first main frequency is caused by pressure fluctuations formed by the condensation of steam on the droplet surface, the other main frequencies may be caused by the formation, accumulation, and rupture of non-condensing gas layers on the droplet

surface as the flow rate increases. The conditions and laws of the occurrence of other main frequencies will be further explored in subsequent work.

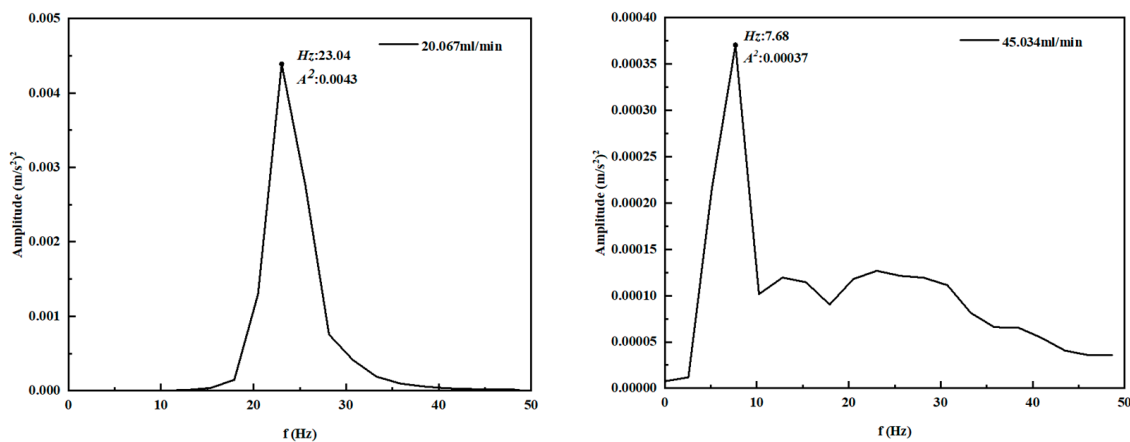


Figure 10. Comparison of auto power spectrum at inlet flow rates of 20.067 mL/min and 45.034 mL/min.

4. Conclusions

The oscillation characteristics of droplets in direct contact with steam during condensation are of great significance to the study of the heat transfer mechanism. In this paper, the experimental study on the pressure oscillation characteristics of the direct-contact process between droplets and steam at sub-atmosphere pressure was carried out. Based on the time-domain and frequency-domain characteristics of the vibration acceleration signal during direct-contact condensation heat transfer, the influence of the inlet flow rate and steam pressure on the oscillation characteristics was emphatically analyzed. The main conclusions are as follows:

- (1) The peak value of the oscillation in the condenser shows pulse fluctuations when pure steam condenses in direct contact with droplets. The energy of the condenser is maximum in the Z direction, and the acceleration RMS value can reach 0.08 m/s².
- (2) When the flow rate is constant, the peak value of the oscillation signal decreases gradually with the increase in absolute pressure, and the time-domain periodic waveform becomes fluctuating. When the absolute pressure is constant, the peak value of the condensation oscillation signal mainly occurs at a low mass flow rate. When the flow rate continues to increase, there is no obvious peak value change.
- (3) In the spectrum waterfall diagram, the energy contribution decreases in the range of 20–30 Hz but increases in the range of 5–20 Hz. The range of 0–50 Hz is where the oscillation frequency changes the most in the process of steam condensation. At a low mass flow rate, the RMS of pressure oscillation does not change significantly, and the peak frequency moves towards a high frequency. As the flow rate gradually increases, frequencies with high energy become unconcentrated. The peak frequency decreases continuously from 23.68 Hz to 7.16 Hz, and the oscillation amplitude decreases in a parabolic pattern.
- (4) The auto power spectrum of the oscillation shows that the main frequency of oscillation is maintained at 23.04 Hz at a low flow velocity, and gradually decreases to 7.68 Hz when the flow velocity continues to increase.
- (5) As the flow rate increases, the main frequency of oscillation is no longer stable and its energy continues to decrease. The auto power spectrum changes from a single peak to a fluctuating characteristic. The amplitude of the first main frequency is approximately 0.00037 (m/s²)², while the amplitude of other dominant frequencies is between 0.00010 (m/s²)² and 0.00015 (m/s²)². Other dominant frequencies may be caused by the formation, aggregation, and rupture of non-condensable gas layers on the surface of droplets.

The results of this study can provide a certain basis for research on the condensation mechanism of steam and liquid droplets in direct contact, and provide new references for the application of direct-contact heat exchangers. In practical applications, on the one hand, excessive flow velocity and reduced vacuum degree should be avoided to prevent low-frequency vibration, which may lead to fatigue damage or even failure of the equipment due to resonance; on the other hand, the state of direct-contact condensation can be inferred based on changes in vibration signals to reduce environmental noise. In subsequent research, the scope of operating conditions will be further expanded to obtain more detailed data, and the heat transfer characteristics of direct-contact condensation between steam and droplets will be correlated with vibration characteristics in combination with heat transfer research results under the same operating conditions.

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