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Inhibition of Dust Re-Deposition for Filter Cleaning Using a Multi-Pulsing Jet

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Abstract: The re-deposition of detached dust during online pulse-jet cleaning is an important issue encountered during filter regeneration. To reduce dust re-deposition, multi-pulsing jet cleaning schemes were designed and experimentally tested. A pilot-scale pulse-jet cleaning dust collector was built with one vertically installed pleated filter cartridge. The effects of pulse duration and interval on the pulse pressure were tested, and the dust re-deposition rate and mechanism were studied and analyzed. It was found that, for the single-pulsing jet, the pulse duration had a critical value of approximately 0.080 s in this test, above which the pulse pressure remained at approximately 0.75 kPa and did not increase further. For the multi-pulsing jet with a small pulse interval (less than approximately 0.10 s), the pulse flows superimposed and reached a higher pulse pressure with a slight inhibition of dust re-deposition. For the multi-pulsing jet with a long pulse interval (over 0.15 s), dust re-deposition was clearly inhibited. The re-deposition rate decreased from 63.8% in the single-pulsing scheme to 24.4% in the multi (five)-pulsing scheme with the same total pulse duration of 0.400 s. The multi-pulsing scheme lengthens the duration of reverse pulse flow, resulting in more elapsed time for the detached dust to freely fall, and inhibiting the re-deposition of dust. The elapsed time in the five-pulsing jet scheme with the recommended pulse duration of 0.080 s and interval of 0.25 s was 2.8 times higher than that of the single-pulsing jet with the same total pulse duration.

Keywords: multi-pulsing jet; air filtration; filter cleaning; dust re-deposition; pulse interval

Citation: Wu, Q.; Li, X.; Xing, Z.; Kuang, Q.; Li, J.; Huang, S.; Huang, H.; Ma, Z.; Wu, D. Inhibition of Dust Re-Deposition for Filter Cleaning Using a Multi-Pulsing Jet. *Atmosphere* **2023**, *14*, 1173. https://doi.org/10.3390/atmos14071173

Academic Editor: Hung-Lung Chiang

Received: 24 June 2023
Revised: 15 July 2023
Accepted: 19 July 2023
Published: 20 July 2023

1. Introduction

Dust collection systems with air filters are extensively utilized in an industry for removing particulate matter or recovering powders [1–4]. As particulates continue to collect on the surfaces of filter cartridges during filtration, the airflow resistance increases. Therefore, filter elements must be cleaned to remove the dust cake formed on filter surfaces for the operation of dust collection. Reverse pulse-jet cleaning is now considered to be an effective technique for the periodical regeneration of filter elements [5–8].

Pulse-jet cleaning can be conducted in online and offline modes. Online cleaning is conducted without stopping the airflow in advance, which is simpler and quicker, and has less influence on the continuity of the filtration/ventilation system. However, the reverse pulse jet lasts for approximately 0.1–0.3 s, which is not long enough to allow the dust that had detached from the filter element to fall into the hopper. When the reverse pulse flow ceases, the filtration airflow begins to recover. Some of the detached dust that does not fall into the hopper is likely to be entrained by the filtration airflow and re-deposits on the filter. The re-deposition rate can reach 9–32% [5] or 38–83% [9], which negatively influences the efficiency of cleaning the filter element.

Many methods have been proposed to improve the effect of pulse-jet cleaning, most of which are focused on improving pulse intensity and uniformity. These methods include the usage of an induced nozzle [10], dual-slit injector [11], velocity-difference nozzle [12], supersonic nozzle [13], annular-slit nozzle [14], special conical diffuser [15], or cone installation [16]; the design of a colliding [17] or multi-pulsing jet scheme [18,19]; and the optimization of the nozzle area ratio [20], jet distance [21], or pleat shape [22]. These methods focus on improving the pulse-jet intensity and uniformity, but less research has been conducted on the inhibition of the re-deposition of detached dust after pulse-jet cleaning. It has been reported that re-deposition can be inhibited by lengthening the pulse duration, decreasing the filtration velocity, or increasing the pulse pressure [23,24]. However, the amount of compressed air will increase sharply when the pulse duration is lengthened, the equipment will be enlarged when the filtration velocity is decreased, and it requires a high amount of energy to sustain an air tank with a higher pressure.

If a reverse pulse jet is separated into multiple airflows and the reverse airflows jet successively to hinder the recovery of the filtration airflow, the time available for the detached dust to re-deposit could be reduced, and the duration could be reduced when using the same amount of compressed air. The multi-pulsing jet cleaning method has been researched [18,19], but the pulse interval was fixed to be short (approximately 0.005 s) to allow the residual gas remaining from the previous jet to interact with the following jet, which could increase the pulse pressure. However, the dust re-deposition issue was not considered, and the longer pulse intervals have not been studied.

The object of this work is to investigate the efficiency of inhibiting dust re-deposition using the multi-pulsing jet scheme. The effects of pulse duration and interval on the pulse pressure were experimentally studied, and the re-deposition rate and cleaning efficiency were tested during dust clogging and cleaning. The inhibition mechanism was further analyzed. This study is useful for optimizing the design of dust filter cleaning.

2. Experimental Section

2.1. Experiment Setup

A schematic depiction of the dust collector test rig is shown in Figure 1. The width, depth, and height of the filtration chamber were 1225 × 750 × 1100 mm, respectively. One pleated filter cartridge that was 320 × 240 × 660 mm in external diameter, internal diameter, and height, respectively, with 120 pleats was installed vertically in the filtration chamber. The cartridge was composed of a non-woven long staple polyester with a porosity and thickness of 59.9–60.1% and 0.55 ± 0.05 mm, respectively. The distance from the outlet of the top nozzle over the filter to the opening mouth of the filter was 250 mm. The inner diameter of the blow tube was 25 mm, and the outlet diameter of the nozzle was 17 mm.

The experimental system also included a dust feeder (LSC-100 with a range of 0–3500 g/min and error of less than 3%), pressure tank (19.7 L), electromagnetic pulse valve (DMF-Z-25 type, 1-inch, Shenchi Pneumatic Co., Ltd., Wenzhou, China), pulse controller (QYM-ZC-10D, Lingchuan Auto Technology Co., Ltd., Shanghai, China), differential pressure recorder (DT-8920 type with a range of 0–5000 Pa, accuracy of 1 Pa, and data acquisition rate of 1 Hz), weigher (range of 0–40 kg, accuracy of 1 g, and data acquisition rate of 1 Hz), and high-frequency pressure-acquisition subsystem (MIK-P350 diffused silicon pressure transmitter with a range of 0–10 kPa and data acquisition rate of 64 Hz, Hangzhou Meacon Automation Technology Co., Ltd., Hangzhou, China).

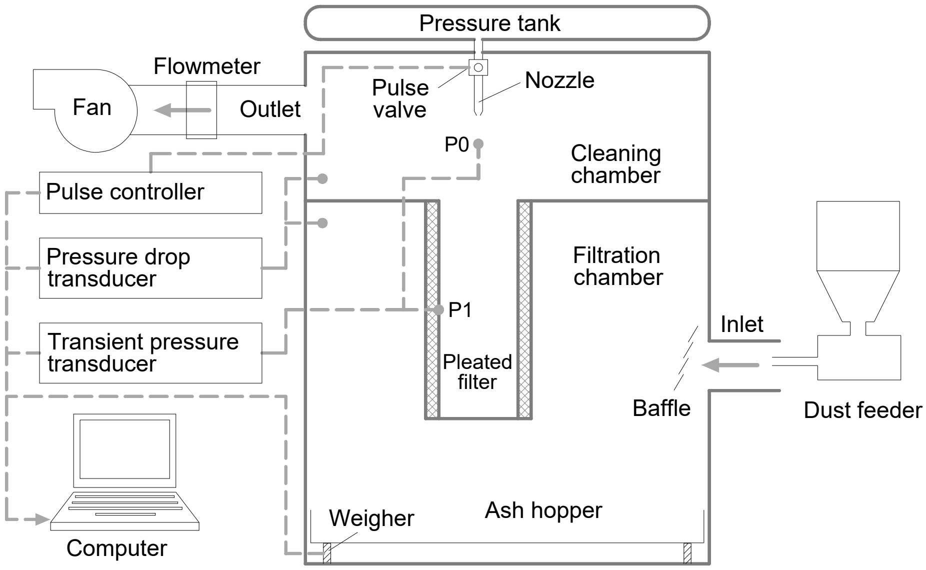

Figure 1. Schematic view of the test rig.

The studied dust was GB 15342-TL75-2.5-C talc powder [25] produced by Guilin Guiguang Talc Development Co., Ltd., Guilin, China. The D10, D50, and D90 of the dust measured with a laser particle size analyzer (Malvern 3000 + Hydor EV, produced by Malvern Panalytical Ltd., Malvern, UK) were 0.42, 0.83, and 2.06 µm, respectively [26].

The experimental system was operated as follows: the fan operation speed was controlled with the frequency converter, and, under the action of the exhaust fan, air was sucked into the dust collector from the inlet and flowed out through the upper outlet. The outlet of the dust feeder was inserted into the dust collector inlet. Dust could be entrained by the air flow into the filtration chamber and collect on the outer surface of the filter cartridge. The pressure-drop transducer was used to monitor the filtration resistance. The duration and interval time of the pulse valve were controlled with the pulse controller. The pulsing airflow from the pressure tank flowed into the filter cartridge through the nozzle when the pulse valve was opened, causing the dust (cake) deposited on the filter surface to be freed and fall into the hopper. The mass of the dust falling into the hopper was monitored with the weigher.

2.2. Experimental Design

In stage I, different pulse pressures (transient pressures on the middle of the filter inner surface) during an offline single-pulsing jet were tested. The selected pulse durations t_d of the single-pulsing jets ranged from 0.020 to 0.500 s. After comparing the pulse pressures, one of the pulse durations was selected for the multi-pulsing jet schemes. The inlet of the pressure tank was closed during each pulse jet for all the scenarios studied in this paper.

In stage II, the pulse pressures were tested under multi-pulsing, with pulse intervals Δt (the interval of the pulse jet during a single cleaning cycle of the multi-pulsing scheme, illustrated in Figure 2) ranging from 0.05 to 0.40 s. The pressures under online and offline multi-pulsing jets were analyzed (online: pulse jetting with the fan still running and airflow unstopped; offline: pulse jetting with the fan and airflow stopped). For the online pulse-jet mode, the filtration pressure drop was maintained at 350 Pa, corresponding to an appropriate test time and cleaning frequency, by adjusting the operating speed of the fan.

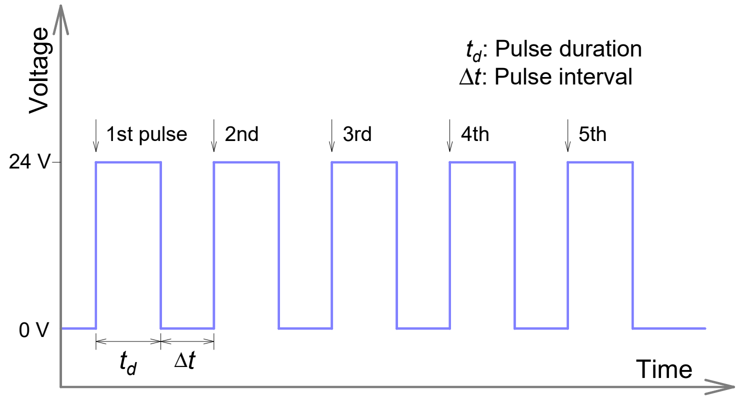

Figure 2. Diagram of the input signal for the magnetic valve in the multi-pulsing scheme.

In stage III, single- and multi-pulsing jets were used in the dust clogging and cleaning operation process. The fan frequency was set at 40 Hz, and the calculated filtration velocity was 0.88 m/min. The inlet dust concentration was set at 15 g/m^3 by adjusting the speed of the dust feeder. Clogging and cleaning operations were conducted in the clean-on-demand mode with the maximum allowable pressure drop set at 350 Pa, which was the same as the filtration pressure drop during the online pulse-jet tests in stage II. The pressure drop and fallen dust mass were recorded in real time with a frequency of 1 Hz using a computer. Each of the filter cleaning tests were conducted five times to obtain stable results.

3. Results and Discussion

3.1. Pulse Pressure during Single-Pulsing Jet

Figure 3 shows the evolution of pulse pressure at the center of the inner surface of the filter during offline pulse jetting with a tank pressure of 0.5 MPa, nozzle diameter of 17 mm, and pulse durations of 0.020–0.500 s.

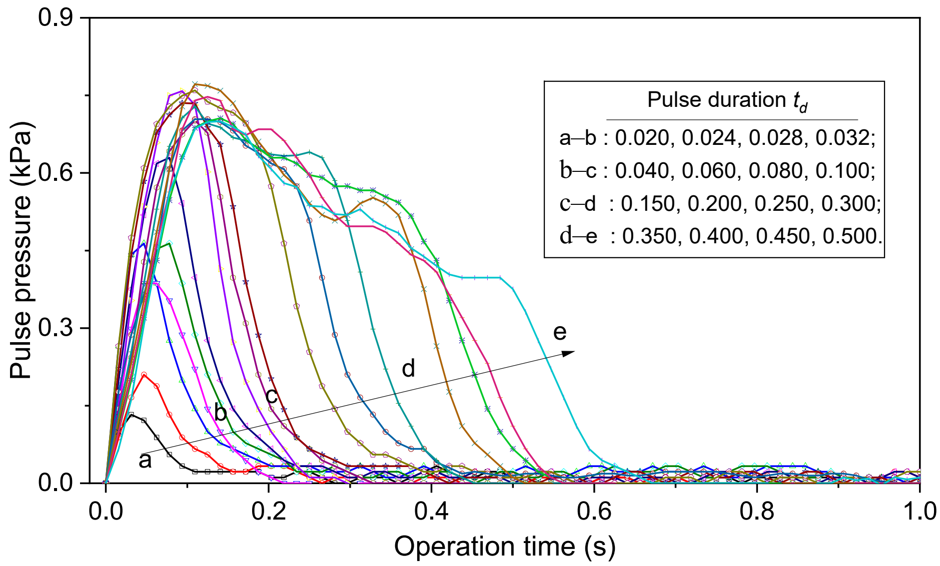

Figure 3. Evolution of the transient pulse pressure on the inner surface of the filter during a single-pulsing jet with pulse duration varying from 0.020 s to 0.500 s in offline cleaning mode.

As the pulse signal was activated, the pulse valve was triggered and the transient pressure increased rapidly. As the pulse valve closed, the transient pressure decreased rapidly. In cases that the pulse duration t_d was below approximately 0.080 s, the peaks of the transient pressures increased with the pulse duration, indicating that pulse duration was the main factor restricting the pulse intensity. When the pulse duration t_d was sufficiently long (over approximately 0.080 s), the peak pressure reached its maximum level of approximately 0.75 kPa at 0.12 s. Two stages were observed during the decrease in transient pressure, one of which was a slowly decreasing stage, and the other was a rapidly decreasing stage. It can be inferred that the rapidly decreasing stage is due to the closure of the valve, and the slowly decreasing stage is due to the decrease in the pressure of the tank due to air consumption.

Regarding the maximum level that the peak pressure reached, it is analyzed that after opening the pulse valve, the compressed air flows from the air tank through the jet tube to the nozzle. Initially, the flow velocity of the air is low and the fluid resistance in the tube is small. As the flow velocity gradually increases, the fluid resistance in the tube increases. Finally, when the power provided by the pressure in the air tank is equal to the resistance in the tube, the flow velocity in the jet tube reaches the maximum and the nozzle outlet pressure also reaches the maximum.

There will be a moment when the pressure of the compressed air is reduced and the power of the compressed air is equal to the resistance in the jet tube, corresponding to the critical time (about 0.08 s in this paper). The outlet pressure of the nozzle also reaches the maximum value.

If the pulse duration t_d is shorter than the critical time, the nozzle outlet pressure cannot reach the maximum value. If the t_d is longer than the critical time, because the air tank pressure has been consumed, it is impossible to increase the flow rate in the jet tube and the nozzle outlet pressure any further.

As the peak transient pulse pressure acting on the filter is commonly used as an indicator of the pulse-jet intensity [13,16,17,27], the peaks and durations of the changes in pressures with the pulse duration were analyzed, as shown in Figure 4. The peak pressure increased rapidly with the pulse duration t_d when $t_d < 0.080$ s, and remained almost the same value when $t_d > 0.080$ s. The pressure duration exhibited a decelerating increase with the pulse duration without a clear critical value. Therefore, from the aspect of pulse intensity, the pulse duration t_d of 0.080 s was selected as the recommended parameter for the research of the multi-pulsing jet in the following step.

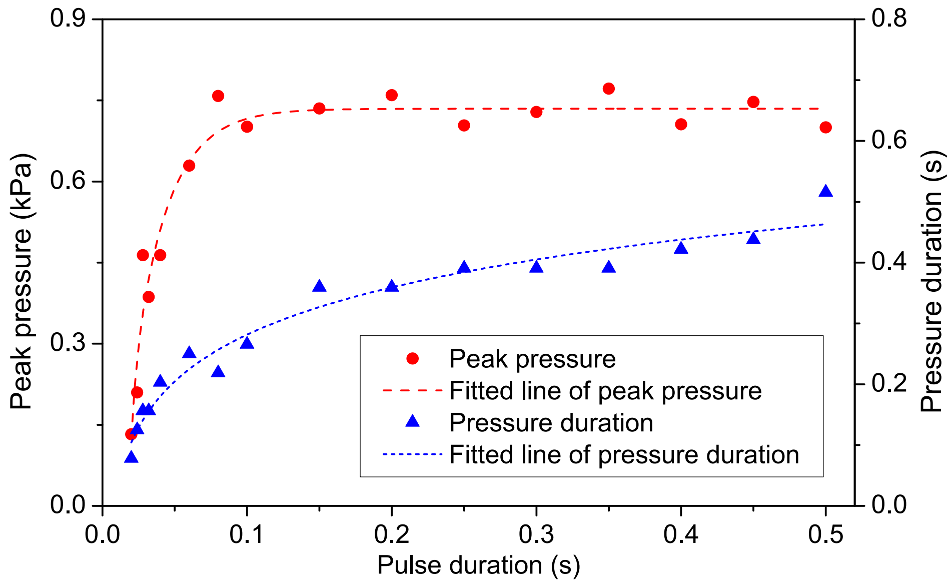

Figure 4. Peaks and durations of pulse pressures with varying pulse durations in the offline single-pulsing scheme.

3.2. Pulse Pressure during Multi-Pulsing Jet

After testing the residual pressure in the tank several times, the compressed air was found to be exhausted when the number of jet pulses reached seven with a pulse duration t_d of 0.080 s. Figure 5 shows the evolution of the transient pulse pressure during multi-pulsing. Figure 5a–c shows the results of the seven-pulsing, five-pulsing, and three-pulsing jet schemes in the offline modes, and Figure 5d shows these in online seven-pulsing jet schemes.

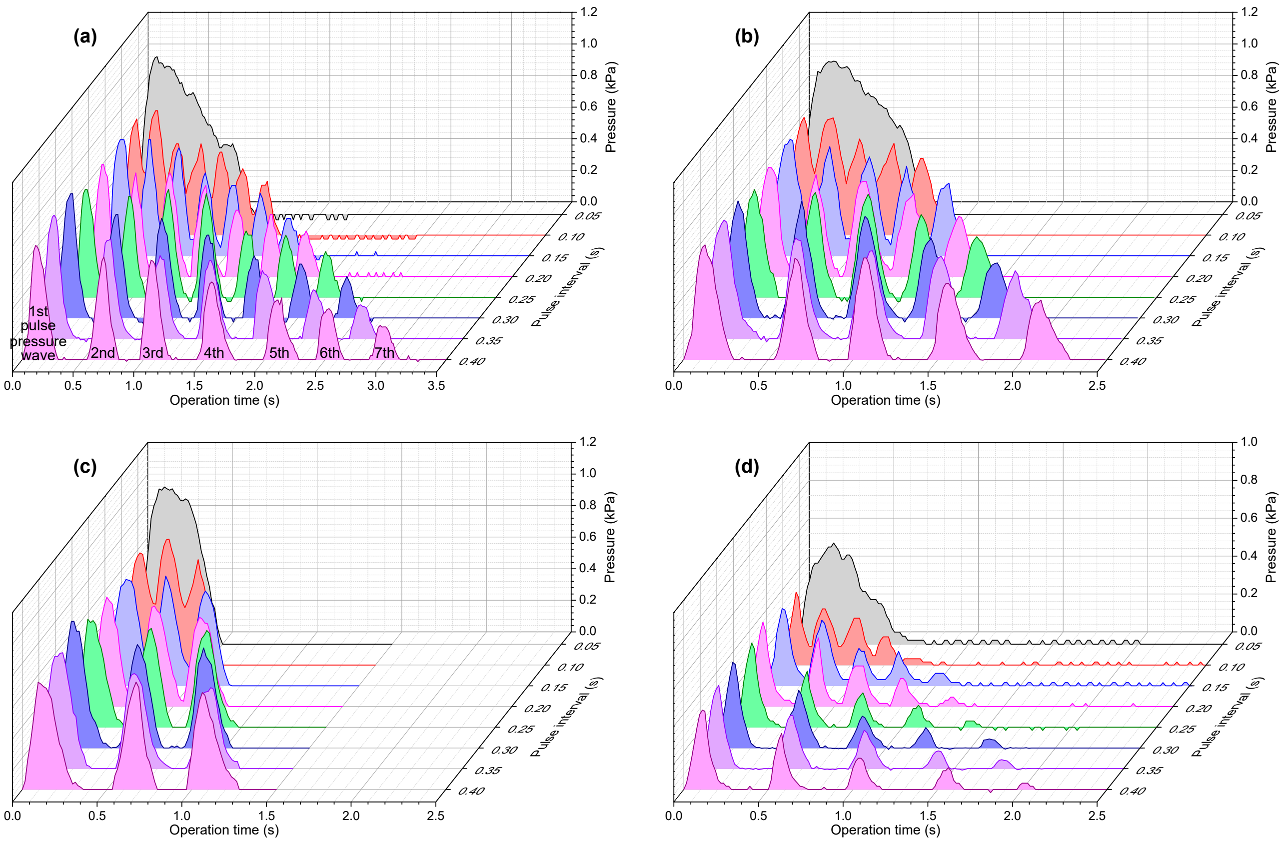

Figure 5. Pulse pressure on the inner surface of the filter during the (**a**) seven-pulsing, (**b**) five-pulsing, and (**c**) three-pulsing jet schemes in the offline cleaning modes, and (**d**) seven-pulsing jet scheme in the online cleaning mode with a pulse duration of 0.080 s and interval of 0.05–0.40 s.

According to the pulse pressure evolution curves in the offline seven-pulsing jet schemes (Figure 5a), the pressure waves overlapped with the adjacent waves when the pulse interval $\Delta t < 0.10$ s and separated when $\Delta t > 0.15$ s. The pressure waves had larger distances with a longer pulse interval. When the waves were separated, their values with the same pulse orders were equal among the varying pulse intervals, with first, second, and final peak pressures of approximately 0.74, 0.68, and 0.25 kPa, respectively. The times at which the pressure waves appeared were consistent with the pulse interval. For instance, the average wave appearance time interval was 0.215 s when the pulse interval was 0.20 s, and 0.397 s when the pulse interval was 0.40 s.

When the pulse interval was 0.050 s, the peak pressure was 0.998 kPa, which was significantly greater than the maximum value of approximately 0.75 kPa in the single-pulsing jet scheme. Therefore, not only were the pulse waves overlapped but also the pulse pressures were superimposed. This type of multi-pulsing jet scheme with a small pulse interval (below the 0.10 s found herein) has already been reported. Chen and Chen [18,19] conducted 3D modeling to investigate the multi-pulsing jet scheme, and found that the interaction of the residue gas from the previous jet pulse and the following jet pulse could form a high-pressure zone. They also found that the peak pressures decreased with the reduced pulsing frequency. These numerical simulation results support our experiment.

Owing to the poor cleaning effect of the negative pressure acting on the filter, the negative pressure was not designed to be tested here, and a transient pressure transducer without negative pressure was used. However, the negative transient pressure value could be revealed during pulse jetting [16].

The pulse pressures in the five- and three-pulsing jet schemes are shown in Figure 5b,c. The times at which the pulse waves and the peak pulse pressures appeared were similar for cases with the same pulse interval order in these three multiple pulsing jet schemes. The following pulse pressure did not influence the previous pulse pressure, and the pulse waves, if they were present, were similar between the different pulsed time multi-pulsing jet schemes.

Figure 5d shows the pulse pressure evolution curves during the online seven-pulsing jet scheme. Owing to the filtration pressure drop of 350 Pa, only five pressure waves were observed on the filter inner surface during the seven jet pulses, with the final two waves disappearing due to the filtration air resistance.

After comparing the pressure waves in the online and offline cleaning modes, the peak pressures in online modes were 0.36 kPa less than those in the offline modes, on average. The times at which the waves appeared with the same pulse order were almost the same between the online and offline modes. An example is the intervals between the times at which pressure waves of approximately 0.27 s appeared when the pulse interval was 0.25 s in both the online and offline cleaning modes. However, the pressure durations in the offline modes were longer than those under the online modes. This is primarily due to the filtration airflow resistance.

3.3. Re-Deposition Rate Testing of Single- and Multi-Pulsing Online Cleaning

To investigate the re-deposition of dust and cleaning efficiency, dust clogging and cleaning operation simulation experiments were conducted with pulse intervals Δt of 0 to 0.40 s. The filtration pressure drop and total fallen dust mass were tested in real time during operation. Each of the pulse-jet schemes was tested five times, and the experimental results with Δt = 0.05–0.15 s are shown in Figure 6. Comparing the pressure drop evolution curves, as well as the fallen dust mass, among the cases with the same pulse interval, it was found that the residual pressure drops, fallen dust masses, and filtration periods (the time between two cleanings) exhibited similar values. Comparing the curves for the cases with different pulse intervals, it was found that, with an increase in the pulse interval, the residual pressure drop decreased, the fallen dust mass increased, and the filtration period increased, indicating that a better pulse-jet cleaning effect was obtained with a longer pulse interval in the range of Δt = 0.05–0.15 s.

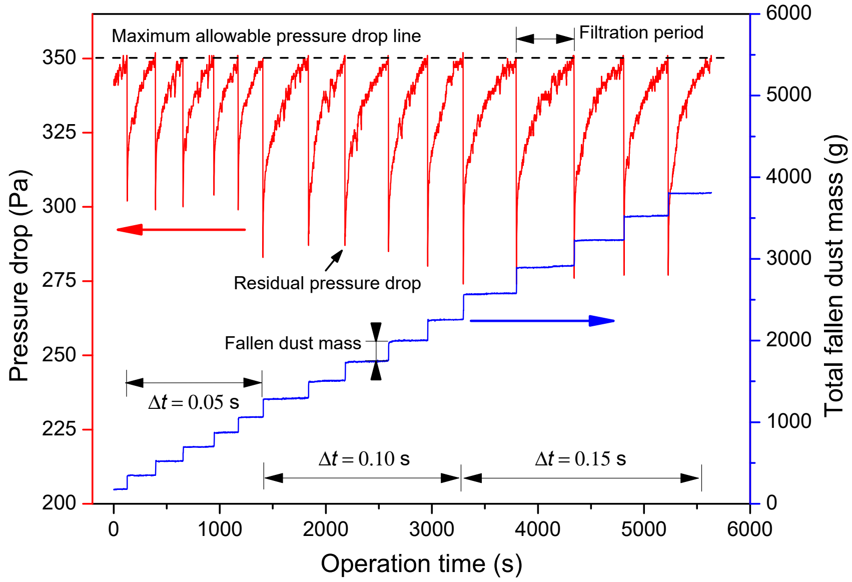

Figure 6. Evolutions of the filtration pressure drop and fallen dust mass under the five-pulsing jet scheme with a pulse duration t_d of 0.080 s and interval Δt of 0.05 to 0.15 s.

The average fallen dust masses with the same pulse interval were calculated to further calculate the cleaning efficiency and dust re-deposition rate. The cleaning efficiency η under the online cleaning mode for each pulse jet can be defined as the ratio of the fallen dust mass m_2 to the detached dust mass m_0, and the re-deposition rate R_{de} can be defined as the ratio of the re-deposited dust mass m_1 to the detached dust mess m_0, as illustrated in Figure 7. However, the detached dust mass m_0 under the online cleaning scheme is not easily tested because just some of the detached dust falls into the hopper. Thus, an approximate value of the detached dust mass needs to be found.

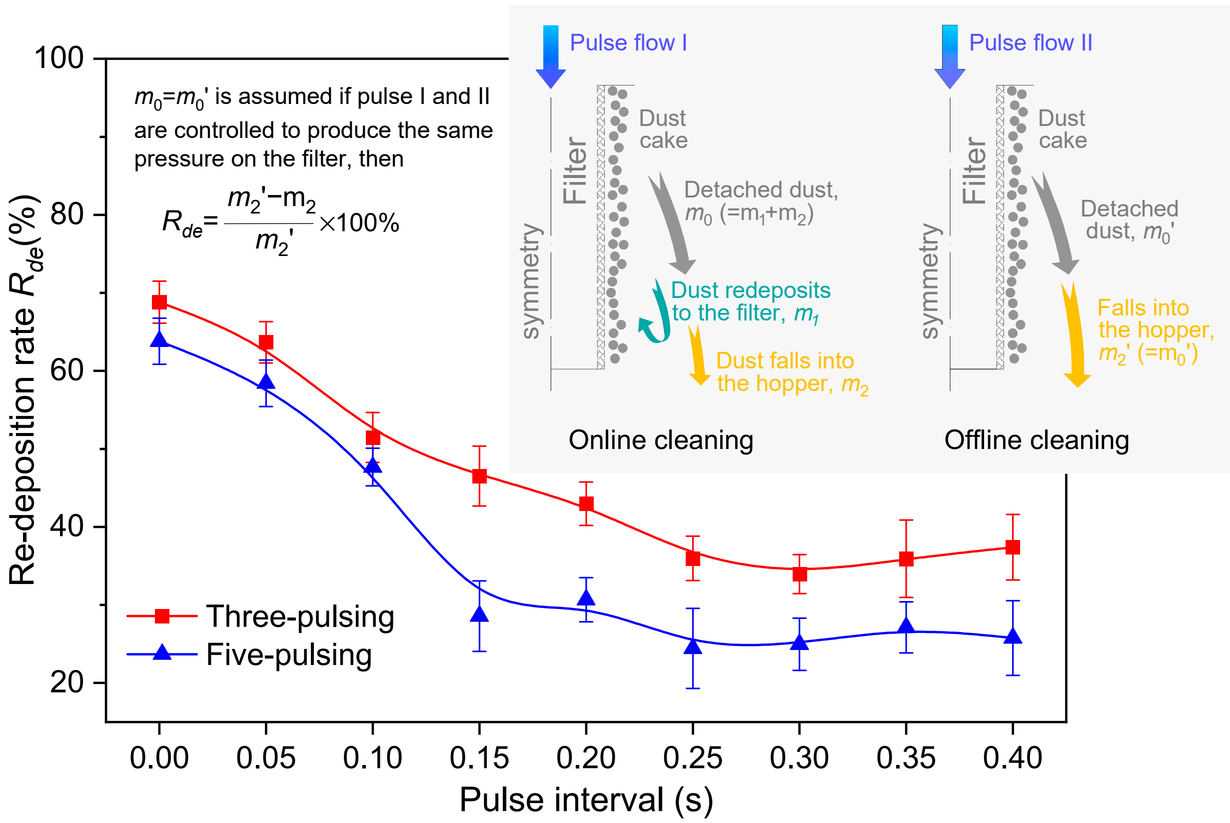

Figure 7. Re-deposition rate for three- and five-pulsing jet cleaning.

It was assumed that the dust masses over the filter surface were the same in cases with the same filtration pressure drops, and the detached dust masses were the same when the filter was subjected to the same pulse pressure, regardless of whether the cleaning mode was online or offline. The pulse pressure under the offline cleaning mode could be controlled to have the same value as that under the online cleaning mode by adjusting the tank pressure. The fallen dust mass m_0 under the online cleaning mode could then be indirectly obtained by testing the fallen dust mass m_0' under the offline mode, i.e., $m_0 = m_0'$. Without the influence of filtration airflow, all of the detached dust under the offline cleaning mode transformed into fallen dust, i.e., $m_0' = m_2'$, as illustrated in Figure 7. Therefore, the cleaning efficiency η can be calculated as the ratio of m_2 to m_2', and the re-deposition rate R_{de} can be calculated as the ratio of m_1 (=$m_2' - m_2$) to m_2'. The changes in the calculated R_{de} value with the pulse interval Δt in three- and five-pulsing jet schemes are shown in Figure 7.

R_{de} decreased with the pulse interval when the pulse interval Δt was <0.25 s, and remained stable when Δt > 0.25 s under both the three- and five-pulsing jet schemes. As indicated by the curves with five-pulsing jet cleaning, R_{de} decreased from 63.8% when Δt = 0 s (i.e., single-pulsing jet) to 24.4% when Δt = 0.25 s, and the corresponding cleaning efficiency η increased from 36.2% to 75.6%. Under the three-pulsing jet cleaning schemes, R_{de} was higher than that under the five-pulsing modes, decreasing from 38.8% when

Δt = 0 s to 36.0% when Δt = 0.25 s. The multi-pulsing scheme was found to notably affect the re-deposition phenomenon. The mechanism of this will be discussed in Section 3.4.

In a previous report, the re-deposition rate was tested within a range of 9–32% [5], which was smaller than that of our overall result. This is mainly because six filters operated in parallel in the previous study, and the influence on the total filtration airflow was lower when only one filter was pulse jetted. The filtration airflow was not concentrated on the cleaning filter and the detached dust could be entrained to the other filters. In another report [9], the re-deposition rate was 38–83%, which was higher than our result. This is mainly because they used a 2.44 m long filter, while ours was 0.66 m long. The detached dust requires more time to fall into the hopper with a longer filter and it is more likely to be re-deposited on the filter by the recovering filtration airflow.

In Section 3.2, the pulse pressure under the small pulse interval (Δt = 0.05 s) was greater than that under other intervals due to the superimposed effect. However, no clear peak of the re-deposition rate corresponding to Δt = 0.05 s was observed, indicating that the re-deposition was less influenced by the superimposing of pulse pressure than it was by the pulse interval. The re-deposition rate became a relatively stable value when the pulse interval exceeded 0.25 s, which was selected as a recommended parameter along with the recommended pulse duration of 0.080 s.

3.4. Mechanism Analysis

To investigate the inhibition mechanism of dust re-deposition in the multi-pulsing scheme, it is necessary to analyze the airflow. However, the filter face velocity is not easily tested. Thus, some assumptions are made here and a semi-quantitative analysis is conducted.

The single-pulsing with a pulse duration of 0.400 s and the five-pulsing with a pulse duration of 0.080 s and intervals of 0.25 s and 0.40 s were selected for comparison. These cases had the same total pulse duration (i.e., the same compressed air consumption).

Based on Darcy's law and ignoring the inertia of the airflow, the filter face velocity is assumed to be proportionate with the pressure difference across the filter when the loaded dust on the filter is fixed. For a better comparison, the average peak pulse pressures in the online five-pulsing jet schemes were calculated for cases with the same pulse order but different pulse intervals. The face velocity of 0.88 m/min corresponding to the pressure drop of 350 Pa indicates face velocities of −1.07, −0.78, −0.49, −0.33, and −0.11 m/min (negative values indicate the flow direction against filtration), corresponding to average peak pulse pressures of 427, 311, 196, 130, and 43 Pa, respectively. The peak pressure of 427 Pa is also the maximum value for the online single-pulsing jet. The time at which the airflow reached the maximum or minimum is assumed to be consistent with the time at which the pulse pressure reached its maximum or minimum value. The change in the face velocity caused by the pulse pressure is assumed to be linear as the pulse pressure increased rapidly. The recovery of filtration velocity is assumed to be a growth curve pattern. The filter face velocity calculated based on a semi-quantitative analysis is shown in Figure 8.

For the single-pulse jet, the face velocity was found to become negative due to the reverse pulse jet, remain at this value, and then recover to the filtration velocity value (line L1 in Figure 8). With the multi-pulsing jet, the face velocity was found to become negative multiple times with a longer duration for the reverse face velocity.

As the detached dust is inert and is at a distance from the filter shortly after the reverse pulse flow ends, the detached dust cannot immediately reach the filter when the filtration flow just begins to recover. Time is required for the detached dust to re-deposit on the filter's surface. It is assumed that line L2 in Figure 8 corresponds to the time at which the detached dust begins to re-deposit on the filter with the entrainment of the recovering filtration flow. The elapsed time required for the detached dust to fall before being re-deposited on the filter under the multi-pulsing cleaning schemes is notably longer than that under the single-pulsing cleaning scheme. The elapsed time t_2 under the multi-pulsing scheme with the recommended pulse interval Δt of 0.25 s is 1.48 s, which is 2.8 times the t_1 value of 0.52 s under the single-pulsing scheme.

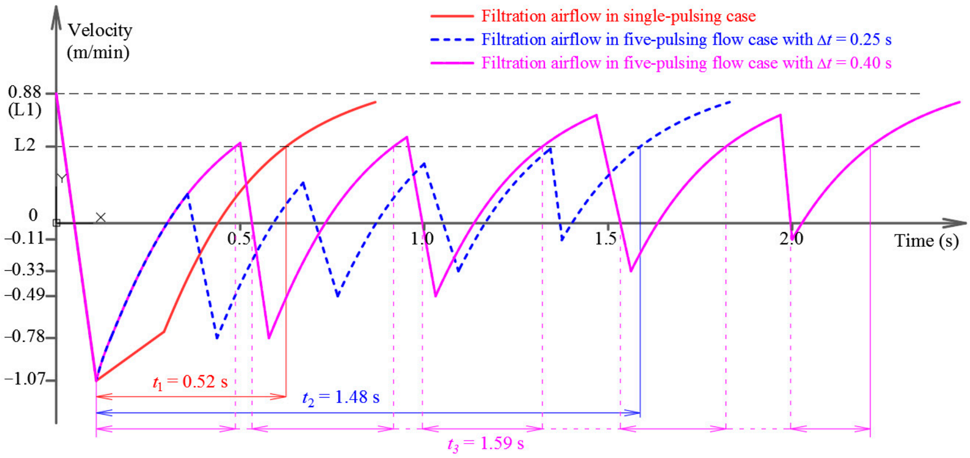

Figure 8. Comparison of the face velocities under the single- and multi-pulsing jet modes.

However, with a longer pulse interval, such as Δt = 0.40 s, the detached dust could reach and re-deposit on the filter prior to the triggering of the following pulse pressure. The re-deposition of the dust continued until the filter face velocity reversed to negative under the action of the following pulse jet. Owing to this phenomenon, a longer pulse interval had no notable effect on further inhibiting dust re-deposition. Dust migration is complicated, and a further analysis should be conducted until more data can be obtained.

It is inferred that the multi-pulsing jet lengthens the duration of the reverse pulse flow, increases the time available for the detached dust to fall before being re-deposited, inhibits the re-deposition rate, increases the fallen dust mass, and improves the cleaning efficiency.

4. Conclusions

Detached dust re-deposition is an important factor restricting online pulse-jet cleaning for filters. To improve the cleaning quality, multi-pulsing jet schemes were designed and experimentally tested.

For the single-pulsing jet, the pulse duration had a critical value of approximately 0.080 s, below which the pulse pressure could not reach the maximum value and above which the pulse pressure did not increase further.

For multi-pulsing with a small pulse interval (less than 0.10 s), the pulse flows were superimposed and reached a notably higher pulse pressure, with the slight inhibition of dust re-deposition. For multi-pulsing with a long pulse interval (more than about 0.15 s), the pulse waves were separated and dust re-deposition was notably inhibited. The pressure wave values with the same pulse orders were equal among the varying pulse intervals. The re-deposition rate decreased from 63.8% in the single-pulsing scheme to 24.4% under the multi (five)-pulsing scheme with the recommended pulse duration of 0.080 s and interval of 0.25 s.

The multi-pulsing scheme lengthens the duration time of reverse pulse flow, increases the time available for the detached dust to fall freely, and inhibits dust re-deposition. The elapsed time under the five-pulsing jet scheme with the recommended parameters is 2.8 times higher than that under the single-pulsing jet scheme.

Author Contributions: Conceptualization, Q.W., X.L., J.L., D.W.; software, X.L., Z.X.; validation, Z.X., S.H., H.H., Z.M.; data curation, Q.W., Q.K.; writing—original draft preparation, Q.W.; writing—review and editing, Z.X., J.L., S.H., H.H., Z.M., D.W.; supervision, J.L.; funding acquisition, J.L., D.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (52064037, 51704166) and the Cultivating Project for Academic and Technical Leader of Key Discipline of Jiangxi Province (20225BCJ23027).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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