



Pilot-scale development of cavitation-jet deinking

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ABSTRACT: A new deinking method for paper recycling using a fluid-jet cavitation technique has been developed. An in-house, laboratory-scale device revealed that cavitation-jet treatment without deinking chemicals decreases ink and dirt content in deinked pulp. As the next step, a pilot-scale deinking device, 10 times larger than the laboratory device, was designed. The specifications of the pilot device were determined by experiments using the laboratory device. The pilot device was installed in a deinked pulp mill, and the effects of multijet nozzles within a reacting vessel, depending on consistencies of the deinked pulp, were investigated. The operation stability of the device was examined as well.

The shape and size of an effective cavitation zone for ink detachment were changed by nozzle diameter and upstream pressure of the jet. The results from batch cavitation treatment of deinked pulp revealed that the device could treat the pulp with consistency up to 3.8% by weight and decrease attached ink, dirt specks, and macrostickies without addition of deinking chemicals. Hydrophobic colloidal materials, including microstickies after cavitation treatment, became more difficult to attach to hydrophobic surfaces. Continuous cavitation treatment gave similar results to those from batch treatment.

Two types of multiple nozzle arrangements, parallel and cross-nozzle modes, decreased dirt specks to the same level as a mill disperser. On the other hand, the reductions of macrostickies by those modes were higher than with the disperser. Because treatment consistency increased more than 3%, treatment efficiency and device performance were significantly improved. This could be a big step toward practical use of cavitation treatment.

Application: Mills can gain new insights into paper recycling technology to reduce dirt specks and stickies in deinked pulp with minimal fiber damage.

The secondary fiber for printing and writing grades requires high brightness and extremely low dirt specks. To produce such a high-quality deinked pulp, high-speed dispersers, low-speed kneaders, or both are used to facilitate ink detachment and dirt comminution [1]. However, those devices also give negative effects, such as fragmentation of pulp fibers and increasing fiber fines [2], resulting in a loss of paper strength and dimensional stability [3]. Thus, it is difficult to obtain high-quality deinked pulp without fiber damage and loss of paper strength using conventional deinking devices.

Cavitation is well known to cause severe damage in fluid machinery, such as pumps, turbines, valves, and screw propellers. Cavitation generates high-impact pressure reaching several GPa in a local region of about several micrometers when cavitation bubbles collapse [4]. If a lot of cavitation bubbles collapse near the fiber surface at the same time, the impact force arrives at the fiber surface directly and detaches and breaks up adhered ink. The bubbles are very small compared with fibers so the impact force is not so strong as to damage the entire fibers. Thus, the authors have developed an in-house, laboratory-scale cavitation-jet (CV-jet) device and investigated the effects of the treatment on paper recycling [5-9]. The results revealed that the treatment decreased dirt specks and macrostickies without deinking chemicals and

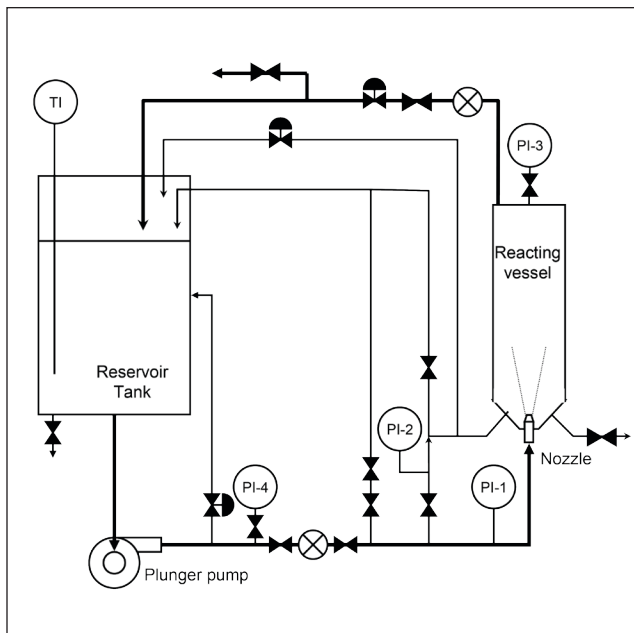
high temperature. Moreover, cavitation treatment minimized fiber damages, resulting in improved strength of paper made from the treated fibers.

In applying this treatment for practical use in industry, however, several points must be considered. The drawbacks of the laboratory device were very low pump throughput, low pulp consistency, and high specific energy. Therefore, the objective of this research is to develop the first pilot-scale CV-jet device that is 10 times larger than the laboratory device with higher treatment consistency and lower power consumption. First, the specifications of the pilot device, such as suitable pump type for pulp slurry, nozzle size and arrangement, and configuration of the reacting vessel, were studied. Second, the performance of the device for dirt and macrostickies reduction was examined. Finally, continuous running and durability of the device were evaluated.

EXPERIMENTAL

Laboratory scale CV-jet device

The details of the laboratory device were described elsewhere [8]. The schematic diagram of the device is shown in **Fig. 1**. The pulp slurry in the reservoir tank was pressurized with plunger pump up to around 13 MPa, and jetted in a reacting vessel. The jet was passed through a nozzle of throat diameter 1.5 mm, and cavitation bubbles were produced around the



1. Schematic diagram of laboratory CV-jet device (PI=pressure gauge, TI=temperature sensor).

submerged jet. The flow velocity of the jet was presumed to be around 70 m/s when the upstream pressure was 7 MPa. The region and intensity of the CV-jet were controlled by pressure difference in the vessel.

The liquid in the reservoir tank is pressurized up to 12-20 MPa and jetted into the reacting vessel through the nozzle of throat diameter 0.7-2 mm. The downstream pressure in the vessel is controlled from 0 MPa to 0.5 MPa by a valve and monitored by a pressure gauge. The liquid, once through the nozzle, can be collected by a sampling line or circulated many times.

Estimation of effective cavitation zone

To determine the specifications of the pilot CV-jet device, such as suitable nozzles (single large nozzle or multiple small nozzles) and configuration of the reacting vessel, a simple test was conducted to make clear the effective cavitation zone. Because of the high pressure inside the reacting vessel, erosion of the vessel and other lines by cavitation should be avoided. In this test, a metal rod was painted with oil-based ink and set into the reacting vessel of the laboratory device. The distance from the cavitation nozzle to the painted rod was varied and the ink detachment area in each condition was checked to confirm the size of the cavitation zone. The influence of upstream pressures of 5 MPa and 7 MPa and nozzle diameters of 1.2 mm and 2 mm, were examined.

Design and manufacture of pilot-scale CV-jet device

The target throughput of the device was 10 times larger than that of laboratory device and the device had multiple nozzles.

Two types of nozzle arrangements were taken into account for the design of the vessel: parallel nozzle mode and cross-nozzle mode. The shape and size of the vessel were determined based on the maximum size of the cavitation zone obtained from the laboratory device.

Performance test of pilot device

The pilot device was installed into the deinking process using old newspapers (ONP) and old magazines (OMG) for a newsprint paper machine at a Nippon Paper Industries mill. The pulp from the outlet of a cleaner or a disk filter using a prethickener ahead of a disperser was treated by the device without addition of deinking chemicals and heating. The consistency of pulp after the cleaner was around 1% by weight and after the filter ranged from 3.4% to 3.8%. The effects of pulp consistency, batch and continuous treatments, parallel and cross-mode treatments, and upstream pressure on dirt and macrostickies reduction were evaluated and compared to those from after the mill disperser. As for batch treatment, turnover time for the treatment (i.e., the cycle a fiber passed through the nozzle) was calculated at approximately 8 min when the upstream pressure was 7 MPa. Therefore, the treatment times of 8, 24, and 40 min corresponded to the turnover rates of 1, 3, and 5 times, respectively. The stability and durability of the device during prolonged operation were examined.

Pulp samples before and after cavitation treatment were hyper-washed to remove detached ink and then standard handsheets were made with them. Dirt measurement of handsheets was done by using Spec Scan 2000 (Apogee Systems; Powder Springs, GA, USA). The number of dirt specks was calculated from particles larger than 0.05 mm². The ISO brightness and ERIC of those sheets were measured using a colorimeter (Murakami Color Research Laboratory Co. Ltd.; Tokyo, Japan) and Color Touch 2 (Technidyne; New Albany, IN, USA), respectively.

Sticks were evaluated by measuring the amount using a modified method based on TAPPI Standard Method T 277 pm-99 "Macro stickies content in pulp: the "pick-up" method." The results were an average of the duplicate samples. The number and total area of macrostickies/kg were obtained from the particles larger than 100 µm in diameter. A quartz crystal microbalance (QCM) was employed to measure deposition of hydrophobic colloidal material including microstickies. The method of using QCM to estimate microstickies deposition was described in detail elsewhere [10,11]. The pulp sample was filtered through a 500-mesh sieve (25-µm opening). The filtrate was injected immediately into the QCM-D300 (Q-Sense; Newport Beach, CA, USA) apparatus to monitor the shift of frequency caused by deposition or adsorption onto the sensor surface. Because the QCM sensor surface was coated with hydrophobic polystyrene before the measurement, it could measure hydrophobic colloidal materials such as microstickies.

RESULTS AND DISCUSSION

Estimation of effective cavitation zone

Figure 2 shows the influence of upstream pressure and nozzle dia. on the effective cavitation zone for ink detachment. For a 1.2-mm nozzle dia. and 5-MPa upstream pressure, the zone was shaped like a candle flame. Increasing the pressure from 5 MPa to 7 MPa extended the length of the zone. Using the larger 2-mm-dia. nozzle expanded the radius, and the zone was shaped as a bicone or dicone (i.e., a geometric shape created by two circular cones placed base to base). The maximum size of the cavitation zone using the 2-mm nozzle at 7 MPa was estimated as a bicone 45 mm in diameter and 45 mm in length.

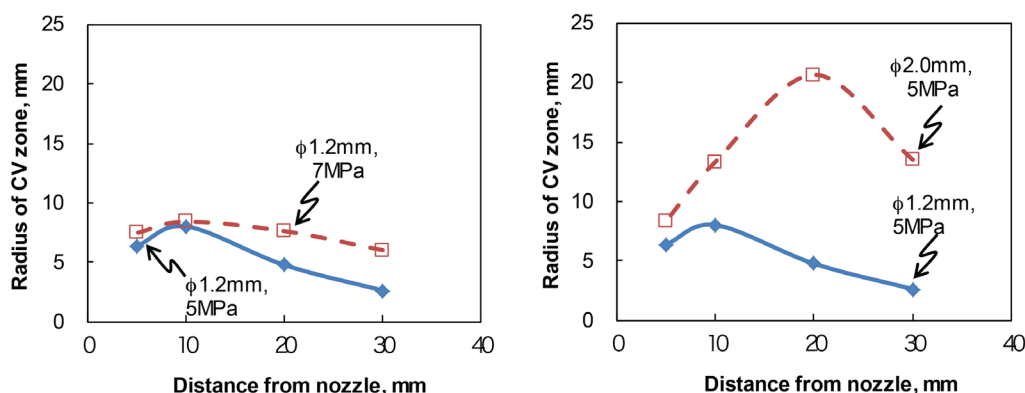
Design and manufacture of the pilot cavitation device

Figure 3 shows the configuration and nozzle arrangement of the reacting vessel and the layout of the pilot cavitation de-

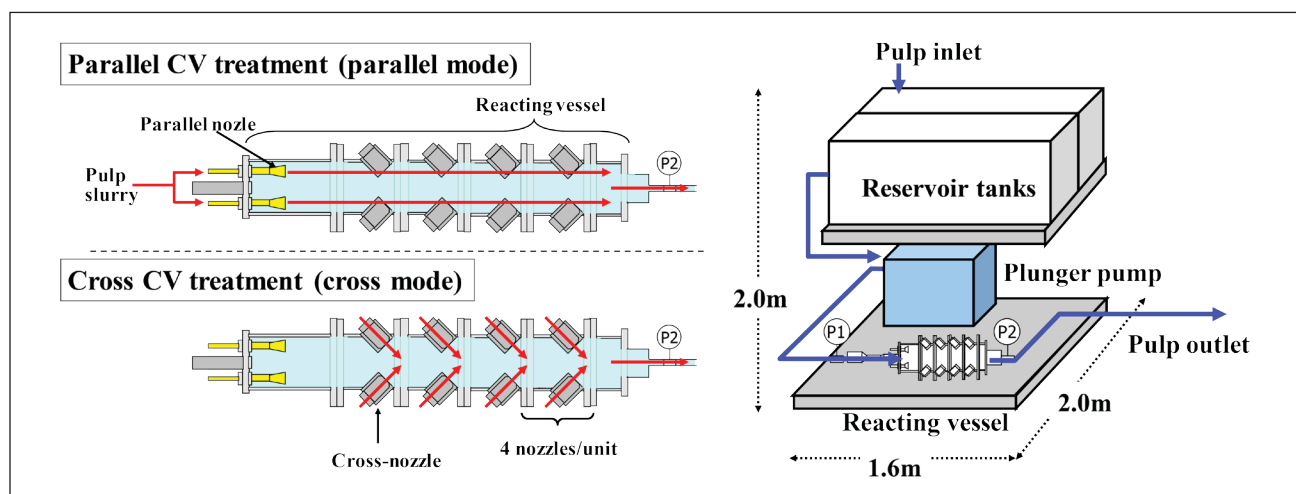
vice, which could test parallel and cross-nozzle modes of treatment. Because the maximum diameter of the cavitation zone per nozzle was 45 mm, the size of the reacting vessel equipped with four parallel nozzles was fixed at a diameter of 100 mm. There are four cross-nozzles in a unit with a 45° angle against the axis of the vessel. Four units comprised the side of the vessel. Pulp slurry was taken into the reservoir tank and then pressurized and jetted into the reacting vessel via parallel or cross-nozzles. The intensity of cavitation was controlled by the upstream pressure, P1, and downstream pressure, P2. This device could run with a batch or continuous treatment.

Batch treatment of deinked pulp using pilot cavitation device

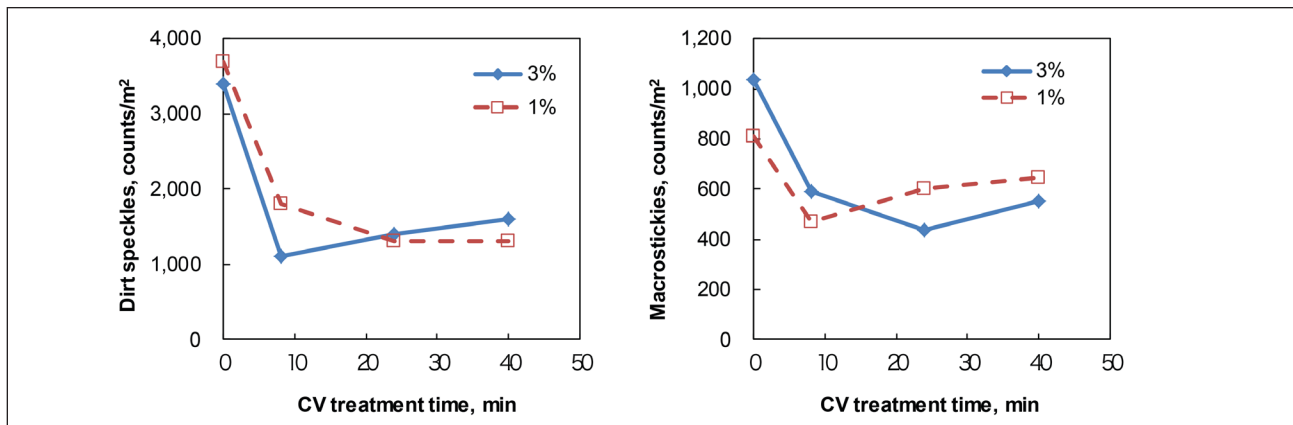
Pulp consistency is important in terms of reducing the specific energy consumption of the treatment. Therefore, the deinked pulp from the outlet of the prethickener with a consistency of 3% by weight was tested by the pilot cavitation device with



2. Influence of upstream pressure (left) and nozzle diameter (right) on the effective cavitation zone. The X axis shows the distance between the cavitation nozzle and the metal rod painted with oil-based ink. The Y axis is the radius of ink detachment area of the rod (i.e., effective cavitation zone for ink detachment).



3. Configuration and nozzle arrangement of reacting vessel (left) and schematic view of the pilot cavitation device (right). Parallel mode: 4 nozzles in the edge of the vessel are used and the lines to the cross-nozzles are closed. Cross mode: 4–16 nozzles in the sidewall of the vessel are used. The throughput of the plunger pump is 5 m³/h; maximum pressure is 9 MPa.



4. Effects of cavitation treatment on the reduction of dirt counts (left) and macrostickies (right) as functions of treatment time. The treatments were conducted at 1% and 3% pulp consistencies with batch treatment (multipass treatment), upstream pressure 7 MPa, and downstream pressure 0.1 MPa.

batch treatment using the 2-mm parallel nozzles, 7-MPa upstream pressure, and 0.1-MPa downstream pressure. The pulp, with consistency around 1% after a cleaner, was treated as well.

Results of dirt and macrostickies counts after cavitation treatment are shown in **Fig. 4**. It was clear that cavitation treatment reduced dirt counts in a short time, and then the effect plateaued. Cavitation treatment decreased macrostickies as well. Norman et al. reported that the effect of ultrasonic transducer treatment on the dirt reduction of pulp from laser-printed paper decreased when increasing the pulp consistency up to 1.5% [12]. In contrast to their observations, cavitation treatment at 3% consistency gave similar results to those of 1% consistency. This difference could be explained by the difference in the method used to generate cavitation bubbles [8].

Because cavitation treatment decreased the number of macrostickies, it was thought that the amount of microstick-

ies increased. Our previous studies revealed that cavitation treatment fragmented macrostickies and modified the nature of stickies. The colloidal materials, including microstickies, after cavitation treatment decreased their hydrophobicity; in other words, those materials become hydrophilic [8,9]. The possibility of microstickies deposition was estimated by QCM measurement. **Figure 5** shows that relative change in Δf after cavitation treatment decreased by half at 24 min and then increased around 70%. The influence of pulp consistency was small. It was verified that the stickies after pilot cavitation treatment did not adhere to the hydrophobic sensor surface easily.

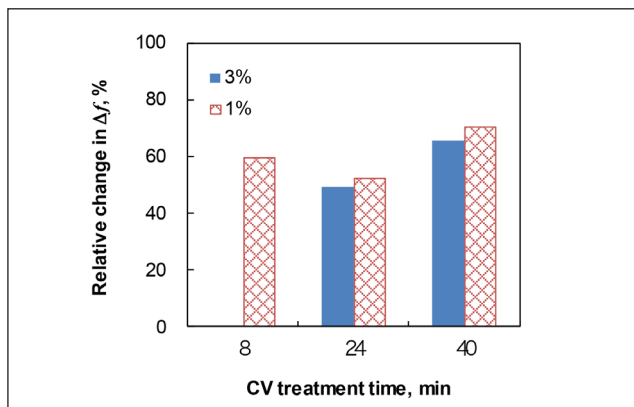
Figure 6 shows the brightness and ERIC values of the hyper-washed pulp before and after cavitation treatment. The brightness was increased after the treatment at 1% consistency, whereas it hardly changed at 3% consistency. The ERIC values decreased after the treatment, with similar results at 1% and 3%. These results suggested that cavitation treatment detaches ink from fiber. The difference of the consistencies on brightness might be lumen loading or precipitation of dispersed ink.

Continuous treatment of deinked pulp

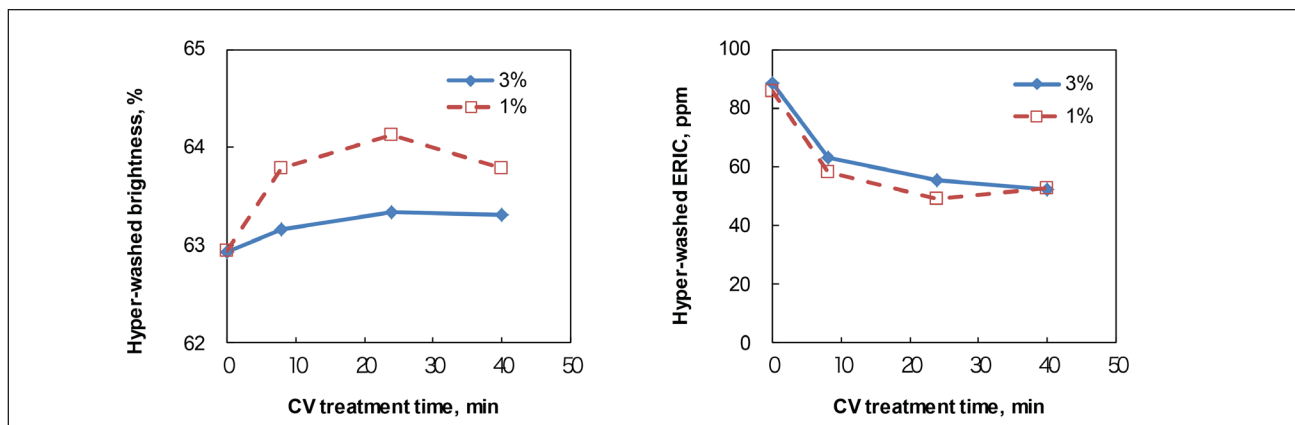
As described previously, the pilot cavitation device could work almost similar to laboratory cavitation [9]. The effect of continuous treatment using the 2-mm parallel nozzles was verified next. The results of continuous treatment (i.e., single-pass treatment) are shown in **Fig. 7**. In this test, the influence of downstream pressure was also examined. Note that cavitation hardly occurred when the downstream pressure was zero. Clearly, cavitation treatment with upstream and downstream pressures of 7 MPa and 0.1 MPa, respectively, decreased macrostickies area and average size.

Comparison of parallel and cross-mode treatment

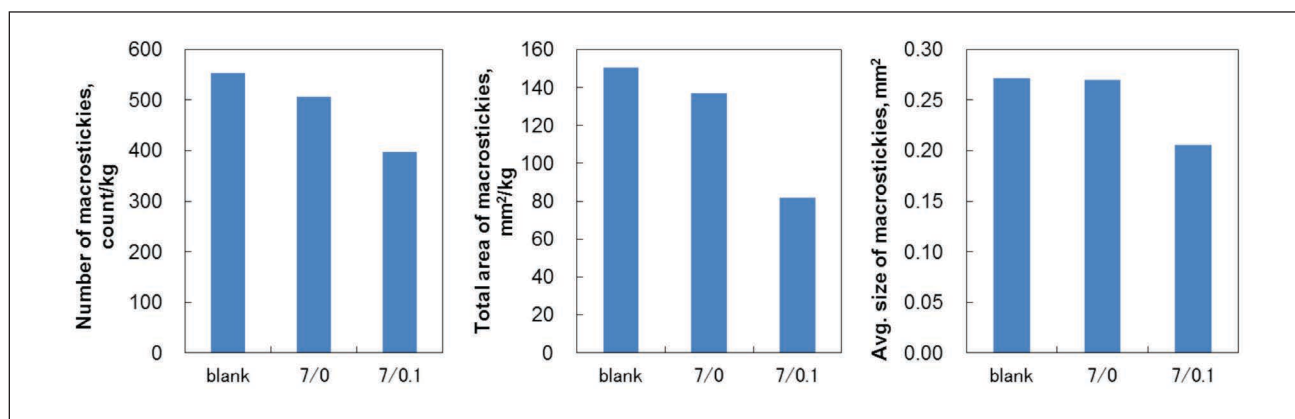
Two types of cavitation treatment mode, using the 2-mm par-



5. Relative changes in the shifts of resonance frequency (Δf) in the quartz crystal microbalance of the samples after cavitation treatment. Relative percentages are calculated from the Δf value after cavitation treatment relative to the samples without cavitation treatment. The conditions of the treatment were the same as in Fig. 4.



6. Effects of cavitation treatment on the brightness (left) and ERIC (right) of hyper-washed pulp as functions of treatment time. The conditions of the treatment were the same as in Fig. 4. The pulp was hyper-washed before and after treatment.



7. Effects of cavitation treatment on count (left), total area (middle), and average size (right) of macrostickies. The treatments were conducted at 3.3% pulp consistency with continuous treatment (single-pass treatment).

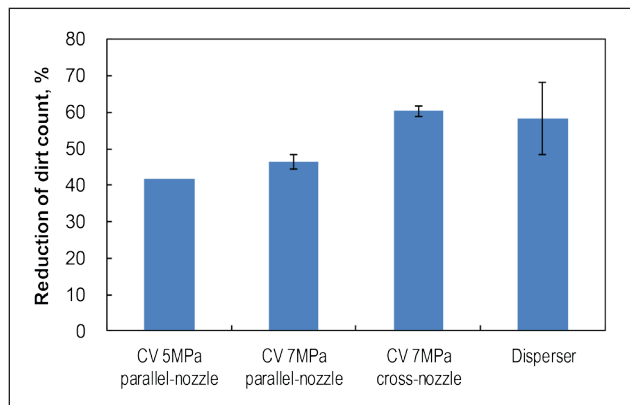
allel or cross-nozzles, were tested and compared with the mill disperser several times. The results of cavitation treatments on dirt reduction are summarized in **Fig. 8**. Pulp consistencies of those treatments were 3.4%–3.8% by weight, and the pulp passed through the device only once.

The parallel-mode cavitation treatment with 5 MPa and 7 MPa decreased dirt specks about 40%. On the other hand, the cross-mode treatment decreased it around 60% — almost the same as the mill disperser. For dirt reduction, therefore, cross mode was better than parallel mode.

Figure 9 shows the effect of those treatment modes on macrostickies reduction. In this case, parallel-mode cavitation treatment with 5 MPa gave the greatest reduction of macrostickies. The difference of cavitation mode at 7 MPa was hardly observed. The reduction after disperser treatment was much lower than cavitation treatments and the results showed considerable variation.

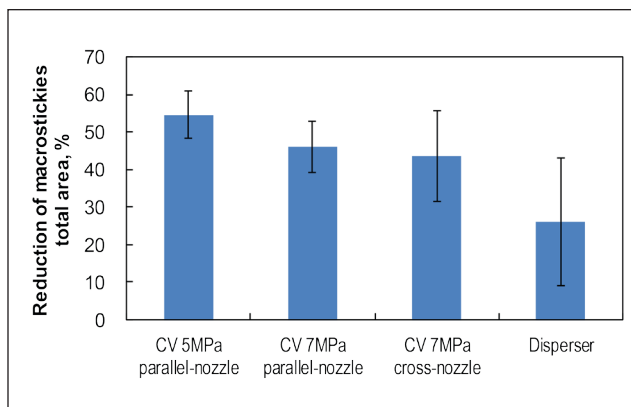
Energy consumption and other findings from pilot cavitation device

The device could treat deinked pulp with consistency up to 3.8% by weight, and the maximum throughput of the device



8. Comparison of cavitation treatment mode and conditions on dirt reduction. The treatments were conducted four times, except for the condition of the 5-MPa parallel nozzle that was conducted twice, at 3.4%–3.8% pulp consistency with continuous treatment (single-pass treatment) on different days.

was 4.5 tons/day. The specific energy consumption of cavitation treatment at the upstream pressure 7 MPa calculated from these results was around 70 kW·h/ton. The energy consumption of the pilot device was found to be relatively high in com-



9. Comparison of cavitation treatment mode and conditions on macrostickies reduction. The conditions of treatments were the same as in Fig. 8.

parison to conventional kneader and disperser (about 20-70 kW·h/ton). However, energy consumption was significantly lower than the laboratory cavitation device and previous liquid whistle treatment [13], at about 400 kW·h/ton and 830-2120 kW·h/ton, respectively.

Continuous running tests, over more than 24 h, were conducted and no major trouble occurred that would stop operation. Erosion and wear of the reacting vessel was hardly observed after the running time of more than 500 h. Some of the nozzle tips of were worn away slightly (data not shown); this might be avoided by selecting suitable material for the tip.

ABOUT THE AUTHORS

We chose this topic to research because of the need for a new technology that can solve the contradiction between optical quality and paper strength of secondary fiber. Although conventional deinking technology uses mechanical force for ink detachment and breakage, we applied cavitation bubbles that acted as a surface-selective force.

The most difficult aspect of our research was to improve the performance of the cavitation device. To address that difficulty, we designed and developed a pilot-scale device to increase treatment con-

sistency. The most surprising finding was that cavitation jet treatment decreased the number of macrostickies and the tackiness of microstickies.

This technology has the potential to simplify the deinking process. The next step is to develop a practical-scale cavitation device.

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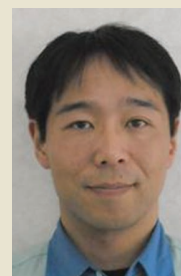
Watanabe



Ono



Tsuji



Onodera

CONCLUSIONS

The first pilot-scale CV-jet device was successfully designed and developed. The pilot device decreased dirt specks and macrostickies like the laboratory-scale device. Hydrophobic colloidal materials, including microstickies after cavitation treatment, became more difficult to attach to hydrophobic surfaces. Continuous cavitation treatment gave similar results to those from batch treatment. The device equipped two treatment modes, parallel nozzle and cross-nozzle, and both treatment modes decreased dirt specks to the same level as the mill disperser. Moreover, the modes reduced macrostickies to a greater extent than a mill disperser. Because treatment consistency increased more than 3%, efficiency of the treatment and performance of the device were significantly improved. Therefore, this could be a big step to practical use of cavitation treatment. **TJ**

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