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Research article

Laboratory prototype proof of appliance for washing sesame seeds

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Abstract

An initial prototype was developed to prove the theoretical background behind the conceptual design of an appliance for washing sesame seeds. Specifically, the study addressed the practical problem of dry, uncleaned sesame seeds being poured into the top of the water tank and not all sinking evenly through the water so that sand grains were not completely separated from the sesame seeds. Two additional parts were introduced in the current work using a laboratory scale prototype: 1) a new extension tank added on top of the original water tank and 2) a perforated dual-disc check valve added in between the old tank and the new extension tank. These modifications resulted in a total time to wash 7 kg of uncleaned sesame seeds being reduced by approximately 61% compared to a common manual method used by Thai farmers. Furthermore, the amount of water used in the cleaning process was reduced by 74%.

Introduction

The ideas or concepts behind sesame seed cleaning machines available in the market today belong to two schools of thought. The first prefers to use air to remove dirt from the uncleaned sesame seeds, based on a winnowing type machine. The second exploits water instead of air to remove dirt from the uncleaned sesame seeds, the so-called water type machines.

Since winnowing type machines such as the machine introduced by Bunsit et al. (2007) use air to separate the dirt and dust from sesame seeds, the operation only removes very fine sand grains which are much lighter than the sesame seeds. Even though the sand grains and dirt that are bigger and much heavier than one sesame seed can be additionally screened out by a sieve and the winnowing process, the sand grains having a similar mass to sesame seeds still remain in the uncleaned sesame seeds.

Similarly, for water type machines such as the sesame seed washing machine developed by RMUTL (Komjing et al., 2009) as well as the seed cleaning machines XMS40 Model (Hebei Ruixue Grain Selecting Machinery Co., Ltd., 2017) and ASL-XMJ10 Model (Zhengzhou Aslan Machinery Co., Ltd., 2013), sand grains having a similar mass to the

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sesame seeds are not separated from the sesame seeds. The sand grains and the sesame seeds with similar masses do not fall to the bottom of water tank due to gravity since the free fall is dominated by the rotation from the stirring mechanism.

The manual cleaning processes by farmers involve winnowing the uncleaned sesame seeds as the first step to get rid of dust and dirt. However, the farmers may not be aware that very fine sand grains which are much lighter than one sesame seed have also been removed simultaneously. In step two, the uncleaned sesame seeds are manually washed in water buckets repeatedly to remove some of the heavier sand grains. This step separates sand grains from the sesame seeds that are much heavier than one sesame seed.

Eventually, in the last step after roasting for 30 minutes, the sand grains are separated from the sesame seeds by winnowing again. The isolated sand grains from this step are sand grains having a similar mass to one sesame seed before roasting. The sand grains and sesame seeds can now be separated because of their mass differences from the roasting process, since the sesame seeds have lost some mass after roasting, while the sand grains have not.

Thus, the winnowing type machines can deal with sand grains that are much lighter than one sesame seed. The water type machines can deal with sand grains that are much heavier than one sesame seed. However, all of the available washing machines are incapable of isolating sand grains that have a similar mass to one sesame seed.

A number of principles come into play to get rid of foreign particles suspended in either in a gas or liquid. An electrostatic precipitator (ESP) seems to be of great interest. ESP uses a high direct current voltage (normally 5–50 kV) to provide particles in the gas with an electrical charge that are then attracted to the collecting electrode walls (Finlayson-Pitts and Pitts, 2000). However, this method is too costly and is only effective for particle sizes in the 0.05–5 μm range.

A baghouse, which comprises an array of long and narrow fabric-filter bags suspended upside down, is similar to the manual sieving process. (Peirce et al., 1997; Schiller and Schmid, 2015) The efficiency of this method depends greatly on filters, similar to the sieving method, so this technique may not be suitable for sesame seeds.

A hydrocyclone uses water mist or vapor to collect fine particles during separation and purification (Zhang et al., 2020; Li et al., 2019). Cyclonic separation can purify particle sizes in the range 5–40 μm and consequently, is not appropriate for 1.41 mm sand particles.

Spray tower traps suspend particles by direct contact with spray of water. A spray tower can generally remove 90% of particulates of about 8 μm (Nathanson, 2010) that are much smaller than 1.41 mm sand particles. However, a spray tower has very large exhaust flows of 50 m^3/s or greater and requires a high inlet water pressure in the range 2,070–3,100 kPa (Schifftner, 2002).

A gravity settling chamber is the oldest and simplest mean of removing suspended particles by reducing the velocity of the stream in a horizontal duct sufficiently to allow particles to settle down (Jones, 2016). A gravity settling chamber is suitable for particle sizes smaller than 50 μm and so is not suitable for 1.41 mm sand particles (Vasarevicius, 2012).

Based on the calculations in the companion paper (Eiamsa-ard et al., 2021), the key concept of the proposed machine is that sand grains sink to the bottom of a water tank faster than sesame seeds because of their shape differences, even though they have similar masses. The machine comprises five components: a water tank, funnel, Y-junction, sand collector and a drain outflow tube, as shown in Fig. 1.

Similar to the manual washing method used by farmers, the uncleaned sesame seeds are winnowed to remove their outer covering and some dust, which are both very much lighter than one sesame seed. In addition, sand grains which are heavier and bigger in size than one sesame seed can be screened out from this winnowing. To ensure that all the sand grains that are smaller and lighter than the sesame seeds can be isolated, an additional process is added, namely a no.14 sieve is used to screen out these as a preparation step, following the ASTM Standard, as shown in Fig. 2. After applying these two processes, the sand grains remaining in the uncleaned sesame seeds have a similar mass to one sesame seed.

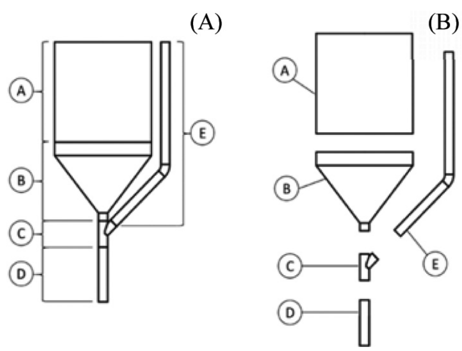

Fig. 1 Conceptual and analytical design: (A) machine assembly; (B) machine components, where A = water tank, B = funnel, C = Y-junction, D = sand collector, and E = drain outflow tube

Fig. 2 (A) sieve no. 14; (B) uncleaned sesame seeds after passing through sieve no. 14

The detailed explanation of the washing system is provided in Eiamsa-ard et al. (2021). Briefly, the process involves the following steps: 1) fill the tank with water and use an air pump to stir up the water in the tank; 2) pour the sieved, uncleaned sesame seeds into the washing machine (Fig. 3A); 3) after stirring for at least 15 s, turn off the air pump; 4) the sand grains sink to the bottom of the tank faster than the sesame seeds (Fig. 3B); 5) the sand grains sink into the sand collector (Fig. 3C) and the sesame seeds accumulate on top of the sand grains; 6) the drain outflow tube can now be lowered (Fig. 3D) to remove the cleaned sesame seeds via the Y-junction, leaving the sand grains in the sand collector.

The washing machine functions properly only when the sesame seeds and sand grains are all immersed in water as shown in Fig. 4A. However, the dry, uncleaned sesame seeds are poured onto the water at the top of the water tank (Figs. 4B and 4C) resulting in unequal speed rates of the seeds as the first seeds to become wet and sink in the water first, as shown in Fig. 4D.

Due to the fact that the sesame seeds and sand grains fall at different speeds, if they are not all immersed in the water at the beginning as mentioned earlier, the sand grains cannot fully separate from the sesame seeds by the time they reach the bottom of the tank. Some of the sesame seeds that are already immersed in the water sink to the bottom rapidly and are subsequently buried under further layers of uncleaned sesame seeds that are floating on the water surface because they drop at different speeds. Although all the sesame seeds and sand grains do eventually drop, a noticeable amount of sand remains mixed with the sesame seeds, similar to the manual washing method by sesame farmers as shown in Fig. 5. The conceptual design ultimately fails if the dry uncleaned sesame seeds are poured onto the water surface at the top of the water tank.

Materials and Methods

The revised process uses unchanged the five necessary machine components (water tank, funnel, Y-junction, sand collector and drain outflow tube). However, to rectify the issues highlighted in the previous section, the following modifications were implemented for further experimentation. Two additional parts were added to the modified washing machine design: a new extension tank added on top of the original water tank and a perforated dual-disc check valve added in between the old tank and the new extension tank, as shown in Fig. 6.

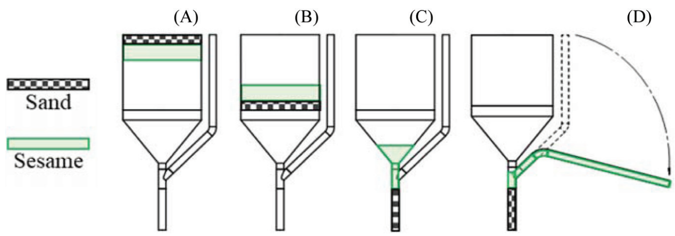

Fig. 3 Conceptual design of the washing machine: (A) sieved uncleaned seeds added; (B) sand grains sink faster than sesame seeds; (C) sand grains accumulate in sand collector; (D) drain outflow opened to remove seeds

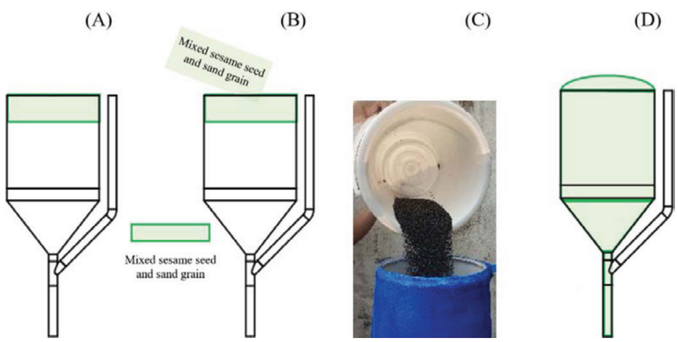

Fig. 4 (A) original water tank; (B) and (C) dry, uncleaned sesame seeds are poured onto the water at the top of the original water tank; (D) some uncleaned sesame seeds are immersed in the water but some remain floating on water surface

Fig. 5 After being washed, the sesame seeds still have sand grains mixed in

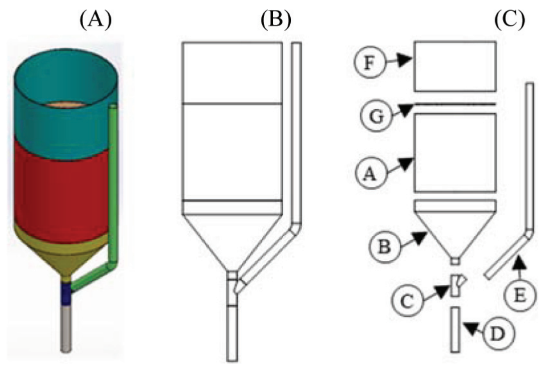

Fig. 6 Modified design of laboratory scale prototype (A) pictorial view of washing machine; (B) front view; (C) exploded view, where A = water tank, B = funnel, C = Y-junction, D = sand collector, E = drain outflow tube, F = new extension tank and G = perforated dual-disc check valve (drawn to scale)

The dual-disc check valve in this crude prototype was made of polypropylene perforated with 1.41 mm diameter holes to allow water to pass through. The dual-disc check valve acts as a barrier to separate the uncleaned sesame seeds from the water, as shown in Figs. 7A, 7B and 7C. Initially, the dual-disc check valve was very difficult to open when it consisted of solid flat plates. However, the added perforations aid in balancing the water pressure when the machine is ready to release the uncleaned sesame seeds, as shown in Fig. 7C. The edges of dual-disc check valve are held in place via ropes. Those ropes can be released to let the dual-disc check valve open under the influence of gravity plus some provided external force.

To guarantee all the uncleaned sesame seeds are immersed in the water before the perforated dual-disc check valve is released, air is pumped through a polyurethane tube above the center of the dual-disc check valve. Once the uncleaned sesame seeds are poured onto the closed perforated dual-disc check valve, the uncleaned sesame seeds are then exposed to the bubbles emanating from this air pump that scrub and wash the uncleaned sesame seeds for around 15 s, as shown in Fig. 7D.

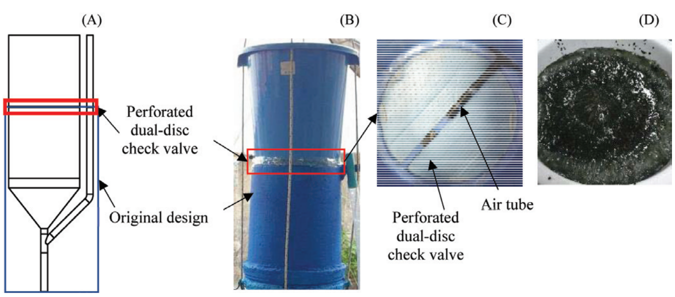

Fig. 7 (A) newly added dual-disc check valve; (B) position of the dual-disc check valve;(C) air tube at center of tank above perforated dual-disc check valve (plan view); (D) uncleaned sesame seeds being washed and scrubbed with air bubbles

Although the water remains in the bottom of original tank, additional water is added into the new extension water tank above the perforated dual-disc check valve. The perforated dual-disc check valve is normally closed before pouring the uncleaned sesame seeds into the extension water tank, as shown in Fig. 8.

Another set of experiments was undertaken using a glass-bottomed water tank by varying the volumes of water in this water tank, as shown in Fig 9. Air was pumped through a polyurethane tube running into this water tank to scrub and wash 7 kg of uncleaned sesame seeds for a short period by turning on the air pump. The time intervals to fully scrub the uncleaned sesame seeds and let the uncleaned sesame seeds become immersed in the water were recorded. A chart between the time interval used to scrub the uncleaned sesame seeds and the amount of water used for scrubbing is plotted in Fig. 10 and was used to determine the optimal amount of water and time interval to scrub the uncleaned sesame seeds.

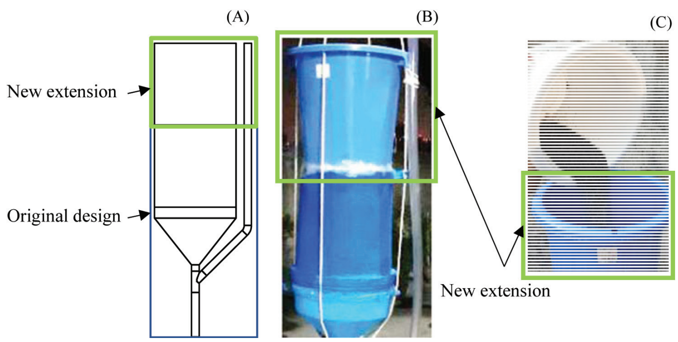

Fig. 8 (A) position of new extension tank; (B) new extension tank added to top of original tank; (C) pouring sesame seeds into new extension tank

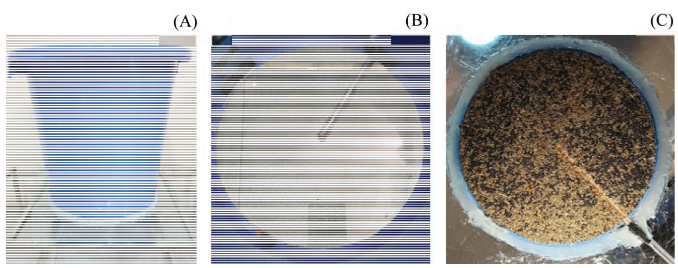

Fig. 9 (A) glass-bottomed water tank with air pump inserted; (B) polyurethane tube in water tank (plan view); (C) testing for optimum volume of water and length of time to wash and scrub uncleaned sesame seeds (plan view)

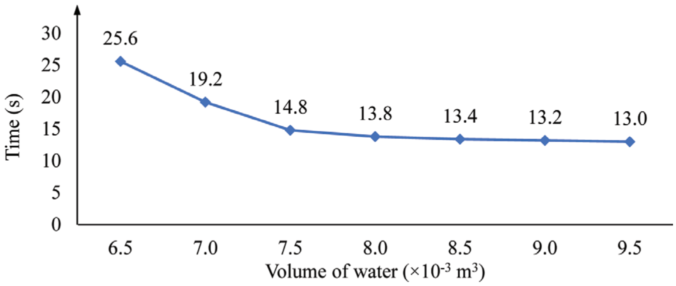

Fig. 10 Impact of addition of water on average washing time

The plotted results indicated that the optimum water volume was 7.5×10^{-3} m^3 for a time interval of approximately 15 s for the uncleaned sesame seeds to be scrubbed. It was noted that the scrubbing time was only reduced by approximately 1 s by adding additional 0.5 L amounts of water (Fig. 10).

The first laboratory scale prototype of the sesame washing machine was attached by four ropes running up the length of the machine to a beam above, as shown in Fig. 11A. The washing machine was filled with water until the volume of water above the perforated dual-disc check valve was 7.5×10^{-3} m^3. Then the dual-disc check valve was closed (Fig. 11B) and the air pump was turned on so that the air was pumped through the polyurethane tube into the water tank extension (Fig. 11C). Next, the uncleaned sesame seeds were poured into the water tank (Fig. 11D) and the uncleaned sesame seeds were scrubbed and washed for 15 s (Fig. 11E), after which the air pump was turned off.

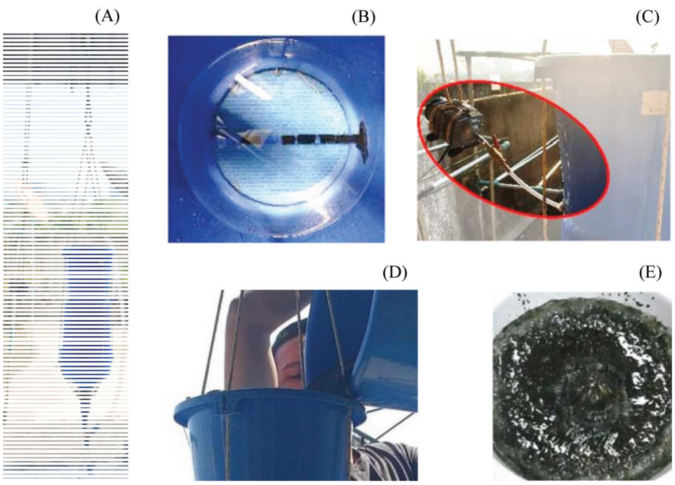

Fig. 11 (A) washing machine; (B) extension tank with polyurethane tube above dual-disc check valve; (C) air pump; (D) pouring in uncleaned sesame seeds; (E) uncleaned sesame seeds being scrubbed with air bubbles

Next, the perforated dual-disc check valve was released (Figs. 12A and 12B) so that the uncleaned sesame seeds formed a cylindrical shape in the water tank as expected in the conceptual design. Notably, the uncleaned sesame seeds were all immersed in the water before the perforated dual-disc check valve was opened. The sand grains sink to the bottom of the water tank faster than the sesame seeds do because of their shape difference even though they have similar masses. After the valve is released, the sand grains (which have a similar mass to one sesame seed) because of their shape difference can now drop faster than the seeds to the bottom of the sand collector. Then, the sesame seeds land on top of the sand grains (Fig. 12C). The drain outflow tube can now be lowered to allow the cleaned sesame seeds to flow out to storage, leaving the sand grains in the sand collector.

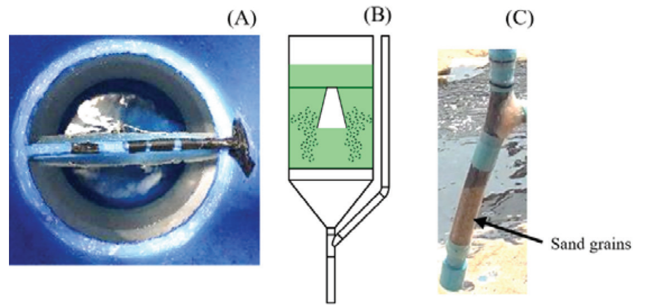

Fig. 12 (A) opened perforated dual-disc check valve; (B) diagram of uncleaned sesame seeds dropping; (C) sand grains (arrow) accumulated in sand collector

Changes in water tank and funnel design

For the additional water volume (V_{ExT}) of 7.5×10^{-3} m^3 for the new extension water tank above the perforated dual-disc check valve and a diameter of the water tank of 0.3 m, the height of the additional water (H_{ExT}) can be calculated using Equation 1:

$$H_{ExT} = \frac{V_{ExT}}{\text{Tank Area}} = \frac{7.5\times10^{-3}}{\pi\left(\frac{0.300}{2}\right)^2} = 0.106\ \text{m} \text{(as shown in Fig. 13)} \quad (1)$$

From Eiamsa-ard et al. (2021), the sinking behavior of the sand grains in water can be classified into two phases. Phase-1 occurs from t = 0 s to t = 0.176 s, where the sand grains accelerate as they sink. Phase-2 occurs from t = 0.176 s onward, where the sand grains sink in the water with a constant terminal velocity of $v_{T,s} = 0.146$ m/s.

Phase-1 ($t < 0.176$ s): Since the period is so small, the acceleration of the sand grains can be approximated using a linear function:

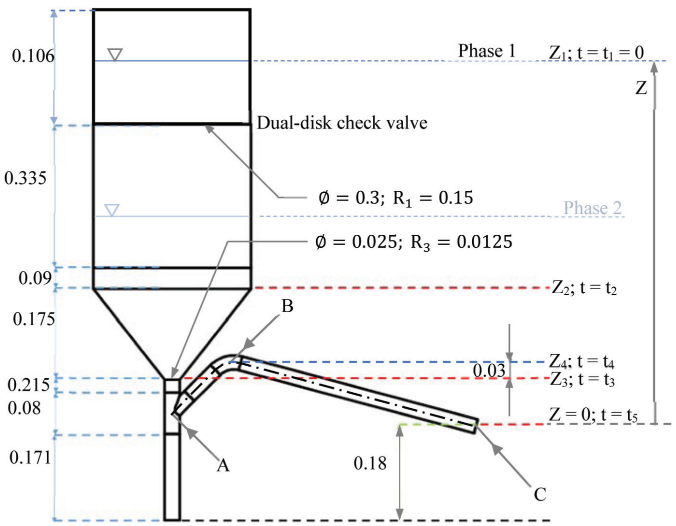

Fig. 13 New configuration of washing machine by adding extension tank and dual-disk check valve, where A = start point of drain outflow tube, B = diminishing point of drain outflow tube, C = the exit of drain outflow tube, R_i = radius of container at phase i, Z_j = height of water at time t_j (not drawn to scale)

$a_S = a_{MAX,S} - \left(\frac{a_{max}}{t_{T,s}}\right)$, where $a_{max,s} = 3.487$ m/s^2 and $t_{T,s} = 0.176$ s.

From Eiamsa-ard et al. (2021),

$$S_{1,S} = \left(\frac{a_{max,s}}{2}\right)t^2 - \left(\frac{a_{max,s}}{6t_{T,s}}\right)t^3$$

$$\left(\frac{3.487}{2}\right)(0.176)^2 - \left(\frac{3.487}{6 \times 0.176}\right)(0.176)^3 = 0.036 \text{ m}$$

Phase-2 ($t \geq 0.176$ s): In this period, the sand grains travel with a constant velocity: $v_{T,s} = 0.146$ m/s.

From Fig. 13,

$S_{Total} = 0.106 + 0.335 + 0.09 + 0.175 + 0.215 + 0.08 + 0.171 = 1.172$ m

From Eiamsa-ard et al. (2021), as shown in Fig. 13,

Height of sand collector (H_{SC}) = 0.171 m

Travel distance of sand grains in Phase-1 ($S_{1,s}$) = 0.036 m

$$S_{2,s} = V_{T,s} \times t_s$$

$$\therefore t_s \; \frac{1.172 - 0.171 - 0.036}{0.146} = 6.61 \text{ s}$$

Therefore, the total time for the initial sand grains to dropping to the top of the sand collector is 6.61 + 0.176 = 6.79 s.

From Eiamsa-ard et al. (2021), Fig. 13 shows the behavior of the sesame seeds sinking in the water, which can be classified into two phases. Phase-1 occurs from t = 0 s to t = 0.170 s, where the sesame seeds accelerate as they sink. Phase-2 occurs from t = 0.170 s onward, where the sesame seeds sink in the water with constant terminal velocity ($v_{T,ss}$) = 0.063 m/s

Phase-1 ($t < 0.170$ s): Since the period is so small, the acceleration of the sesame seeds can be approximated using a linear function:

$a_{SS} = a_{MAX,SS} - \left(\frac{a_{max}}{t_{T,ss}}\right)t$ where $a_{max,ss} = 1.803$ m/s^2 and $t_{T,ss}$ = 0.170 s.

From Eiamsa-ard et al. (2021),

$$S_{1,ss} = \left(\frac{a_{max,ss}}{2}\right)t^2 - \left(\frac{a_{max,ss}}{6t_{T,ss}}\right)t^3$$

$$\left(\frac{1.803}{2}\right)(0.170)^2 - \left(\frac{1.803}{6 \times 0.170}\right)(0.170)^3 = 0.0174 \text{ m}$$

Phase-2 ($t \geq 0.170$ s): In this period, the sesame seeds travel with constant velocity ($v_{T,ss}$) = 0.063 m/s.

From Fig. 13,

$S_{Total} = 0.106 + 0.335 + 0.09 + 0.175 + 0.215 + 0.08 + 0.171 = 1.172$ m

From Eiamsa-ard et al. (2021), as shown in Fig. 13,

Height of sand collector (H_{SC}) = 0.171 m

Travel distance of sesame seed in Phase-1 ($S_{1,ss}$) = 0.0174 m

Height of sesame seeds in water tank (H_{ss}) = 0.1707 m

$$S_{2,ss} = v_{T,ss} \times t_{ss}$$

$$\therefore t_{ss} = \frac{1.172 - 0.171 - 0.0174 - 0.1707}{0.063} = 12.9 \text{ s}$$

Therefore, the total time for the first cleaned sesame seeds to sink and reach the top surface of the sand sediment in the sand collector is 12.9+0.17 = 13.07 s.

Changes in drain outflow design

As shown in Fig. 13, the flow from the drain outflow tube can be divided into five phases: 1) Phase-1 from Z_1 to Z_2; 2) Phase-2 from Z_2 to Z_3; 3) Phase-3 from Z_3 to Z_A; 4) Phase-4 from Z_A to Z_4 and 5) Phase-5 from Z_4 to Z = 0. The times spent in Phase-1 and Phase-2 dominate the times in for the other three phases. Ideally, the velocity of pure water at the end of drain outflow tube (v_C) can be calculated using Bernoulli's equation as Equation 2:

$$P_A + \frac{1}{2}\rho v_A^2 + \rho g Z_A = P_C + \frac{1}{2}\rho v_C^2 + \rho g Z_C \quad (2)$$

$$\rho g(Z - Z_A) + 0 + \rho g Z_A = 0 + \frac{1}{2}\rho v_C^2 + 0$$

$$\therefore v_{C\,(Ideal)} = \sqrt{2gZ}$$

The ideal volume flow rate of pure water ($v1 = \sqrt{2gZ}$) is reduced due to the vena contracta effect for a sharp-edged outlet to Q1 = 0.61A , where $A\sqrt{2gZ} = \pi r^2$, as shown in Fig. 14, so that . $v_2 = 0.61v_1$ However, the cleaned sesame seeds accumulate along the bottom of the drain outflow tube causing clogging that reduces the volume flow rate at the end of the tube. Since the tube is not very large, the effect of the accumulation can be approximated by a linear velocity profile of the water and cleaned sesame seeds, as shown in Fig. 14.

Draining Phase-1: determining the drain out time in Phase-1 (t_2)

From Fig. 14; $H = 2 \times r$; and $v = \frac{h}{H} v_{max}$

$$h - r = r \cdot \sin\theta \quad \rightarrow \quad dh = r \cdot \cos\theta \cdot d\theta$$

$$x = r \cdot \cos\theta \quad \rightarrow \quad dx = -r \cdot \sin\theta \cdot d\theta$$

$$dQ = (2x)\left(\frac{h}{H}\right) v_{max} \cdot dh$$

$$\frac{H}{2v_{max}} dQ = x \cdot h \cdot dh = (r^2\cos^2\theta)(r + r \cdot \sin\theta)d\theta$$

$$\frac{H}{2v_{max}} \int_0^Q dQ = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} (r^3\cos^2\theta)d\theta + \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} (r^3\cos^2\theta\sin\theta)\, d\theta$$

$$\frac{H}{2v_{max}} Q = r^3\left[\frac{\theta}{2} + \frac{\sin 2\theta}{4} + C_1\right]_{-\frac{\pi}{2}}^{\frac{\pi}{2}} + r^3\left[\frac{\cos^3\theta}{3} + C_2\right]_{-\frac{\pi}{2}}^{\frac{\pi}{2}} = \frac{\pi}{2} r^3$$

$$\therefore Q = \left(\frac{r}{H}\right) v_{max}(\pi r^2) = \frac{v_{max}(\pi r^2)}{2}$$

Therefore, the flow rate of water at the end of drain outflow tube is

$$Q_C = \frac{C_C}{2} \cdot A_C \cdot v_C = \frac{C_C}{2} \cdot \pi \cdot r_C^2 \cdot v_C = (\frac{0.61}{2})\pi(0.01025)^2 \cdot v_C$$

$$Q_C \cdot dt = \frac{C_C}{2} \cdot \pi \cdot r_C^2 \cdot v_C \cdot dt = -dV = -A_{Tank} \cdot dZ = -\pi \cdot R^2 \cdot dZ$$

$$dt = -\frac{2R^2 \cdot Z^{-\frac{1}{2}}}{C_C \cdot r_C^2 \cdot \sqrt{2g}} dZ$$

$$\int_{t_1=0}^{t_2} dt = -\frac{2R^2}{C_C \cdot r_C^2 \cdot \sqrt{2g}} \int_{Z_1}^{Z_2} Z^{-\frac{1}{2}} dZ$$

$$t_2 - 0 = -\frac{2R^2}{C_C \cdot r_C^2 \cdot \sqrt{2g}} \left[2Z^{\frac{1}{2}}\right]_{Z_1}^{Z_2}$$

$$\therefore t_2 = -\frac{2\sqrt{2} \times 0.15^2}{(0.61) \times 0.01025^2 \cdot \sqrt{9.81}} \left[Z_2^{\frac{1}{2}} - Z_1^{\frac{1}{2}}\right]$$

$$= -\frac{2\sqrt{2} \times 0.15^2}{(0.61) \times 0.01025^2 \cdot \sqrt{9.81}} \left[\sqrt{0.461} - \sqrt{0.992}\right]$$

$$= 100.51 \text{ s}$$

Draining Phase-2: determining the drain out time in Phase-2 (t_3)

From Fig. 15,

$z = Z - Z_3$ and $\frac{h_3}{R_3} = \frac{h}{R} \quad \rightarrow \quad h = h_3 \frac{R}{R_3}$

$$V = \frac{1}{3}\pi R^2 h - \frac{1}{3}\pi R_3^2 h_3 = \left(\frac{\pi}{3}\right)[R^2 h - R_3^2 h_3] = \left(\frac{\pi}{3}\right)\left(\frac{h_3}{R_3}\right)[R^3 - R_3^3]$$

$$= \left(\frac{\pi}{3}\right)\left(\frac{h_3}{R_3}\right)(R - R_3)(R^2 + R_3^2 + RR_3) = \left(\frac{\pi}{3}\right)(z)(R^2 + R_3^2 + RR_3)$$

$$\frac{R_2 - R_3}{Z_2 - Z_3} = \frac{R - R_3}{z} \quad \rightarrow \quad R = \left(\frac{R_2 - R_3}{Z_2 - Z_3}\right) z + R_3$$

$$V = \left(\frac{\pi}{3}\right)(z)\left(\frac{(R_2 - R_3)^2 z^2}{(Z_2 - Z_3)^2} + \frac{2(R_2 - R_3)R_3 z}{(Z_2 - Z_3)} + R_3^2 + R_3^2 + \frac{(R_2 - R_3)R_3 z}{(Z_2 - Z_3)} + R_3^2\right)$$

$$= \left(\frac{\pi}{3}\right)\left(\frac{(R_2 - R_3)^2 z^3}{(Z_2 - Z_3)^2} + \frac{3(R_2 - R_3)R_3 z^2}{(Z_2 - Z_3)} + 3R_3^2 z\right)$$

$$dV = (\pi)\left(\frac{(R_2 - R_3)^2 z^2}{(Z_2 - Z_3)^2} + \frac{2(R_2 - R_3)R_3 z}{(Z_2 - Z_3)} + R_3^2\right) dz$$

QC • dt = –dV

$$\frac{C_C}{2} \cdot A_C \cdot v_C \cdot dt = -(\pi)\left(\frac{(R_2 - R_3)^2 z^2}{(Z_2 - Z_3)^2} + \frac{2(R_2 - R_3)R_3 z}{(Z_2 - Z_3)} + R_3^2\right) dz$$

$$\frac{C_C}{2} \cdot \pi \cdot r_C^2 \cdot v_C \cdot dt = -(\pi)\left(\frac{(R_2 - R_3)^2 z^2}{(Z_2 - Z_3)^2} + \frac{2(R_2 - R_3)R_3 z}{(Z_2 - Z_3)} + R_3^2\right) dz$$

$$dt = -\frac{2}{C_C \cdot r_C^2 \cdot \sqrt{2g}}\left(\frac{(R_2 - R_3)^2 z^{\frac{3}{2}}}{(Z_2 - Z_3)^2} + \frac{2(R_2 - R_3)R_3 z^{\frac{1}{2}}}{(Z_2 - Z_3)} + R_3^2 z^{-\frac{1}{2}}\right) dz$$

$$\int_{t_2}^{t_3} dt = -\frac{2}{C_C \cdot r_C^2 \cdot \sqrt{2g}} \int_{Z_2 - Z_3}^{0} \left(\frac{(R_2 - R_3)^2 z^{\frac{3}{2}}}{(Z_2 - Z_3)^2} + \frac{2(R_2 - R_3)R_3 z^{\frac{1}{2}}}{(Z_2 - Z_3)} + R_3^2 z^{-\frac{1}{2}}\right) dz$$

$$\therefore t_3 - t_2 = -\frac{2}{C_C \cdot r_C^2 \cdot \sqrt{2g}}\left[\frac{2(R_2 - R_3)^2 z^{\frac{5}{2}}}{5(Z_2 - Z_3)^2} + \frac{4(R_2 - R_3)R_3 z^{\frac{3}{2}}}{3(Z_2 - Z_3)} + 2R_3^2 z^{\frac{1}{2}}\right]_{Z_2 - Z_3}^{0}$$

$$\therefore t_3 = \frac{2(Z_2 - Z_3)^{\frac{1}{2}}}{C_C \cdot r_C^2 \cdot \sqrt{2g}}\left[\frac{2(R_2 - R_3)^2}{5} + \frac{4(R_2 - R_3)R_3}{3} + 2R_3^2\right]$$

$$= \frac{2(0.175)^{\frac{1}{2}}}{0.61 \times 0.01025^2 \times \sqrt{2 \times 9.81}}\left[\frac{2(0.1375)^2}{5} + \frac{4(0.1375)(0.0125)}{3} + 2 \times 0.0125\right]$$

$$= 29.96 \text{ s}$$

Draining Phase-3: determining the draining time in Phase-3 (t_4)

$$\therefore t_4 = -\frac{2r_C^2}{C_C \cdot r_C^2 \cdot \sqrt{2g}}\left[2Z^{\frac{1}{2}}\right]_{Z_3}^{Z_A} = -\frac{2\sqrt{2}}{(0.61) \times \sqrt{9.81}}\left[Z_A^{\frac{1}{2}} - Z_3^{\frac{1}{2}}\right]$$

$$= -\frac{2\sqrt{2}}{(0.61) \times \sqrt{9.81}}\left[\sqrt{0.211} - \sqrt{0.466}\right] = 0.34 \text{ s}$$

Draining Phase-5: determining the drain out time in Phase-5 (t_6)

$$Z = \frac{Z_B}{L_B} L \quad \rightarrow \quad dZ = \frac{Z_B}{L_B} dL$$

$$Q_{Dr} \cdot dt = -dV$$

$$\pi \cdot r_C^2 \cdot v_C \cdot dt = -\pi \cdot r_C^2 \cdot dL$$

$$dt = -\frac{Z^{-\frac{1}{2}}}{\sqrt{2g}} dL = -\left(\frac{L_B}{Z_B\sqrt{2g}}\right) Z^{-\frac{1}{2}} dZ$$

$$\int_{t_5}^{t_6} dt = -\left(\frac{L_B}{Z_B\sqrt{2g}}\right) \int_{Z_4}^{Z_C} Z^{-\frac{1}{2}} dZ$$

$$\therefore t_6 - t_5 = -\left(\frac{2L_B}{Z_B\sqrt{2g}}\right)\left[Z^{\frac{1}{2}}\right]_{Z_4}^{Z_C}$$

$$\therefore t_6 = \left(\frac{\sqrt{2} \times 1.06}{0.316 \times \sqrt{9.81}}\right)\left[\sqrt{0.496} - \sqrt{0.18}\right] = 0.424 \text{ s}$$

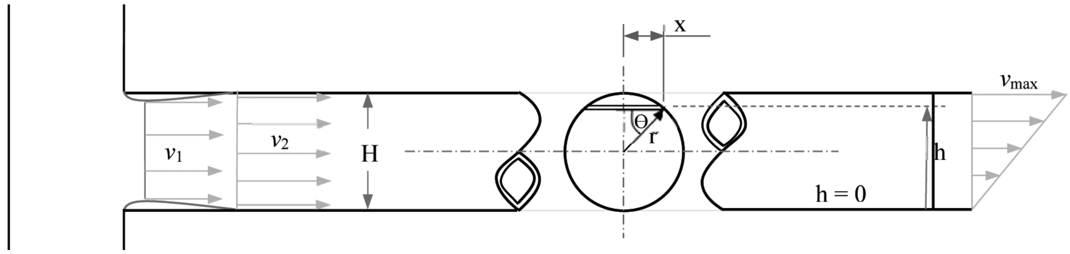

Fig. 14 Vena contracta effect (v_2) for a sharp-edged outlet and clogging caused by sesame sediment accumulating along drain outflow tube, where v_1 = ideal volume flow rate of pure water, H = maximum height of water in the tube, r = tube radius, h = vertical distance measured from the bottom edge of the tube, v_{max} = maximum velocity at the exit of drain outflow tube (not drawn to scale)

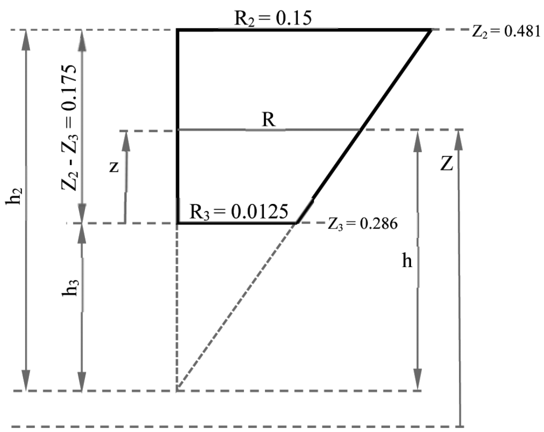

Fig. 15 Dimensions of washing machine funnel, where R_i is the radius of the truncated-cone- shaped funnel at height h_i, z_i = height of water measured from the lower end of the funnel, Z_j = height measured from the top of the flipped cone (not drawn to scale)

Draining Phase-4: determining the drain out time in Phase-4 (t_5)

$$\therefore t_5 - t_4 = -\left(\frac{2L_B}{Z_B\sqrt{2g}}\right)\left[Z^{\frac{1}{2}}\right]_{Z_A}^{Z_4}$$

$$\therefore t_5 = \left(\frac{2 \times 0.316}{\sqrt{9.81}}\right)\left[\sqrt{0.316} - \sqrt{0.211}\right] = 0.02 \text{ s}$$

Total drain out time $t_{Dr} = t_1 + t_2 + t_3 + t_4 + t_5$ = 100.51 + 29.96 + 0.34 + 0.424 + 0.02 = 131.25 s

Note that in the calculations above, the quantity of sand grains blended in 7 kg of uncleaned sesame seeds was doubled in Eiamsa-ard et al. (2021) to cope with uncertainties. Therefore, the total drain-out time of 131.25 s from the calculations above may be excessive compared to the real test results.

Results and Discussion

All parameters as mentioned earlier were implemented and tested using the laboratory scale prototype. The times used to wash 7 kg of uncleaned sesame seeds for this sesame seed washing machine prototype can be summarized as follows:

- Time for filling water to the washing machine = approximately 58 s.
- Time for scrubbing uncleaned sesame seeds = approximately 15 s.
- Time for sand grains falling into the sand collector = approximately 13 s.
- Time to release sesame seeds from the drain outflow = approximately 114 s.

Therefore, the total time to wash 7 kg of uncleaned sesame seeds using this laboratory scale prototype was approximately 200 s, consuming 3.628×10^{-2} m^3 of water, as shown in Table 1.

It was not possible to soak all the uncleaned sesame seeds in the water before starting the washing process without using the perforated dual-disk check valve. Therefore, pouring the dry uncleaned sesame seeds onto the water surface at the top of water tank resulted in unequal rates of sinking, as some seed would fall quickly but some would remain floating on the water surface before sinking; hence, the sand grains could not be fully separated from the uncleaned sesame seeds. With the perforated dual-disk check valve closed, the uncleaned sesame seeds could all be immersed in the water and then washed and scrubbed thoroughly by the air bubbles from the air pump installed in the new extension tank added on top of the original water tank.

Table 1 Volume of water and time used for protype machine compared to manually wash by farmers

Method	Sesame seed mass (kg)	Time (s)			Volume of water (m^3)	
		Set up Machine (for 1 cycle)	Operation (for 1 cycle)	Total time (per 1 kg sesame seed)	For Operation	Per 1 kg sesame seed
Farmer	7	32	480	73.143	0.140	0.0200
Prototype	7	58	142	28.571	0.036	0.0052
% Reduction		$\frac{(512 - 200) \times 100}{512} \approx 61\%$			$\frac{(0.14 - 0.036) \times 100}{0.14} \approx 74\%$	

Fig. 16 shows the results after washing the uncleaned sesame seeds using this laboratory scale washing machine prototype. Clearly, Fig. 16B shows that very fine sand grains could be successfully separated from the sesame seeds shown in Fig 16A.

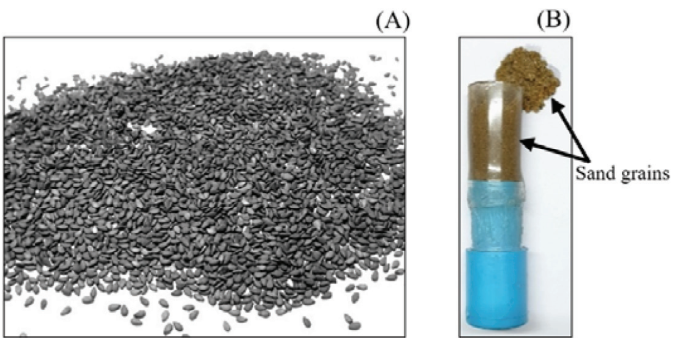

Fig. 16 Result after washing (A) sesame seeds after being washed by prototype machine; (B) sand grains (arrow) separated from sesame seeds by a prototype machine

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

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