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Research article

Conceptual and analytical design of sesame seed washing machine

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Abstract

Sesame is one of the oldest oilseed crops that has been domesticated for well over 3,000 years; it remains a common ingredient in cuisines globally. Sesame seeds are protected by a capsule that only bursts when the seeds are completely ripe; consequently, they must be cleaned before being used in the next process because of the fine to very fine sand grains that usually are attached to the uncleaned seeds. However, this cleaning-up process is both water- and time-consuming. The manual process currently used by farmers to clean the sesame seeds requires 0.14 m^3 (140 L) of water and takes 480 s for only 7 kg of sesame. A couple of washing machines that have been tested for this cleaning-up process were able to separate the coarse and fine sand particles, but were inefficient at separating the very fine grains that also damaged the machinery. The current study investigated the development of a conceptual and analytical design of a new washing machine using 0.035 m^3 (35 L) of water, which is considerably less than for current machines, with a cleaning-up process of 126 s.

Introduction

Sesame has one of the highest oil contents of any seeds, with a high nutritional value containing approximately 44–60% of essential oil and has considerable economic significance in Thailand due to the large area of farmland where it can be produced (Wongyai, 2005). Farmers are currently failing to meet the daily demand of 1,000 kg a day, as quality control continues to find sand grains mixed in with the final product, resulting in its rejection by the sweetmeat industry (Komjing et al., 2009).

One of the key reasons why sesame farmers cannot respond to the demand at the present time is because they can only wash 420–440 kg per day by blowing air through the grains to remove its outer covering, known as winnowing, followed by cleaning the seeds in water to remove any sand grains (Komjing et al., 2009).

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Traditionally, the seeds are cleaned manually. First, farmers put 7 kg of uncleaned sesame seeds into buckets as shown in Fig. 1A. Second, they add around 0.02 m^3 (20 L) of water into the buckets and stir by hand. Third, they scoop out the sesame seeds that naturally form on top of the sand grains after they both sink to the bottom of the bucket (Fig. 1B). All three steps are then repeated a further six times, with seven times in total.

Clearly, this traditional method consumes a lot of time and water (8 min to wash 7 kg of sesame seeds in about 0.14 m^3 (140 L) of water. Notably, this time excludes filling and refilling the water in the buckets. Therefore, this manual method is inefficient for larger-scale production to supply the demand (Wongyai, 2005; Komjing et al., 2009).

After the washing process previously described has been done, farmers roast the 7 kg of washed sesame seeds in a roasting machine taking approximately 30 min. After roasting, there is still a considerable amount of sand grains remaining with the sesame seeds. Therefore, further time is be needed to separate the leftover sand grains from sesame seeds using the winnowing process again, as shown in Fig. 2.

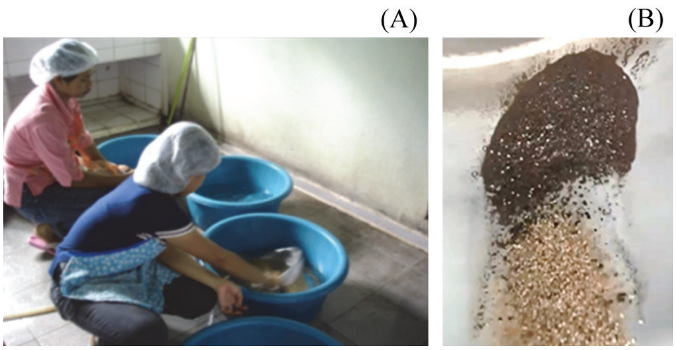

Fig. 1 Manual method: (A) adding water and stirring; (B) separating sand from sesame seeds

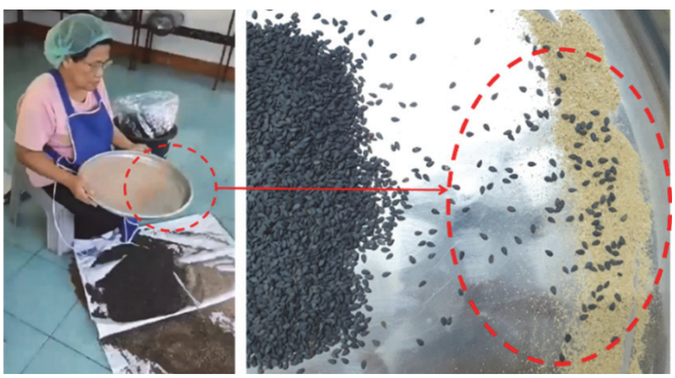

Fig. 2 Winnowing the sesame seeds after roasting to further remove sand grains

There are several options for sesame seed cleaning machines currently available. These machines can be categorized into: 1) winnowing type machines and 2) water type machines.

The winnowing type machines use air to remove the sesame seeds from dirt, as shown in Figs. 3A and 3B (Bunsit et al., 2007). The problem with this machine is that the air does not remove enough of the sand grains in with the uncleaned sesame seeds and is not satisfactory for a production process as the farmers need to wash the uncleaned sesame seeds with water afterward.

The water type machines shown in Fig. 4 use water to clean and separate sand from the seeds. These machines usually involve the operation of motors, valves and conveyors. The manual ASL-XMJ10 washing machine, shown in Fig. 4A (Zhengzhou Aslan Machinery Co., Ltd., 2013) uses water pressure to isolate the sand grains from the sesame seeds. This machine requires approximately 5 min and 0.058 m^3 (58 L) of water to clean 10 kg of sesame seeds, using the following steps: 1) the machine is filled with water and the uncleaned sesame seeds are poured into the machine; 2) the uncleaned seeds are washed by circulating the inner cylindrical bowls; and 3) the sesame seeds are scooped out from the top of the machine. However, this manual washing machine is incapable of fully extracting the sand from the seeds and very fine sand grains can potentially get stuck in the valve and cause damage to the machine.

The sesame washing machine (Fig. 4B), developed by Rajamangala University of Technology Lanna (RMUTL; Komjing et al., 2009) operates as follows: 1) the tank is filled with water and the machine is run for about 5 min; 2) uncleaned sesame seeds are poured into the tank filled with water; 3) the uncleaned sesame in the tank is stirred to separate the sand from seeds; 4) the screw conveyor inside the machine delivers some of the sesame seeds vertically from the top of the machine so only the heavy sand grains sink to the bottom of the tank, though light sand grains may accompany the seeds coming out from the top of the machine; and 5) the entire process takes approximately 9 min with 0.39 m^3 (390 L) of water to clean 18 kg of sesame seeds.

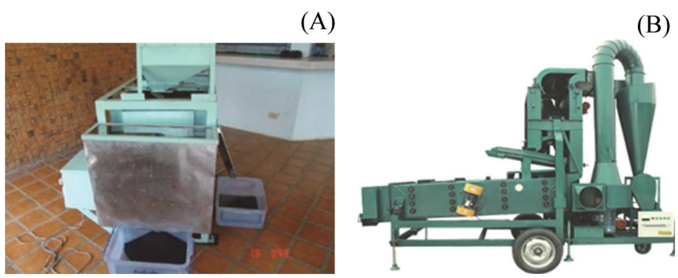

Fig. 3 Winnowing machine types: (A) sesame cleaning and roasting machine; (B) seed cleaner and grader

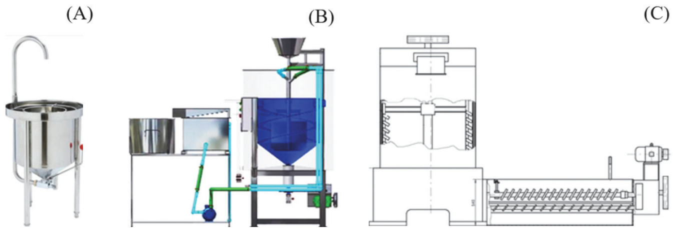

Fig. 4 Water type machines: (A) manual washing machine model ASL-XMJ10; (B) sesame washing machine from Rajamangala University of Technology Lanna; (C) seed cleaning and drying machine model XMS40

The sesame cleaned using this RMUTL machine is still not purified as there are some remaining very fine sand grains with similar weights to the sesame seeds, as shown in Fig. 2. In addition, the machine is damaged by the sand grains stuck in the screw conveyor. Thus a large amount of cleaning time is required combined with a large volume of water. Thus, this RMUTL machine does not satisfactorily address the time and water issues.

The seed cleaning and drying machine model, XMS40 (Hebei Ruixue Grain Selecting Machinery Co., Ltd., 2017), shown in Fig. 4C, also uses a screw conveyor and a valve similar to the RMUTL machine. However, the uncleaned sesame seeds are fed into the machine horizontally for washing before moving vertically to separate the sand grains through the water before passing the seeds out at the top.

The dimension of the XMS40 are 1,920 mm × 760 mm × 1,700 mm and thus, this machine is suitable for larger-scale production as it can clean 1,000 kg of sesame seeds/h using 0.5 m^3 (500 L) of water. Nonetheless, leftover sand grains still cause damage to the valve and the screw conveyor in the machine similar to the ASL-XMJ10 machine. Both machines are unable to purify the sesame seeds adequately.

Therefore, the current study investigated a new design to solve this problem.

Materials and Methods

Basic properties of sesame seeds and sand grains

A prerequisite was the properties of sesame seeds and sand grains before and after their contact with water. Sesame has a density (ρ_{ss}) of 1,224 kg/m^3 with a bulk density ($\rho_{b,ss}$) of 580 kg/m^3 and most characteristics are similar for seed though seed size may vary (Akintunde and Akintunde, 2004; Komjing et al., 2009). Division of the thickness of the seeds following a line from the highest point to the lowest point (Figs. 5A and 5B) indicated the thicknesses of the two sides was frequently not the same. The center of mass point (CM point) then leans toward the thicker side, as shown in Fig. 5B.

By inspection of sesame seed shapes, the average dimensions are roughly estimated by width (W), length (L) and thickness (T) shown in Fig. 5 to represent the seeds.

A bootstrapping method (Ruppert, 2011) was used to estimate the dimensions of sesame seeds because: 1) collected samples may not provide the best representative dataset of the sesame seed population and therefore, the arithmetic mean and standard deviation of the sample dataset may not be reliable, especially when samples contain outliers; 2) the bootstrapping method is a statistical technique which is flexible and efficient when applied to a small dataset; and 3) the collected data are resampled with replacements in the bootstrapping method, and hence the data set can grow reasonably. Thus, the estimated mean and standard deviation of the dataset are more reliable with less correlation from outliers.

The bootstrapping method involved: 1) collecting 100 samples from the sesame seed population to generate a dataset of 100 entries; 2) sampling 100 samples from the collected data set using the replacement technique to generate a new dataset of 100 entries; 3) repeating step 2 199 times to generate 200 new datasets in total including the original dataset from step 2; 4) Calculating the arithmetic means for all 200 new datasets yielding; 5) computing the arithmetic mean of the 200 arithmetic means in step 4, namely, the bootstrapping mean; 6) computing the standard deviation of the 200 arithmetic means in step 4, namely, the bootstrapping standard error. The bootstrapping means and their corresponding standard errors were used as the representative sample of the seeds in the current study.

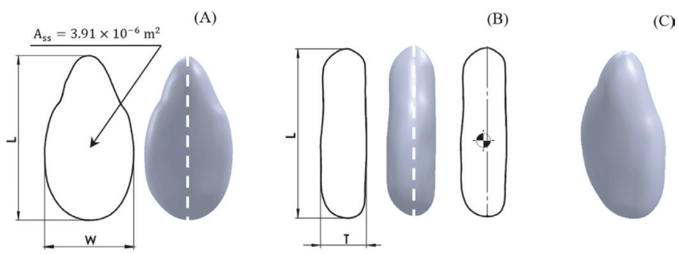

Fig. 5 Sesame seed (A) front view; (B) side view showing center of mass point; (C) isometric view, where A_{ss} is the cross-sectional area of sesame seed, W is the width and T is the thickness

Based on the bootstrapping mean and standard error values, the representative sesame seed with width (W) of 1.690 mm (SE = 0.007), length (L) of 3.122 mm (SE = 0.008) the thickness (T) of 0.851 mm (SE = 0.004) were modelled in a computer-assisted drawing software package (SOLIDWORKS 2020; Applicad Public Company Limited, Bangkok, Thailand), as shown in Fig. 5. Using the CAD software, the volume and mass of one sesame seed were 1.795×10^{-9} m^3 and 2.197×10^{-6} kg, based on Equations 1 and 2, respectively.

$$\text{Volume one sesame seed: } V_{SS} = 1.795 \times 10^{-9}\ \text{m}^3 \quad (1)$$

Mass one sesame seed:

$$M_{SS} = \rho_{SS} \times V_{SS} = 1{,}224 \times 1.795 \times 10^{-9} = 2.197 \times 10^{-6}\ \text{kg} \quad (2)$$

Sand collected by farmers using the traditional method described above was used in a number of experiments based on Archimedes principle to determine the true density of the sand. The water displaced by sand was weighed to calculate the equivalent volume of water, and hence the true volume of dry sand. The weight of dry sand before being immersed in the water was used to calculate the equivalent mass of dry sand. The true density of sand was calculated as the equivalent mass of dry sand divided by the true volume of dry sand.

On the other hand, the bulk density of sand can be determined in a much simpler way. A certain amount of dry sand was poured into a beaker from which the bulk volume of dry sand was determined and the sand in the beaker was weighed. The weight of sand in the beaker was used to calculate the equivalent total mass of sand in the beaker. Similarly, the bulk density of the sand was calculated as the total mass of the dry sand in the beaker divided by the bulk volume of the dry sand.

The results indicated that fine sand grains collected by farmers had an average true density (ρ_s) of 1,550 kg/m^3 and an average bulk density ($\rho_{b,s}$) of 1,520 kg/m^3. Since the true densities of sesame seeds and sand grains are greater than that of water, they will both sink to the bottom of a water container when they are poured into water. Sesame seeds do not float on the water surface.

Uncleaned sesame seeds and fine sand grains collected by farmers were classified by shaking them with three consecutive ASTM standard-sized sieves: no.12, no.14 and no.16. Sieve no.12 has a sieve opening of 1.68 mm, which is too coarse for classifying the size of sand grains because both the sesame seeds and fine sand grains can pass through this sieve. Sieve no.16 has a sieve opening of 1.19 mm, which is fine enough for sesame seeds not to pass through this sieve. However, fine sand grains could pass through sieve no.16 and would be too small to be accounted for in the following calculations.

Sesame seeds cannot pass through sieve no.14 that has a sieve opening of 1.41 mm. while sand grains with diameters smaller than 1.41 mm can pass through sieve no.14. Therefore, the smallest sand grain that cannot pass though sieve no.14 probably has a diameter of around 1.41 mm. Similarly, given that the sand grains can pass through sieve no. 12, the biggest sand grain probably has a diameter of around 1.68 mm. Therefore, the diameters of sand grains remaining with the uncleaned sesame seeds after sieving should be in the range 1.41–1.68 mm. The bigger the sand grains are, the faster the sand grains drop to the bottom of the water container. Sand grains with a diameter of 1.41 mm, which is the smallest, and hence the lightest would drop to the bottom of the container at the slowest speed. Thus, a diameter of 1.41 mm was used in the following calculations.

Assuming that a sand grain is spherical, the volume and mass of a single sand grain would be 1.468×10^{-9} m^3 and 2.275×10^{-6} kg, respectively, as shown in Equations 3 and 4, respectively:

$$\text{Volume one sand grain: } \frac{4}{3}\pi r^3 = \frac{4}{3}\pi\left(\frac{1.41\times10^{-3}}{2}\right)^3 = 1.468\times10^{-9}\ \text{m}^3 \quad (3)$$

Mass one sand grain:

$$M_S = \rho_S \times V_S = 1{,}550 \times 1.468 \times 10^{-9} = 2.275 \times 10^{-6}\ \text{kg} \quad (4)$$

These calculations clearly indicate that sesame seeds and sand grains after sieving have similar masses and hence similar equivalent weights. Based on the external rotational forces in the washing machine, sesame seeds and sand grains with similar weights should behave similarly. Therefore, sesame seeds and sand grains with similar weights are the main reason that the previous machines could not successfully separate the very fine sand grains from the sesame seeds.

Regarding the farmers' method, approximately 7 kg of sesame seeds are washed, and the bulk volume can be estimated using Equation 5:

Bulk volume of 7 kg sesame seed:

$$\frac{m_{ss}}{\rho_{b,ss}} = \frac{7}{580} = 1.207 \times 10^{-2}\ \text{m}^3 \quad (5)$$

Again, with regard to the farmer method and with reference to the RMUTL machine (Komjing et al., 2009), there were approximately 63.68×10^{-3} kg of sand grains blended with the 7 kg sesame seeds. This reference number was doubled to 127.36×10^{-3} kg in the following calculation to cope with uncertainties. Consequently, it can be estimated as shown in Equation 6:

Sand grain bulk volume in 7 kg seeds:

$$\frac{m_s}{\rho_{b,s}} = \frac{127.36 \times 10^{-3}}{1{,}520} = 8.379 \times 10^{-5}\ m^3 \quad (6)$$

Maximum acceleration rates of sesame seeds and sand grains

Drag force theory (Jarawae et al., 2015; Sukaphan, 2015) states that when one drops objects (sesame seeds and sand grains in this case) in fluid (water in this case) as shown in Fig. 6, the objects start sinking into the fluid (water) with maximum acceleration ($a_{max,ss}$ and $a_{max,s}$, both measured in meters per squared seconds) and zero velocities ($v_{ss} = v_s = 0$ m/s). After that, acceleration will be reduced from the maximum ($a_{max,ss}$ and $a_{max,s}$, both measured in meters per squared seconds) to zero ($a_{ss} = 0$ m/s^2; $a_s = 0$ m/s^2), yet the velocity will increased from zero ($v_{ss} = v_s = 0$ m/s) to the maximum at a constant terminal velocity ($v_{ss} = v_{T,ss}$; $v_s = v_{T,s}$, both measured in meters per squared seconds), which vary with the dimensions of the drag coefficients ($C_{D,ss}$; $C_{D,s}$) and cross-sectional areas (A_{ss}; A_s) of the sesame seeds and sand, respectively.

Before the actual documented dropping experiments started, some rehearsal tests were used to check the behavior of both the sesame seeds and sand grains. During the rehearsals, the times were estimated at which the sesame seeds and sand grains sank at constant speeds. The estimated times from the previous step were then used to determine when to start the timer in the real documented dropping experiments.

Following force theory, the free body diagram in Fig. 7 shows the balance of the three forces of weight, buoyancy force and drag force, as shown in Equations 7, 8, and 9, respectively:

Weight : $W = Mg = \rho g V$ (7)

Buoyancy force: $F_B = \rho_W g V$ (8)

Drag force: $F_D = \frac{1}{2}\rho_W A C_D v_T^2$ (9)

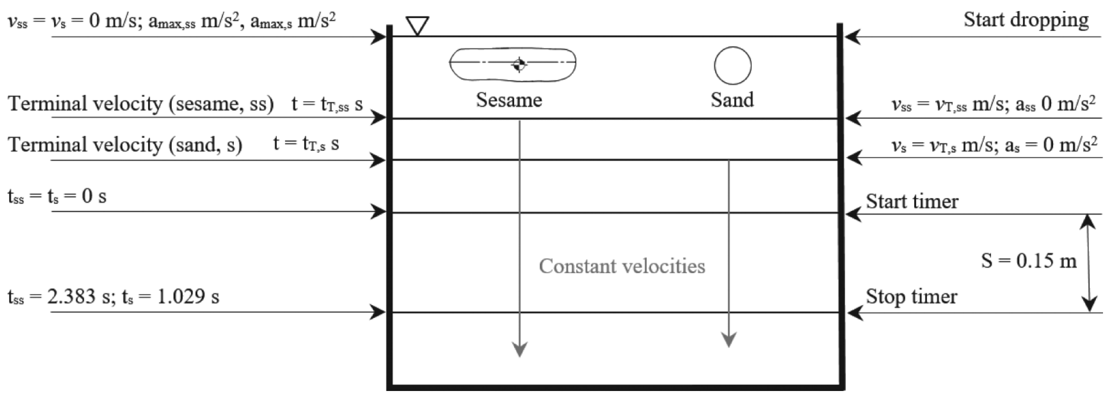

Fig. 6 Dropping objects (sesame seed and sand grain) into water, where not drawn to scale

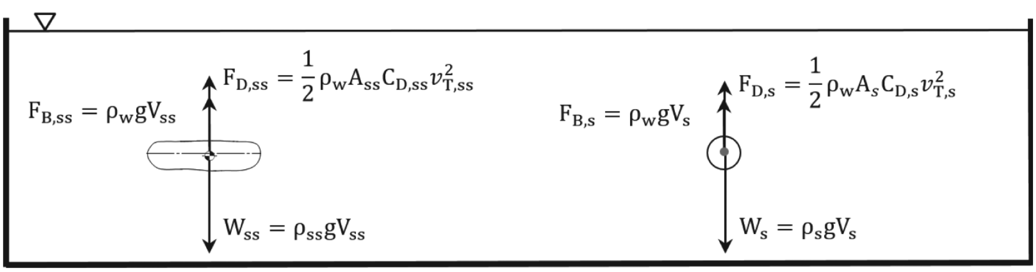

Fig. 7 Free body diagram of a particle falling in water, where not drawn to scale

At t = 0 s → $v = 0$, a = a_{max}

From Newton's 2nd law; ΣF = Ma

$$\rho gV - \frac{1}{2}\rho_W AC_D v^2 - \rho_W gV = \rho_W AC_D v^2 - \rho_W gV = \rho Va_{max}$$

$$\rho gV - 0 - \rho_W gV = \rho Va_{max}$$

$$\therefore a_{max} = (1 - \frac{\rho_W}{\rho})g$$

The maximum acceleration of sesame seeds ($a_{max,ss}$) is shown in Equation 10:

$$a_{max,ss} = \left(1 - \frac{\rho_w}{\rho_{ss}}\right) g = \left(1 - \frac{999}{1{,}224}\right) 9.81 = 1.803 \text{ m/s}^2 \quad (10)$$

The maximum acceleration of sand grains ($a_{max,s}$) is shown in Equation 11:

$$a_{max,s} = \left(1 - \frac{\rho_w}{\rho_s}\right) g = \left(1 - \frac{999}{1{,}550}\right) 9.81 = 3.487 \text{ m/s}^2 \quad (11)$$

Terminal velocities of sesame seeds and sand grains

To find the terminal velocities, the times were recorded for one sesame seed and one sand grain to travel a distance (S) of 0.15 m in water after the falling objects were moving at constant speeds (terminal velocities), as shown in Fig. 6. Since the objects were moving at constant speeds, their terminal velocities can be calculated using Equation 12:

$$v_T = \frac{S}{t} = \frac{0.15}{t} \quad (12)$$

where S is the travel distance of 0.15 m, and t is the travel time.

After the previously described dropping processes had been repeated 40 times for each of the objects, the average dropping times for sesame seeds for sand grains were 2.383 s and 1.029 s, as shown in Equations 13 and 14, respectively:

Terminal velocity of sesame seed:

$$v_{T,ss} = \frac{S}{t_{ss}} = \frac{0.15}{2.383} = 0.063 \text{ m/s} \quad (13)$$

Terminal velocity of sand grain:

$$v_{T,s} = \frac{S}{t_s} = \frac{0.15}{1.029} = 0.146 \text{ m/s} \quad (14)$$

Drag coefficients of sesame seeds and sand grains

After the seed started sinking in the water, because that the CM of the seed was not in the middle, the flat side containing the CM (thicker side), as shown in Fig. 5(A), was facing down perpendicular to the direction of sinking. Thus, the cross-sectional area of the sesame seed (A_{SS}) could be estimated from the CAD drawing in Fig. 5 ($A_{ss} = 3.91 \times 10^{-6}$ m^2). Since it was assumed that the shape of a sand grain is a sphere with a diameter of approximately 1.41 mm, the cross-sectional area of a sand grain (A_S) = $\pi r^2 = \pi(0.705 \times 10^{-3})^2 = 1.56 \times 10^{-6}$ m^2.

From Newton's 2nd law: $\sum F = Ma$ (v_T constant → a = 0)

$$\rho gV - \rho_w gV - \frac{1}{2}\rho_w AC_D v_T^2 = 0$$

$$\frac{1}{2}\rho_w AC_D v_T^2 = \rho gV - \rho_w gV$$

Drag coefficient: $$C_D = \frac{2gV(\rho - \rho_w)}{\rho_w A\, v_T^2}$$

Drag coefficient (sesame): $$C_{D,ss} = \frac{2gV_{ss}(\rho_{ss} - \rho_w)}{\rho_w A_{ss} v_{T,ss}^2}$$

$$= \frac{2 \times 9.81 \times 1.795 \times 10^{-9}(1{,}224 - 999)}{1.000 \times 3.91 \times 10^{-6} \times 0.063^2} = 0.511$$

Drag coefficient (sand): $$C_{D,s} = \frac{2g\, V_s(\rho_s - \rho_w)}{\rho_w A_s v_{T,s}^2}$$

$$= \frac{2 \times 9.81 \times 1.468 \times 10^{-9}(1{,}550 - 999)}{1{,}000 \times 1.56 \times 10^{-6} \times 0.146^2} = 0.477$$

Times at terminal velocities of sesame seeds and sand grains

Different drag coefficients can be expected to lead to different types of falling behavior. The times to their terminal velocities for both sesame seeds and sand grains are determined below.

At $0 < t \le t_T$ s → $0 < v \le v_T$, $a = \frac{dv}{dt}$

From Newton's 2nd law, ΣF = Ma

$$\rho gV - \frac{1}{2}\rho_w AC_D v^2 - \rho_w gV = \rho V\frac{dv}{dt}$$

$$\left(1 - \frac{\rho_w}{\rho}\right) g - \frac{1}{2\rho V}\rho_w AC_D v^2 = \frac{dv}{dt}$$

Let $K_1 = \left(1 - \frac{\rho_w}{\rho}\right) g$; $K_2 = \frac{\rho_w AC_D}{2\rho V}$; and $K_3 = \sqrt{\frac{K_2}{K_1}}$

$$K_1 (1 - K_3^2 v_T^2) = \frac{dv}{dt}$$

$$\int_0^{t_T} dt = \int_0^{v_T} \frac{dv}{K_1 (1 - K_3^2 v_T^2)}$$

$$\therefore t_T = \frac{\tanh^{-1}(K_3 v_T)}{K_1 K_3}$$

For sesame seeds,

$$K_{1,ss} = \left(1 - \frac{\rho_w}{\rho_{ss}}\right) g = \left[\left(1 - \frac{999}{1,224}\right)(9.81)\right] = 1.803$$

$$K_{2,ss} = \frac{A_{ss}\rho_w\, C_{D,ss}}{2\rho_{ss} V_{ss}} = \frac{(3.91 \times 10^{-6})(999)(0.511)}{2(1,224)(1.795 \times 10^{-9})} = 454.242$$

$$K_{3,ss} = \sqrt{\frac{K_{2,ss}}{K_{1,ss}}} = \sqrt{\frac{454.242}{1.803}} = 15.873$$

$$\therefore t_{T,ss} = \frac{\tanh^{-1}(K_{3,ss}\ \nu_{T,ss})}{K_{1,ss}\, K_{3,ss}} = 0.170 \text{ s}$$

For sand grains,

$$K_{1,s} = \left(1 - \frac{\rho_w}{\rho_s}\right) g = \left(1 - \frac{999}{1,550}\right)(9.81) = 3.487$$

$$K_{2,s} = \frac{A_s\rho_w\, C_{D,s}}{2\rho_s V_s} = \frac{(1.561 \times 10^{-6})(999)(0.477)}{2(1,550)(1.468 \times 10^{-9})} = 163.455$$

$$K_{3,s} = \sqrt{\frac{K_{2,s}}{K_{1,s}}} = \sqrt{\frac{163.455}{3.487}} = 6.846$$

$$\therefore t_{T,s} = \frac{\tanh^{-1}(K_{3,ss}\ \nu_{T,s})}{K_{1,ss}\, K_{3,ss}} = 0.176 \text{ s}$$

From the previous calculations, it was concluded that the remaining miniscule sand grains left with the sesame seeds were actually sand grains having a similar mass to that of the sesame seeds. Since the drag coefficients of sand grains and sesame seeds are not that much different, the dynamics of the sand and seed will be similar if external rotational forces are applied. On the other hand, the terminal velocities are doubled based on the analysis. Thus, the sand grains will definitely reach the bottom of the water container before the sesame seeds, providing the sinking distance is not too shallow.

Several issues to consider at this stage are: (1) the components needed in the washing machine; (2) the importance of these components; (3) The amount of water required for the washing machine; (4) The size of the components; (e) the weight of uncleaned sesame seeds that can be washed in the machine; (5) the optimum heights of the components; and (6) the time required to clean the sesame seeds. These issues were addressed through modeling the dropping types of behavior of the sesame seeds and sand grains according to the laws of particle dynamics and fluid dynamics as detailed in the methods below.

Conceptual design

From the conclusions stated at the end of the previous section, the key concept of the proposed machine was as follows. The sand grains beat the sesame seeds in sinking even though they have a similar weight if the sinking distance is great enough and there are no external rotational forces. The machine consists of five components: (1) water tank, (2) funnel, (3) Y-junction, (4) sand collector and (5) drain outflow tube, as shown in Fig. 8.

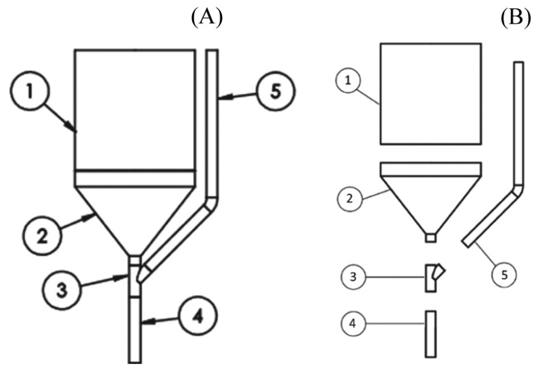

Fig. 8 Conceptual design for prototype machine: (A) machine assembly; (B) machine components, where 1 = water tank, 2 = funnel, 3 = Y-junction, 4 = sand collector, 5 = drain outflow tube

The sesame cleaning machine process can be described in six steps: 1) fill the tank with water and use an air pump to stir up the water in the tank; 2) prepare sesame seeds by shaking them through sieve no.14 and sieve no.12 (ASTM Standard) to screen out very fine sand grains and coarse sand grains, respectively; then, pour the sieved sesame seeds into the washing machine. The worst case scenario would be that all the sand grains were on top of the sesame seed layer, as shown in Fig. 9A; 3) turn off the air pump, after stirring the water for at least 15 s to remove stains and to soak the sesame seeds; 4) the sand grains sink to the bottom of the tank faster than sesame seeds, as shown in Fig. 9B, and hence are successfully separated from the sesame seeds; 5) the sand grains sink into the sand collector shown in Fig. 9C and the sesame seeds land on top of the sand grains; and 6) to drain out the tank filled with cleaned sesame seeds, the drain outflow tube can be lowered, as shown in Fig. 9D to allow cleaned sesame seeds to flow through the Y-junction, leaving the sand grains in the sand collector.

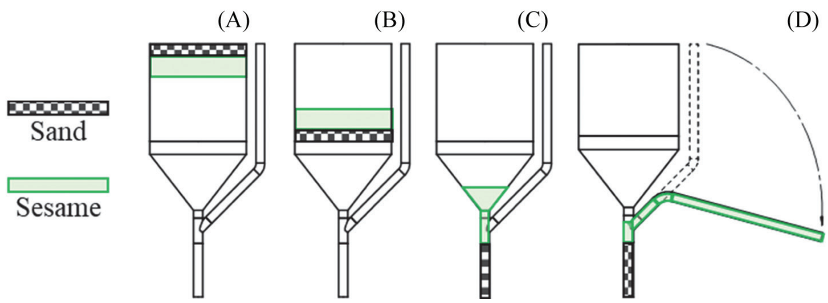

Fig. 9 Conceptual design of sesame seed washing machine: (A) all the sand grains are on top of the sesame seed layer; (B) the sand grains sink to the bottom of the tank faster than sesame seeds; (C) the sand grains sink into the sand collector and the sesame seeds land on top of the sand grains; (D) the drain outflow tube can be lowered to allow cleaned sesame seeds to flow through the Y-junction, leaving the sand grains in the sand collector

Water tank and funnel design

The height of the water tank can be determined from the water-sinking behaviors of the sesame seeds and sand grains, as shown in Fig. 10, based on three phases: 1), starts from t = 0 s to t = 0.170 s (Fig. 10A), where the worst case scenario is assumed in the calculation, so all the sand grains are on top of the sesame seed layer at the start of Phase 1, with both the sesame seeds and sand grains accelerating as they sink; 2) starts from t = 0.170 s to t = 0.176 s (Fig. 10B), where the sand grains sink in the water and accelerate whereas the sesame seeds sink at constant terminal velocity ($v_{T,SS}$) so that it is possible for sesame seeds to catch up with sand grains while sinking; and 3) starts from t = 0.176 s onward (Fig. 10C), where both the sesame seeds and sand grains sink in the water at constant terminal velocities of , $v_{T,SS}$ and $v_{T,S}$ respectively. At this point, the sesame seeds overtake the sand grains sinking before the end of Phase 3.

Let t_T = time when the dropped objects reach their terminal velocities

Phase-1: t < 0.170 s (as shown in Fig. 10A)

Since the period is so short, the accelerations of sesame seeds and sand grains can be approximated using a linear function:

$$a = a_{max} - \left(\frac{a_{max}}{t_T}\right)t$$

and the travel speed in Phase 1 (v_1) can be calculated using:

$$v_1 = \int_0^t a\,dt = C_1 + a_{max}t - \left(\frac{a_{max}}{2t_T}\right)t^2$$

since $v_1 = 0$ at $t = 0$; $C_1 = 0$

$$\therefore v_1 = a_{max}t - \left(\frac{a_{max}}{2t_T}\right)t^2$$

the travel distance in Phase 1 (S_1)can be calculated by

$$S_1 = \int_0^t\int_0^t a\,dt\,dt = D_1 + \left(\frac{a_{max}}{2}\right)t^2 - \left(\frac{a_{max}}{6t_T}\right)t^3$$

since $S_1 = 0$ at $t = 0$; $D_1 = 0$

$$\therefore S_1 = \left(\frac{a_{max}}{2}\right)t^2 - \left(\frac{a_{max}}{6t_T}\right)t^3$$

For sesame seeds: $= \left(\frac{a_{max,ss}}{2}\right)t^2 - \left(\frac{a_{max,ss}}{6t_{T,ss}}\right)t^3$

$$= \left(\frac{1.803}{2}\right)(0.170)^2 - \left(\frac{1.803}{6\times0.170}\right)(0.170)^3 = 0.0174\text{ m}$$

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

$$= \left(\frac{3.487}{2}\right)(0.170)^2 - \left(\frac{3.487}{6\times0.176}\right)(0.170)^3 = 0.0342\text{ m}$$

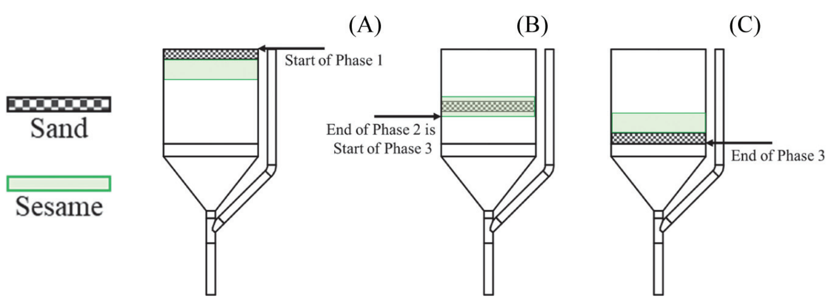

Fig. 10 Three phases of sinking behavior for sesame seeds and sand grains: (A) both accelerate as they sink; (B) sand grains continue to accelerate but sesame seeds sink at constant velocity; (C) both sink at constant velocities

Phase 2: $0.170 \leq t \leq 0.176$ (as shown in Fig. 10B)

The sesame seeds travel with constant terminal velocity: $v_{T,SS}$

For the sesame seeds: $S_{2,SS} = v_{T,SS} \times t_2 = 0.063 \times (0.176 - 0.170) = 0.0004$ m

The total distance for the sesame seeds in phases 1 and 2 is given by:

$S_{1+2,SS} = S_{1,SS} + S_{2,SS} = 0.0174+0.0004 = 0.0178$ m

The acceleration of the sand grains can still be approximated by the previous linear function: $a_{max} - \left(\frac{a_{max}}{t_T}\right) t$

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

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

Phase 3: $t \geq 0.176$ (as shown in Fig. 10C)

Both the sesame seeds and sand grains travel at their constant velocities: $v_{T,SS}$ and $v_{T,S}$ respectively.

The water tank is used to separate the sand grains from the sesame seeds. To check the developed prototype, a 0.3 m diameter paint bucket ($D_{WT} = 0.3$m) was used as it can be easily found in a local market.

The height of sesame seeds forming a cylindrical volume in the water tank can be calculated using Equation 15:

$$H_{ss} = \frac{V_{ss,7}}{\text{Tank area}} = \frac{1.207 \times 10^{-2}}{\pi\left(\frac{0.3}{2}\right)^2} = 1.707 \times 10^{-1} \text{ m} \tag{15}$$

Similarly, the height of the sand grains forming a cylindrical volume in the water tank can be calculated using Equation 16:

$$H_s = \frac{V_{s,7}}{\text{Tank area}} = \frac{8.379 \times 10^{-5}}{\pi\left(\frac{0.3}{2}\right)^2} = 1.185 \times 10^{-3} \text{ m} \tag{16}$$

From Fig 11, the total travel distances of sesame seeds and sand grains are related by Equation 17:

$$S_S = S_{SS} + H_{SS} + H_S \tag{17}$$

where S_S is the total travel distance of the sand grains from Phase 1 to Phase 3 and S_{SS} is the total travel distance of the sesame seeds from Phase 1 to Phase 3.

The time in Phase 3 (t_3) can be calculated as:

$(S_{1+2,S} + S_{3,S}) = (S_{1+2,SS} + S_{3,SS}) + H_{SS} + H_S$

$(0.036 + (0.146 \text{ x } t_3)) = (0.0178 + (0.063 \times t_3)) +$

$(1.707 \times 10^{-1}) + (1.185 \times 10^{-3})$

$\therefore T_3 = 1.825$ s

The total travel time for the sand grains to surpass the sesame seeds is given by:

$t_{WT} = t_{1+2} + t_3 = 0.176 + 1.852 = 2.028$ s

The travel distance of the sand grains is given by:

$S_S = S_{1+2,S} + S_{3,S} = S_{1+2,S} + (v_{T,S} \times t_3)$

$= 0.036 + (0.146 \times 1.852) = 0.306$ m

From Fig. 11C, the height of the water tank can be calculated as:

$H_{WT} = S_S + H_S$

$= 0.306 + (1.185 \times 10^{-3} = 0.307$ m

By calculation, $H_{WT} = 0.307$ m; however, the closest height for a 0.3 m diameter paint bucket available in the market was 0.335 m, as shown in Fig. 12A. The 0.3 m diameter funnel has a straight portion with a height of 0.09 m, as shown in Fig. 12B. The total height of the straight cylindrical-shaped portion is 0.335+0.09-0.307 = 0.118 m beyond the calculated required length. From the available dimensions of the paint bucket, $D_{WT} = 0.3$ m and $H_{WT} = 0.335$ m, so the volume of the water tank $V_{WT} = \pi(0.15^2)(0.335) = 0.02368$ m^3 = 23.68 L.

The 0.3 m diameter funnel shown in Fig. 12(B) is typically available in this size with an inlet diameter of 0.3 m and an outlet diameter of 0.025 m. The CAD drawing of the funnel suggested that the volume of funnel (V_F) = 0.011 m^3 = 11 L.

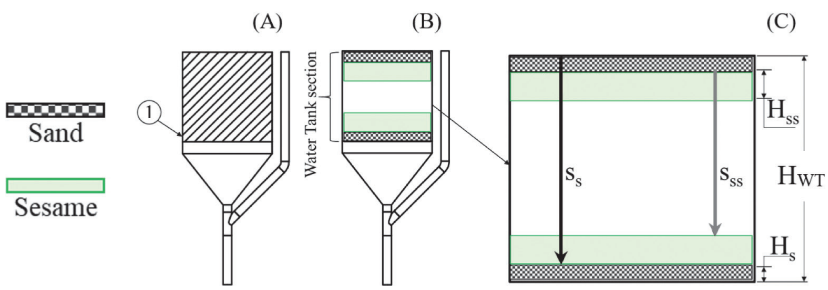

Fig. 11 (A) water tank; (B) sesame seeds and sand grains at their start positions (upper) and by final (lower) positions the sand grains have overtaken the sesame seeds; (C) relationship between distances, where $S_S = S_{SS} + H_{SS} + H_S$ and not drawn to scale

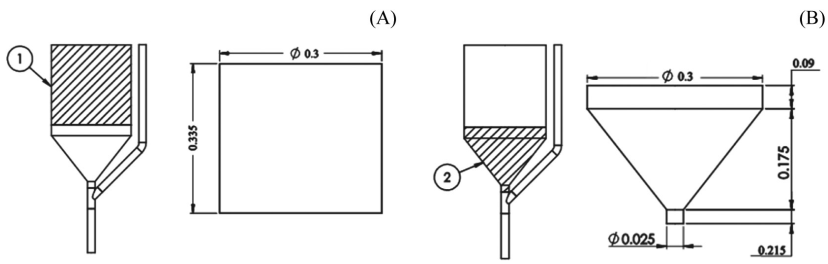

Fig. 12 (A) water tank; (B) funnel, where not drawn to scale and dimensions are in meter

Y-junction and sand collector design

The Y-junction (Fig. 13A) only lets the sand grains pass down through to the sand collector (Fig. 13B). At this point, the sand grains cannot pass through the 0.025 m diameter drain outflow tube on the side of the Y-junction because the water level in the drain outflow tube is as high as the water level in the water tank. Again, the CAD drawing of the Y-junction suggests that the volume of the Y-junction (V_{YJ}) = 5.89×10^{-5} m^3 = 0.0589 L.

The sand collector contains all the sand grains passing through the sesame cleaning machine. Therefore, $V_{SC} = V_{S,7}$ = 8.379×10^{-5} m^3 ≈ 0.084 L. The height of the sand collector.

$$H_{SC} = \frac{V_{SC}}{A_{SC}} = \frac{8.379 \times 10^{-5}}{\pi(\frac{0.025}{2})^2} = 0.171 \text{ m.}$$

Since, water tank: H_{WT} = 0.335 m
funnel: H_F = 0.09 + 0.175 + 0.215 = 0.48 m
Y-junction: H_{YI} = 0.08 m
sand collector: H_{SC} = 0.171 m,
the total height of the sesame cleaning machine is given by:

$$H_{TOt} = H_{WT} + H_F + H_{YI} + H_{SC}$$
$$= 0.335 + 0.48 + 0.08 + 0.171 = 1.066 \text{ m}$$

The time for the sesame seeds in the initial drop to reach the top of sand collector is:

$$H_{Tot} - H_{SC} - S_{1,ss} - H_{SS} = \nu_{T,ss} \times t_{ss}$$
$$\therefore t_{ss} = \frac{1.066-0.171-0.0174-0.1707}{0.063} = 11.22 \text{ s} \approx 12 \text{ s}$$

The time for the sand grains in the initial drop to reach the top of the sand collector is:

$$H_{Tot} - H_{SC} - S_{1+2,s} = \nu_{T,s} \times t_s$$
$$\therefore t_s = \frac{1.066-0.171-0.036}{0.146} = 5.88 \text{ s} \approx 6 \text{ s}$$

The total dropping time for the sand grains in the initial drop to reach the top of sand collector equals 5.88 + 0.176 = 6.06 s. In addition, the total time for the sesame seeds in the initial row to drop to the top of sand collector equals 11.22+0.17 = 11.39 s. Therefore, the first sesame seed lands on top of the sand grain accumulation in the sand collector at around 12 s after starting to sink (t_{on_sand} = 12 s).

Drain outflow design

The drain outflow shown in Fig. 14 allows the sesame seeds to drain from the cleaning machine. The 0.025 m diameter tube can be purchased from any hardware store. The volume of the drain outflow is given by: V_{Dr} = 0.0004 m^3 = 0.04 L.

To drain the water tank filled with the water and the cleaned sesame seeds, the drain outflow tube is lowered to make a height difference between the water level in the tank and the water level in the drain outflow tube, as shown in Fig. 15. Once there is height difference, gravity forces the flow of the cleaned sesame seeds through the Y-junction and the drain outflow tube, leaving the sand grains in the sand collector.

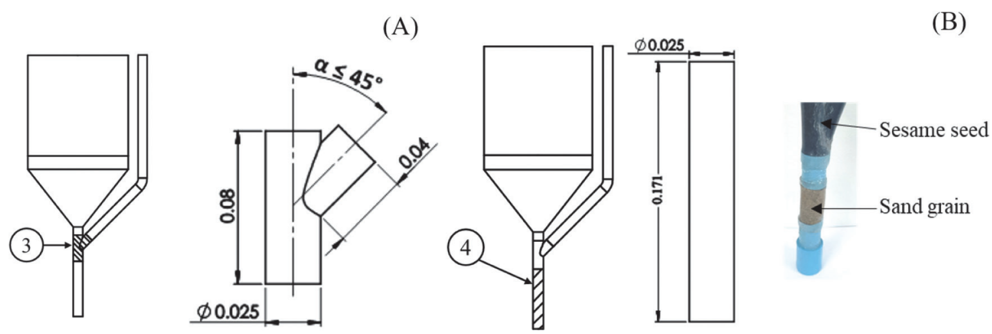

Fig. 13 (A) Y-junction; (B) sand collector, where not drawn to scale and dimensions are in meter

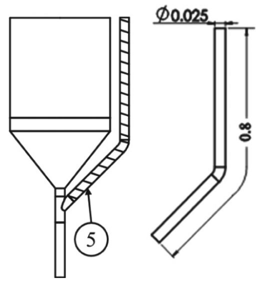

Fig. 14 Drain outflow, where not drawn to scale

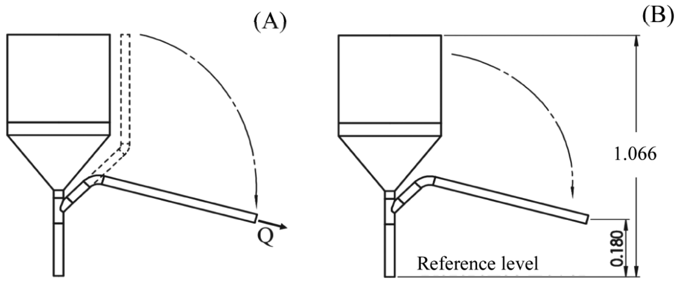

Fig. 15 (A) Lowered drain outflow tube to allow removal of sesame seeds; (B) height difference between the water level in water tank and water level in drain outflow tube, where all measurements are in meters

As shown in Fig. 16, the flow from the drain outflow tube can be divided into five phases: 1) from Z_1 to Z_2; 2) from Z_2 to Z_3; 3) from Z_3 to Z_A; 4) from Z_A to Z_4; and 5) from Z_4 to $Z = 0$. The times in Phases 1 and 2 dominate compared to the times for the other three phases.

The proofs and calculations for the following formulae are discussed in detail in a companion paper, Laboratory prototype proof of appliance for washing sesame seeds. (Eiamsa-ard et al., 2021)

Draining Phase 1: Determine the draining time in Phase 1 (t_2):

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

$$= -\frac{2\sqrt{2}\times 0.15^2}{(0.61)\times 0.01025^2 \cdot \sqrt{9.81}}\left[\sqrt{0.461}-\sqrt{0.886}\right] = 83.16 \text{ s}$$

Draining Phase 2: Determine the draining time in Phase 2 (t_3):

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

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

$$= 29.96 \text{ s}$$

Draining Phase 3: Determine the draining time in Phase 3 (t_4):

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

$$= -\frac{\sqrt{2}}{(0.61)\times\sqrt{9.81}}\left[\sqrt{0.211}-\sqrt{0.466}\right] = 0.17 \text{ s}$$

Draining Phase : Determine the draining time in Phase 4 (t_5):

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

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

Draining Phase 5: Determine the draining out time in Phase 5 (t_6):

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

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

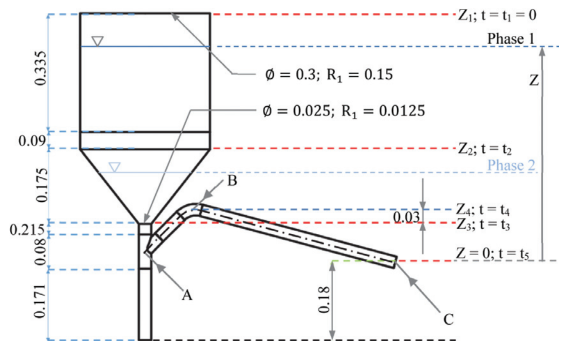

Fig. 16 Sesame cleaning machine, where not drawn to scale and dimensions are in meter

Total draining time: (t_{Dr}) = $t_1+t_2+t_3+t_4+t_5$ = 83.16 + 29.96 + 0.17 + 0.02 + 0.424 = 113.73 s ≈ 114 s

The draining process can start as soon as all the sand grains have settled in the sand collector. However, as a precaution, the drain outflow is only lowered once the sesame seeds have already piled up to the bottom edge of the Y-junction.

Total operation time = t_{on_sand} + t_{Dr} = 12 + 114 = 126 s

Since, water in tank: V_{WT} = 0.02368 m^3

funnel: V_F = 0.011 m^3

Y-junction: VYI = 0.0000589 m^3

sand collector: VSC = 0.000084 m^3

drain outflow: V_{DO} = 0.0004 m^3,

the total volume of sesame cleaning machine is given by:

$V_{Tot} = V_{WT} + V_F + V_{YI} + V_{SC} + V_{DO}$

= 0.02368 + 0.011 +0.0000589 + 0.000084 + 0.0004

= 0.035 m^3

Results and Discussion

Table 1 compares the startup times, operation times and total times as well as the volume of water used in the current conceptual and analytical designs for the sesame seed washing processes proposed by the authors, the sesame farmers and for three machines currently available.

Table 1 Comparisons of volume of water and times between the current proposed machine and other methods

Method	Sesame seed weight (kg)	Time (s)			Volume of water (m^3)	
		Startup* (for 1 cycle)	Operation (for 1 cycle)	Total time per 1 kg of sesame	For operation	per 1 kg of sesame
Farmer	7	0	480	68.6	0.14	0.02
RMUTL	18	300	540	46.7	0.39	0.0217
proposed Machine	7	0	126	18	0.035	0.005
ASL-XMJ10	10	0	300	30	0.058	0.0058
XMS40	1,000	0	3,600	3.6	0.5	0.0005

Note: * excluding time for filling machines with water.

The conceptual and analytical designs proposed by in the current study could potentially solve the sand separation problem in sesame seed cleaning processes, as shown in Table 1. Furthermore, compared to the manual cleaning process, the proposed design could reduce the time for cleaning by 73.75% and the water consumed in the cleaning process by 75% to treat 7 kg of sesame seeds. Currently, farmers have a daily maximum limit of 420 kg of sesame seeds. By using this prototype machine, farmers could potentially increase daily production to 1,600 kg of sesame seeds (approximately 3.81 times more). In addition, the sesame farmers could reduce the amount of water needed for the process from 8,400 L to 2,100 L to treat 420 kg of sesame seeds.

Compared to the RMUTL and ASL-XMJ10 machines, the proposed machine consumed less water and had a shorter production time. However, compared to the XMS40 machine the proposed machine would require more water and more time. However, overall, unlike the other machines currently available, the proposed machine can separate sand grains of a similar weight to sesame seeds.

In conclusion, the rotational forces provided in other designs of washing machines are the root cause of the separation problems because a sesame seed and a grain of sand have similar masses. Uncleaned sesame seeds can be washed and scrubbed in water using air bubbles emanating from an air pump and the scrubbed sesame seeds sink to the bottom of the water container slower than the sand grains do if the container is high enough, as was assumed in the calculations. Notably, at this stage the seed and sand should have similar masses so that sand grains that are lighter or heavier should have already been separated using earlier winnowing and sieving processes. The sand collector is located at the very bottom of the prototype machine to trap the sand grains, unlike other washing machines. In other washing machines, some of the sand grains remain at the bottom of the water container but some are repelled back into the water with the sesame seeds because of the rotation. There is no valve or moving mechanism such as a screw conveyor in this design but instead a Y-junction is used. Consequently, the sand can no longer get stuck in the machine or in moving components.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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