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Study of Coffee Bean Displacement Inside Drum Roaster Using Force Balance Analysis

Hasbi Mubarak Suud[1]✉, Noer Novijanto[2], Rufiani Nadzirah[3], Dyah Ayu Savitri[1]

[1] Program Study of Agricultural Science, Faculty of Agriculture, University of Jember, INDONESIA
[2] Program Study of Agro-Industrial Technology, Faculty of Agricultural Technology, University of Jember, INDONESIA
[3] Program Study of Agricultural Engineering, Faculty of Agricultural Technology, University of Jember, INDONESIA

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✉Corresponding Author:
hasbimubarak@unej.ac.id

ABSTRACT

The drum roaster's design and operating method significantly affect the coffee roasting process. The coffee bean displacement inside the drum roaster can be observed to compare the drum roaster's different designs and operating methods. The coffee bean movement is crucial since it affects the heat transfer distribution among coffee beans inside the drum roaster. The more dynamic displacement of coffee beans gives more even heat distribution. Force balance analysis can be used to predict the coffee bean displacement since it can predict particle movement with mutable variables. This paper compares the coffee bean displacement inside the drum roaster with flippers and without flippers using simple force balance analysis. The analysis involves tangential force, centrifugal force, frictional force, and the beans' weight itself. The analysis shows that the radius of the drum roaster (r) and angular acceleration (ω) significantly change the resultant force's dynamic, and the various tilt angle of flippers (β) did not too significantly affect it. The bigger radius (r) and angular acceleration (ω) generate a stronger centrifugal force influencing the bean's equilibrium. The direction change of force resultant applied to the bean is more smooth in the drum with flippers than without flippers.

1. INTRODUCTION

The drum roaster is a type of coffee roaster that is often used. The design is simple and has not many changed much over the years. The drum roaster is a cylinder rotating on the horizontal axis (Schmidt, 2012). Usually the drum is built from stainless steel material with food grade standard. The drum roaster also has working capacity were is defined from weight of bean and roasting time (Lubis *et al.*, 2023). This paper discusses how coffee beans behave inside the drum when roasting through simple force balance analysis. Two designs of drum roasters were taken up: with and without flippers. The design without flippers is usually used in small drum roasters or household scales, and the drum roaster with flippers is used to roast heavier batches. The drum roaster without flippers usually adopts a perforated drum to maximise heat convection (Huschke, 2007). The flipper performs mixing during heating inside the drum roaster. It makes the bean not make longer contact with the surface of the drum to avoid burning due to excessive heat convection. Around 70% of drum roaster heating should be from convection and the rest from conduction (Rao, 2014).

The processing of particles in rotating cylinders is heavily influenced by the types of flow regimes within the cylinders during rotation (Cristo *et al*., 2006). Batch size and drum rotation speed significantly affect particle movement inside the drum. The coffee roaster is usually operated with angular velocities of the drum roster around 40 – 80 rpm, depending on the weight of the batch sizes (Rao, 2014; Suryadi *et al*., 2023). The coffee beans will tend at the bottom of the drum at low angular velocity. If the velocity increases, the lifting position of the coffee beans will be higher, and they will fall again to the bottom naturally, so beans are mixed with a certain degree of evenness. The coffee beans will tend to stick to the drum walls at a higher speed because the resulting centrifugal force is quite large (Dwiartomo *et al*., 2022). This fact gives us comprehension that the drum roaster's design and operation method will affect the heat distribution to roast the coffee bean. So it needs to clarify how the bean moves inside the drum while operating, especially for achieving the perfect roasting process.

This paper uses a force balance analysis approach to explain the coffee bean movement inside the drum roaster using force balance analysis. Force balance analysis has been widely used to model phenomena involving magnetic flux, particle movement, collision, or subduction (Chen *et al*., 2006 ;Li & Gurnis, 2022). The dynamic particle can be captured using positron emission particle tracking (PEPT). However, this method is complicated but can clearly give a picture of events (Al-Shemmeri *et al*., 2023). The force balance analysis is not only used to predict extensive material but also can be used to analyse small particle movement or even fluid. The advantage of using this method is that variables like size, mass, or velocity can be manipulated to easily predict the impact on the particle (Aussems *et al*., 2017). The coffee bean is assumed as a single particle to simplify the calculation in this paper. This approach was chosen to simplify the analysis by eliminating the collision factor among beans and focusing on drum rotation's effect on the bean. Hopefully, through the elaboration on force balance analysis that happened in coffee beans, there is more comprehension about drum roaster design and operation to further development.

2. MATERIALS AND METHODS

This paper discusses two drum roaster designs, as shown in Figure 1. The illustration of a drum roaster without flippers, as shown in Figure 1(a), and a drum roaster with flippers refers to Daywin *et al*. (2020), as shown in Figure 1(b). The coffee beans' characteristic data retrieved from Yuwana *et al*. (2014) is shown in Table 1. The primary purpose of the calculation is to find the turning point angle. Turning point angle is the drum roaster turn angle (θ) at which the bean starts resisting the drum rotation direction and moving away from the drum surface. The other objective of the analysis is also to see the resultant force change dynamics since it can significantly affect coffee bean movement. The analysis conducted in this paper neglected the heat transfer process and only focused on the movement of the bean during roasting.

2.1. The Resultant Force Calculation on Coffee Beans inside The Drum Roaster without Flippers

There are two conditions to predict when the bean is turned down inside the drum roasted without flippers. The first condition was calculated when the drum rotated from speed zero with angular acceleration. The second condition was calculated with no angular acceleration or stable angular velocity. The force resultant (ΣF) diagram on coffee beans inside a rotating drum roaster without flippers is illustrated in Figure 2 and can be calculated using equations (1) to (6). The difference between the condition with and without angular acceleration is the value of tangential force (Ft). The tangential force is zero when angular acceleration is removed.

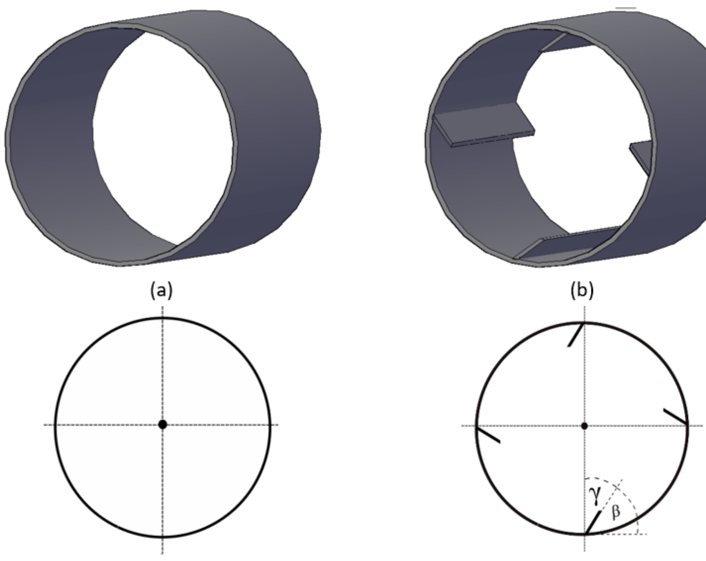

Figure 1. The pictorial illustration of (a) drum roaster without flippers, and (b) with flippers and the cross-section illustration of (c) drum roaster without flippers, and (d) with flippers

Table 1. The physical characteristic of coffee beans and the drum roaster for calculations in this paper (Yuwana *et al*., 2014)

Characteristics	Value
Spherecity of coffee bean	0.75
Static friction coefficient	0.33
Angle of repose	24.8
Length of coffee bean(average)	8.19 mm
Width of coffee bean (Average)	6.11 mm
Thickness of coffee bean (Average)	4.6 mm
Weight of coffee bean (average)	0.3 g
Radius of drum roaster 1	324 mm
Radius of drum roaster 1	150 mm

$$\Sigma \mathrm{Fx} = \mathrm{Ft} + \mathrm{Ff} - W \sin\theta \tag{1}$$

$$\Sigma \mathrm{Fy} = \mathrm{Fc} - W \cos\theta \tag{2}$$

$$\Sigma F = \Sigma Fx + \Sigma Fy \tag{3}$$

$$Fc = M.r.\omega^2 \tag{4}$$

$$Ft = M.r.\alpha \tag{5}$$

$$Ff = N.fs \tag{6}$$

The following are descriptions of variables in Eq. 1 to Eq. 6: ΣF is resultant force (N), Ft is tangential force (N); Ff is frictional force (Newton); Fc is centrifugal force (N); W is weight of coffee bean (N); M is mass of coffee bean (kg); Fs is static friction coefficient; ω is angular velocity (rad/s); α is angular acceleration (rad/s^2); r is radius of drum roaster (m); t is time (s); N is normal force (N); and θ is turn angle of drum roaster (°). The positive value of ΣF indicates the resultant force directed towards the centre of rotation. The negative value of ΣF indicates that the resultant force direction tends to move away from the centre of rotation, pushing the bean to persist and stick on the drum surface.

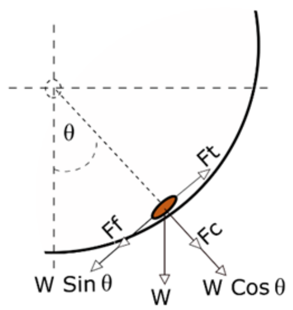

Figure 2. Force diagram on a coffee bean inside rotating drum roaster without flipper during roasting

2.1. The Resultant Force Calculation on The Coffee Bean inside The Drum Roaster with Flippers

The movement analysis of the coffee bean is conducted without angular acceleration since it is assumed that the influence of flippers on the bean's movement is greater. The analysis can be divided into two stages. The first stage starts when coffee beans move up and snag to the flipper, and the second stage starts when the flipper is at the critical angle. Figure 3 shows the illustration of force balance in the first stage, second stage, and third stage. The critical angle occurs when the bean is free to move and can be defined in condition as equation (7).

$$\theta + \epsilon \geq 180^o \tag{7}$$

The resultant force (ΣF) is only influenced by ΣFx since the displacement at the y-axis is assumed to be locked by the clip resistance of flippers and drum surface. Thus, the value of ΣF is calculated using equation (8).

$$\Sigma F = Fc \sin\theta - Ff - W \sin(\theta - \gamma) \tag{8}$$

and γ is defined by equation (9), where β is tilt angle of flipper (degree). The value of γ is

$$\gamma = 90^o - \beta \qquad (9)$$

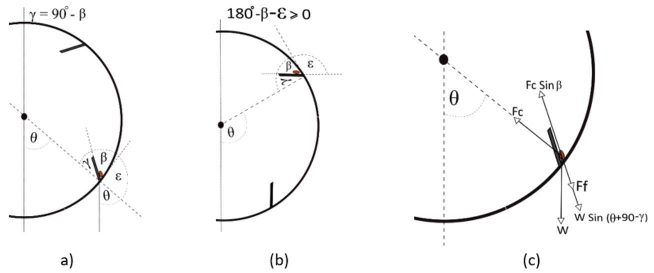

Figure 3. Illustration of coffee bean displacement inside drum roaster with flipper at (a) first stage, (b) second stage, and (c) the resultant force diagram

2.2. Comparing resultant force on a coffee bean in multiple conditions

The analysis is calculated in multiple conditions to understand how the resultant force hits the coffee beans in various conditions. Parameters considered in the calculations include surface type, the radius of drum roaster (r), angular acceleration (α), angular velocity (ω), and tilt angle of flippers (β). Table 2 describes the simulation conditions with a drum roaster without flippers, and Table 3 describes the simulation conditions with a drum roaster with flippers.

Table 2. Various simulation conditions of the resultant force calculation in drum roaster without flippers

Surface Type	r	α	Condition type
Drum roaster without flipper	324 mm	With various angular acceleration	A1
		No angular acceleration / With various angular velocity	A2
	150 mm	With various angular acceleration	A3
		No angular acceleration / With various angular velocity	A4

Table 3. Various conditions on the simulation of the resultant force calculation in drum roaster with flipper

Surface Type	r	β	ω	Condition code
Drum roaster with flipper	324 mm	80°	With various angular velocity	B1
		With various angle of flipper	60 rpm	B2
	With various drum diameter	80°	60 rpm	B3

Seven conditions, so-called condition type, were simulated to know the resultant force in a coffee bean during roasting, as shown in Table 2 and Table 3. The condition type is a marker to define the combination of calculation conditions to simplify the calculation designation.

3. RESULTS AND DISCUSSION

The calculation was carried out based on multiple conditions, as shown in Table 2 and Table 3. The drum roaster without flippers gives no barriers to the bean for moving along the drum surface, and the bean's movement is only affected by the acceleration and velocity of the drum. Angular acceleration generates a tangential force that pushes the bean to move along the velocity direction. Angular velocity generates a centrifugal force that drives the bean to move away from the center of rotation. The bean's direction while moving can be described by comparing tangential acceleration with centrifugal acceleration. However, the direction is divided into positive and negative to make it easier to point the direction, as shown in Figure 4. The negative direction indicates the bean move approaching the center of rotation, and the positive direction is vice versa.

The faster angular acceleration will give more dynamic movement to the coffee bean since it generates more dynamic tangential force. The graph in Figure 5(a) confirms this assumption since the force on the x-axis (ΣFx) has more dynamics in bigger angular acceleration. The graph in Figure 5(c) indicates that the bean tends to dock on the drum surface because it does not generate negative resultant force values.

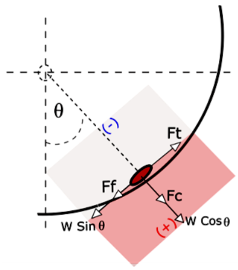

Figure 4. Resultant force diagram of the coffee bean inside drum roaster without flippers

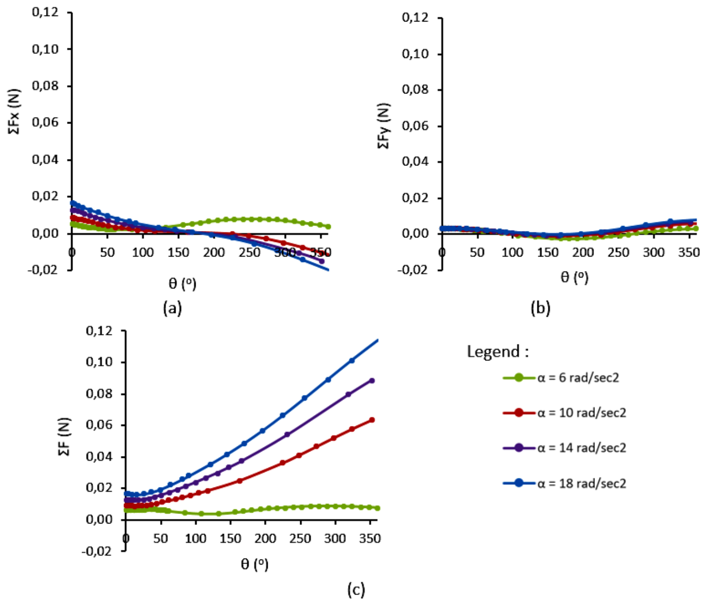

Figure 5. The graph of force simulation that hits coffee bean inside rotating drum roaster with condition type of A1 on (a) the x-axis (ΣFx), (b) the y-axis (ΣFy), and (c) the resultant force (ΣF)

Moreover, big dynamics of centrifugal force in condition type A1 almost cannot be detected, as shown in Figure 5(b). However, the drum radius factor greatly impacts the resultant force dynamics. It can be seen if we compare the graph of the resultant force that hits the coffee bean with condition type A1, as shown in Figure 5, and with condition type A3, as shown in Figure 6. The shorter drum radius, which is shown at condition type 1, generates more dynamics of the resultant force. This result explains that the surface drum without flippers or a flat surface is more suitable for a drum roaster with a shorter radius.

The shorter radius from the drum center turns the force from the coffee's weight, and the gravity affects the coffee movement more, and centrifugal and tangential force becomes less dominant. Based on the graph in Figures 6(a) and 6(b), the resultant forces in the x-axis and y-axis move in negative and positive directions alternately. The coffee bean tends to stick to the surface of the drum surface which rotates with angular acceleration (α) of 6 rad/sec^2 when the rotation angle (θ) is below 100^o, as shown on the graph in Figure 6(c). The bean is going to fall into the rotation center after the rotation angle is bigger than 100^o. The faster the angular acceleration, the longer the bean is going to stick to the drum surface, as shown in the graph in Figure 6 (c). The centrifugal force caused the bean to be slicked to the wall drum and would not be correctly mixed. Tangential force only has little effect on bean movement, but it illustrates how much power is needed to rotate the drum (Faris *et al*., 2019).

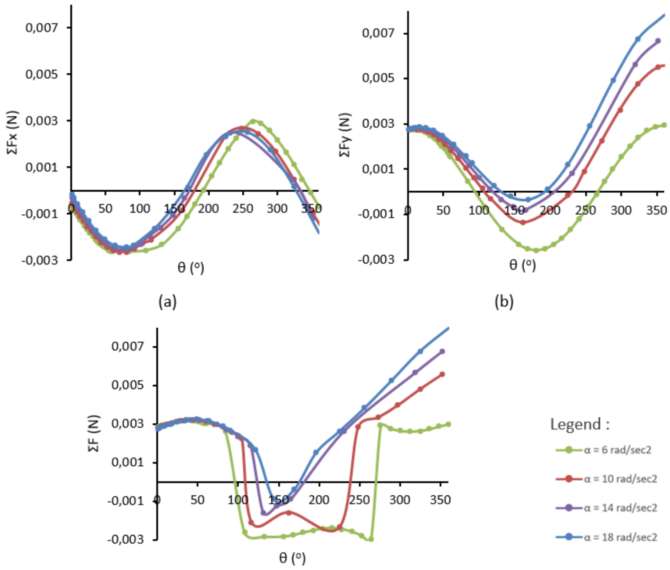

Figure 6. The graph of force simulation that hits coffee bean inside rotating drum roaster with condition code of A3 on (a) the x-axis (ΣFx), (b) the y-axis (ΣFy), and (c) the final resultant force (ΣF)

The actual operation of a coffee roaster is usually based on angular velocity, not angular acceleration. The roaster drum is driven by an electrical motor as a power source with a fixed rotating speed (Sutarsi *et al*., 2010). Condition types A2 and A4 illustrate the bean movement inside the different radii of the drum roaster with various fixed angular velocities. The angular velocity is an important parameter in roasting. If the angular velocity is plodding, the bean will be in touch with the drum longer and get burned. But if too fast, the bean will stick to the drum surface and get burned (Hidayat *et al*., 2020). Graphs in Figures 7 and Figure 8 exhibit the bean's movement inside the drum roaster with different radii in various drum velocities. A similar graph pattern exists between the resultant force on the x-axis and y-axis, as shown in the graph in Figure 7(a) vis a vis 8(a) and Figure 7(b) vis a vis 8(b). The tangential force does not influence the resultant force in the y-axis (ΣFy) since there is no angular acceleration in a rotating drum with fixed speed.

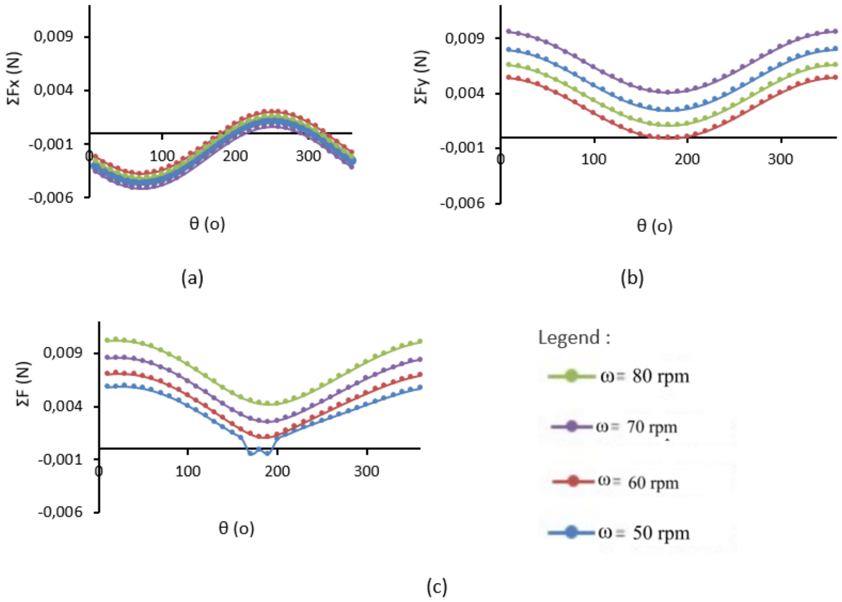

Figure 7. The graph of force simulation that hits coffee bean inside rotating drum roaster with condition code of A2 on (a) the x-axis (ΣFx), (b) the y-axis (ΣFy), and (c) the final resultant force (ΣF)

The bean movement is more influenced by the drum's angular velocity and the bean's weight in conditions type A2 and A4. In smaller radii of a drum roaster, the bean is easier to fall as indicated by resultant negative force (ΣF) as shown in Figure 8(c). On the contrary, in larger radii of the drum roaster, the resultant force on the bean tends to stay in the positive direction or tends to stick to the drum surface, as shown in Figure 7(c). Based on the graph in Figure 8(c) also indicates the duration of the bean to move in the negative direction (indicated with a negative value of resultant force) has a longer duration at lower angular velocities. The turning point angle in the drum roaster with a bigger radius looks more clearly, as shown in Figures 7(c) and 8 (c). It means the smaller drum radius is better for bean displacement during roasting. This result is in accordance with the evaluation by (Hidayat et al., 2020), which states that the larger the radius of the drum roaster, the slower the drum must turn to prevent the bean from sticking to the wall. The lower speed of rotating drums can prevent the bean stays at the drum wall without falling. Therefore the larger drum radius tends to generate poorer mixing than the smaller radius. In the drum without flippers, the bean tends to reach the turning point at the drum turn angle (θ) around 100^{o}.

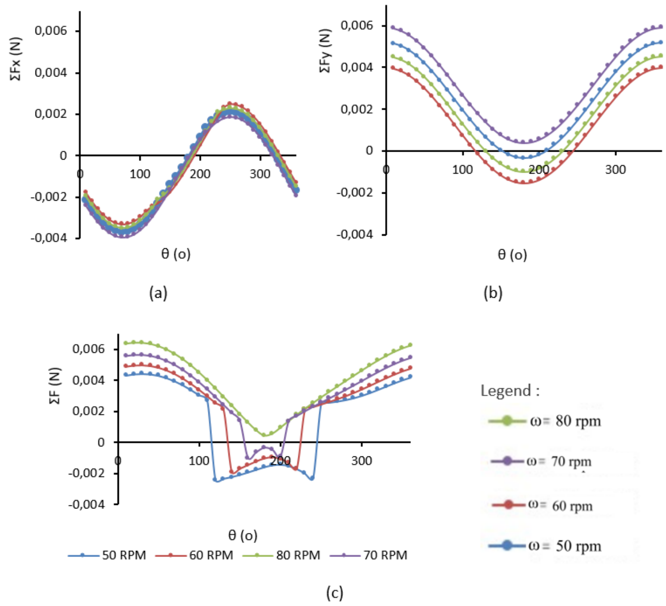

Figure 8. The graph of force simulation that hits coffee bean inside rotating drum roaster with condition code of A4 on (a) the x-axis (ΣFx), (b) the y-axis (ΣFy), and (c) the final resultant force (ΣF)

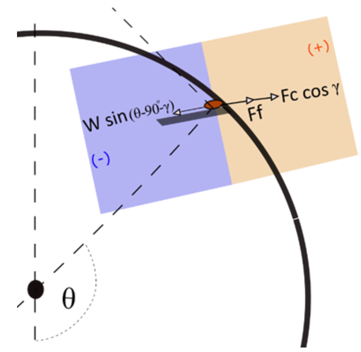

Figure 9. Resultant force diagram of the coffee bean inside drum roaster with flipper

A drum roaster with flippers gives better displacement to the coffee bean since the flippers can trap the bean until it falls at the turning point angle. A negative resultant force (ΣF) value indicates the turning point angle, as shown in Figure 9. The flippers in the coffee roaster also provide conduction heat to the bean longer. The longer direct contact with the heat source, the greater the risk of scorching. Scorching happens when only a small area of the beans is in contact with the drum, leading to dark, charred patches on the flat sections of their surface and giving rise to unwanted characteristics, such as burnt, smoky, and bitter flavors (Pavoni, 2021). However, the discussion here does not extend to heat transfer, only discussing the effectiveness of turning coffee beans in a drum roasting.

Based on the graph in Figure 10, The turning point angle with an angular velocity of 30 rpm occurred after the drum turn angle (θ) of 100^o. The higher the angular velocity, the shorter the turning point duration. The other factor influencing the bean movement is the tilt angle of the flippers, as shown in Figure 11. The tilt angle of flippers (β) can affect the bean's resultant force but is not too significant. The graph in Figure 11 indicates the more upright the flippers or the bigger the tilt angle (β), the shorter the turning point duration. The choice of the simple design of flippers can be the reason why the tilt angle of flippers is not too significant. Flipper designs are developed mostly using spiral designs (Sofii, 2014). And the difference in the spiral design of flippers can significantly impact the bean displacement (Hussein *et al*., 2022). The bigger drum radius also caused the longer turning point duration, as shown in Figure 12. This calculation indicates that the radii of the drum roaster and rotation speed are the most factors in optimizing turning point duration. The direction change of force resultant applied to the bean is more smooth in the drum with flippers than without flippers.

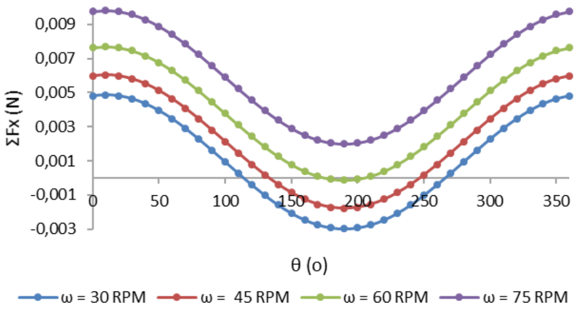

Figure 10. Graph of force simulation that hits coffee bean inside rotating drum roaster with condition code of B1

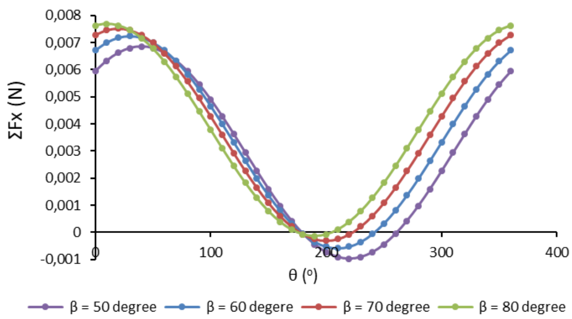

Figure 11. Graph of force simulation that hits coffee bean inside rotating drum roaster with condition code of B2

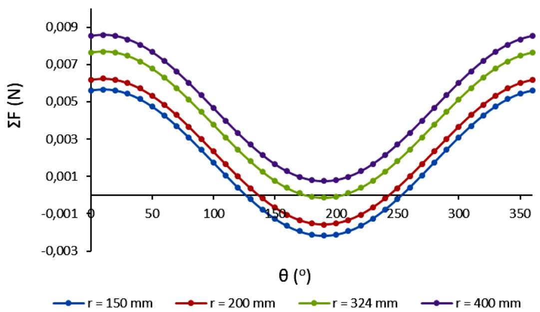

Figure 12. Graph of force simulation that hits coffee bean inside rotating drum roaster with condition code of B3

The limitation of force balance analysis in this paper is that only conducted for a single bean. Thus, the impact of beans inside the drum is not discussed. However, it can be confirmed that the radius of the drum roaster and rotation speed are significant factors for bean displacement inside the drum roaster. Several formulas can be used to specify the diameter of drum coffee roaster, such as demonstrated by Ogunjirin *et al*. (2020), but this study still can be used to understand the phenomenon inside the drum roaster. The most dominant force affecting the bean's force balance is centrifugal force since the impact of frictional force is not dominant. The drum radius gives different effects through the existence of centrifugal force (Fc). The bigger radius generates a stronger centrifugal force that coerces the bean to move toward the center of the drum roaster. The more drastic the change in resultant force, the more active the displacement of the bean since the change in resultant force indicates that the bean cannot maintain a stationary state. The next hope is that the method in this study can be simulated to depict the real situation using Matlab software, which had been done by Krishna *et al*. (2017) to described rice grain movement inside winnowing machine.

4. CONCLUSION

Based on the resultant force balance analysis, the drum roaster's radius (r) and the rotating drum's angular velocity (ω) significantly affected the turning point duration of the bean during roasting. Furthermore, the angular acceleration also significantly impacts the bean displacement. But because most drum roasters use constant rotating speed, the adjustment of angular acceleration cannot be made practically. The other factor influencing the bean displacement is the flipper's tilt angle (β), which is not too significant. In the drum without flippers, the bean tends to move away from the drum surface to the rotation center at the drum turn angle (θ) around 100^o. The direction change of force resultant applied to the bean is smoother in the drum with flippers than without flippers. The flippers can have more impact on the bean movement in more advanced designs, such as spiral flippers design. The future force balance analysis can be improved by considering the collision between the beans and using a more advanced flippers design.

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