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Research article

CFD study of self-cleaning system of multi-stage tangential roller threshing unit for precise buckwheat breeding

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ABSTRACT

Buckwheat is a globally recognized, nutritionally rich crop with robust adaptability, serving as a multi-purpose plant for its health benefits. Achieving precise and mechanized plot seed harvesting is a critical step in obtaining accurate results in breeding experiments. However, plot breeding requires no seed retention, no mixing, and ensures no accumulation of seed in the threshing unit. A self-cleaning technology was developed to prevent seed retention, mixing, and accumulation in the multistage tangential cylinder threshing unit. The newly designed cleaning system has five air inlets and a centrifugal fan for pneumatic cleaning. CFD simulations were conducted for each inlet position, coupled with four varying inlet velocities and the rotation speed of the main threshing cylinder. During the post-processing stage of the CFD modeling, a line consisting of fifty points was drawn beneath the threshing drums, and the air velocity at these points was recorded. The optimal configuration of inlet position, inlet air velocity, and main threshing drum rotation speed for efficient cleaning was identified based on the ratio of points beneath the drums where the airflow speed surpassed the suspension speed of buckwheat to the points where the airflow speed was lower than the suspension speed of buckwheat. The optimal configuration for "inlet_1" was identified based on the suspension velocity of buckwheat grain, with an inlet velocity of 4 m/s and a main threshing drum speed of 450 rpm.

1. Introduction

Buckwheat is a significant pseudo-cereal grain that is frequently cultivated in the arid and hilly regions of world. Its gluten-free protein, harmonious amino acid composition, and the presence of bioactive flavonoids that promote health, collectively establish it as a promising crop for the future [1–3]. Its widespread cultivation can be attributed to its favorable general and genetic traits, with

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planting observed in regions such as China, India, Russia, and Eastern Europe. Its center of origin was in southwest China, where it was first developed. It has been cultivated in China for an exceptionally long time [4].

In recent years, as the nutritional and economic value of buckwheat has grown, there has been a steady increase in demand for buckwheat products globally [5]. Consequently, there is an urgent need to address the mechanized production, harvesting, and cleaning of buckwheat. This cleaning technique is insufficient for the breeding and threshing machinery since buckwheat threshing varies from that of other crops like rice and wheat owing to high moisture content and tiny grain size, which results in contamination of grains [6]. The breeding and harvesting machinery, in addition to threshing, higher requirements are put forward for cleaning, because it must ensure that as many threshing grains are not lost as possible and ensure that no threshing grains are present in the threshing unit. It is necessary to ensure that there is no grain residue in the threshing drum, this needs to add auxiliary equipment. Therefore, this brings great difficulties to the development of cleaning system for buckwheat thresher. Several researchers have investigated the cleaning of threshing devices using different approaches. For example, Huang et al. [7] focused on cyclone separation and cleaning, finding that the cleaning rate and loss rate can be improved by optimizing parameters such as the speed of the suction fan, the speed of the feeding fan, and the length of the suction pipe. The cleaning rate of buckwheat using a cyclone separation and cleaning system was found to be 94.78%. Hussain et al. [8] focuses on the computational fluid dynamics simulation and optimization of the threshing unit of a buckwheat thresher for effective cleaning of the cleaning chamber. Similarly, Xu [9] designed cleaning equipment for tartary buckwheat improves the cleaning effect of the buckwheat and allows for continuous fishing of the buckwheat in real time. Xueqing [10] described the golden buckwheat cleaning device, which aims to achieve the convenient cleaning of the annular brush, thereby improving the cleaning process for golden buckwheat. Another study was presented by Gebrehiwot et al. [11] to investigate effect of crossflow opening on fan performance through computational and experimental study on effective grain cleaning. The distribution of the airflow field and its impact on working parameters were studied using computational fluid dynamics (CFD) simulations and experimental measurements [12]. Olatunde et al. [13] used CFD modeling to investigate the airflow distribution in rice bin storage systems with different grain mass configurations. The results showed that non-uniform airflow distribution dominated peaked and inverted grain mass configurations.

In conventional and existing threshing machines and devices, the cleaning is carried out with the help of a sieve provided at the bottom of the device, which is sometimes assisted with a blower to sweep out the residues and dust. However, the dust is residues stuck in the different corners, and parts of the threshing drum are not thoroughly cleaned. These residues remain accumulated in the drum and contaminate the next rotation of the crop or breed. Hence, it is direly needed that a threshing unit should be designed and equipped with a self-cleaning system to clean up the inner side of the threshing unit thoroughly.

Multi-stage threshing device has been introduced with several advantages over single-stage threshing. For instance, multi-cylinder threshing improves the operation efficiency of threshing unit [14]. Multi-cylinder threshing allows for an adjustable threshing gap, which enables the radial distance between the toothed bar and the main shaft to be adjusted. This adjustable threshing gap results in simplicity and convenience in control, stability and reliability in working, and increased threshing efficiency and quality [15,16]. Moreover, multi-cylinder threshing with a differential axial flow threshing device reduces grain breakage, avoids blockage, and prevents threshing losses [17]. By arranging a movable concave plate screen, the trafficability of grains and stalks is enhanced, further preventing blockage. However, air circulation and cleaning efficiency is a major challenge faced during application of such technologies to different agricultural crops. There is need to optimize such machines with respect to ensure sustainable operating approaches with less input cost.

Keeping in view the above both problems faced during the threshing of buckwheat, in the breeding mechanical harvesting equipment, a self-cleaning system has been added to the multistage tangential roller threshing unit designed by [18] to ensure that after the threshing of each plot is completed, there will be no residual grains in the threshing device, which will affect the plot yield and produce mixed seeds. Computational fluid dynamics modeling approach was used to simulate and optimize the flow field condition for good cleaning of grains and threshing unit.

2. Materials and method

2.1. Airflow design of the self-cleaning system

Despite the increasing buckwheat demand, low yield remains a significant challenge, particularly due to conventional threshing methods. Enhancing agronomic characteristics like yield stability is vital for increasing buckwheat production. Additionally, high-value-added operations could significantly boost its cultivation. Several researchers employed similar threshing and cleaning techniques in plot experiments to enhance buckwheat's chemical and physical attributes [19,20]. However, mixing different breeds in threshing units is a major challenge to maintaining grain purity. Therefore, the development of a self-cleaning system is urgently needed to ensure thorough cleaning and prevent grain mixing or contamination between varieties. This research project addressed this issue by studying and developing a self-cleaning system.

The newly designed cleaning system features a centrifugal fan for pneumatic cleaning, driven by a frequency conversion motor that controls the impeller's speed to regulate air velocity at the fan's air outlet. An SW6016 anemometer measures airspeed at the air outlet to monitor the required air volume in the threshing device. Five strategically positioned air inlets are integrated along the 50 mm wall length of the machine. The airflow direction within the threshing device adopts a transverse flow configuration. Despite the air velocity intake, the buckwheat feeding inlet is thoughtfully maintained on the same side within this innovative self-cleaning system. The air outlet of the cleaning system is located at the rear end of the threshing unit, positioned at a height of 500 mm from the base of threshing unit as shown in Fig. 1.

The clean system structure coupled with the threshing unit is shown in Figure-1. The centrifugal fan (1) blows the wind from the five air inlets into the separation mechanism through the air supply pipe (3) to clean the inside of the threshing unit and remove the remaining impurities. The air outlet (8) discharges the air to achieve a clean effect. The technical parameters of the clean system are shown in Table-1.

2.2. Airflow calculation for the system

Based on the suspension velocity of buckwheat grain, which ranges from 4.47 to 10.18 m/s [21–23], the inlet air velocity was chosen using the buckwheat grain's lowest rate of suspension as a reference point so, the air speed range of a single air inlet is 2.5–6 m/s, calculate the air volume of a single air inlet as specified by equation (1):

$$Q\_Single = \frac{vs}{\eta} \quad \text{Equation 1}$$

The air volume of a single air inlet, denoted as Q-Single, is calculated as 0.02 m^3/s, with parameters such as air speed (v) set at 7 m/s, the area of a single air inlet (s) determined as 0.002 m^2, and the air loss efficiency (η) assumed to be 75%, as specified in the fan manual.

The self-cleaning system contains five air inlets in total. According to the above calculation, the air volume of a single air inlet is 0.02 m^3/s, and the air volume in the air transmission pipeline is at least 0.1 m^3/s.

To determine the air volume at the fan outlet, in accordance with the expression given by equation (2):

$$Q = \frac{5(Q_{Single})}{\eta_1} \quad \text{Equation 2}$$

in the given formula, where Q represents the air volume at the fan outlet, Q-Single denotes the air volume of a single air inlet. The pressure loss in a given airflow is influenced by various factors such as pipeline length, surface roughness, curvature, changes in cross-sectional area, properties of the pipeline, and air speed within it. These combined factors are denoted by the loss efficiency symbolized as η_1, which is assumed as 70% according the recommendations of fan manual [24]. The calculated air volume Q at the fan outlet is determined to be 0.15 m^3/s.

With an air density of 1.23 kg/m^3 and an air speed of 14.03 m/s at the inlet and exhaust pipes, the air pressure (P) at the fan's intake and exhaust pipes is calculated to be approximately 121.07 Pa, as determined by equation (3):

$$P = \frac{\rho v^2}{2} \quad \text{Equation 3}$$

The airflow volume for the centrifugal fan is determined by equation (4):

$$Q = \frac{\beta q}{\mu \rho}(m^3/s) \quad \text{Equation 4}$$

in the formula q is the thresher feeding amount (kg/s) taken as 2.5 kg/s, β is the removal of impurities as a percentage of the machine's feeding taken as 20%, ρ is air density (kg/m^3) with a value of 1.225 kg/m^3, μ is mixing concentration ratio of the air stream carrying impurities taken as 0.2. The calculated airflow volume is 2.04 m^3/s.

2.3. Design of centrifugal fan

The research object was a centrifugal cleaning fan for self-cleaning system coupled with multistage threshing unit. The threshing unit was used for test bench with approximate feed rate of 1.2 kg/s so, the centrifugal fan was designed for this feed rate. The

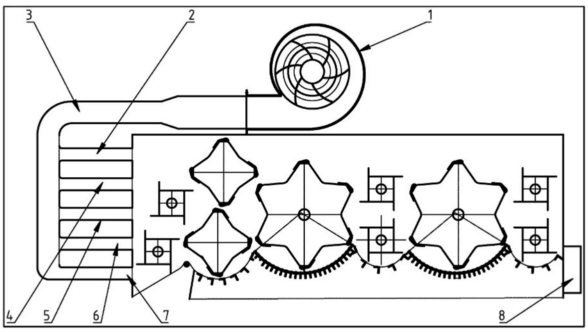

Fig. 1. Schematic diagram of self-clean system structure (1- Centrifugal fan; 2- Air inlet 1; 3- Air supply pipeline; 4- Air inlet 2; 5- Air inlet 3; 6- Air inlet 4; 7- Air inlet 5; 8- Air outlet).

Table 1
Clean system technical parameter.

Element	unit	parameter
Air pipeline diameter	mm	90
Number of air intakes	Unit mm	5
Air inlet diameter		50
Air inlet spacing	mm	60
Air inlet air speed range	m/s	2.5–6
Air outlet diameter	mm	150
Number of air outlets	Units	1

centrifugal fan composed of a transmission shaft, volute, and impeller. The housing of the air suction centrifugal fan adopts a spiral volute, as shown in Fig. 2. The side length of the square in the figure is A/4 where A = 88 mm and R1 = 73.5 mm, R2 = 283 mm, R3 = 305 mm, and R4 = 327 mm represent the arc radii drawn by the circle's center at the four top corners of the square. The three-dimensional model of the centrifugal fan is shown in Fig. 3. The basic parameters of the centrifugal fan are shown in Table-2.

2.4. CFD modeling approach

In the breeding and harvesting machinery, in addition to threshing, there are higher requirements for cleaning, because it must ensure that the threshing unit should completely clean for every plot experiment and not grain contamination occurs. So, self-cleaning systems are also of significant importance as buckwheat breed threshing system. Currently, the barrier to maximizing material throughput is the separation process in the cleaning system of harvesters. Due to the unsatisfactory grain loss, the machine's performance is below its installed capacity.

Optimization is frequently conducted empirically nowadays using a "trial and error" methodology, which is ineffective. These tests take time and money, are difficult to duplicate, and infrequently provide process insight views. The movement of the extruded matter in the airfield of the threshing device under the action of the airflow is relatively complicated [25,26]. To observe the flow field under different inlets positions and different inlet air speeds, analyze its motion laws such as speed and pressure are of great significance for the design and application of the clean system of the detachment device. Furthermore, measurements of the flow field and particle movement are challenging. A wide range of variables and their multi-layered dependencies impact the separation process. In addition, the short harvesting season hinders the development of experimental machines. While laboratory experiments are feasible all year round, there are limitations on their significance and ability to be compared to field tests. Recent years have developed highly effective numerical algorithms for modeling scattered multiphase flows. The current research, however, only examines the distribution of the air flow field in the cleaning device using the CFD approach in the multi-stage threshing unit.

In this CFD analysis, the 2D modeling of the threshing unit was initially designed using Autodesk Professional 2016, illustrated in Fig. 4. Subsequently, this model was imported into Ansys Workbench for further analysis. Meshing is the most crucial step in numerical calculation. Most of the calculation areas in the design are more complex, so computational fluid dynamics in the mesh's irregular area is critical. Since the analysis was steady, an unstructured meshing approach was used to create a moving reference frame configuration. Due to the threshing drums' uneven form, the calculation domain was created by combining various mesh sizes for various surfaces. Fig. 5 shows the meshed grid for the multi-stage threshing combine harvester. It is set to be the mesh interface between adjacent sections. Before meshing, it is essential to carefully select the mesh size [27,28]. An improper choice could lead to inaccuracies. In this case, a mesh unit size of 0.01 m was utilized. The results after meshing are illustrated in Fig. 5, showing 1,994,296 elements and 2,008,874 nodes.

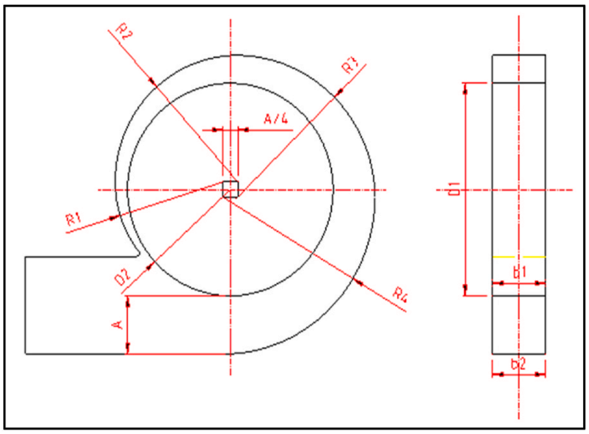

Fig. 2. Centrifugal fan shell spiral drawing.

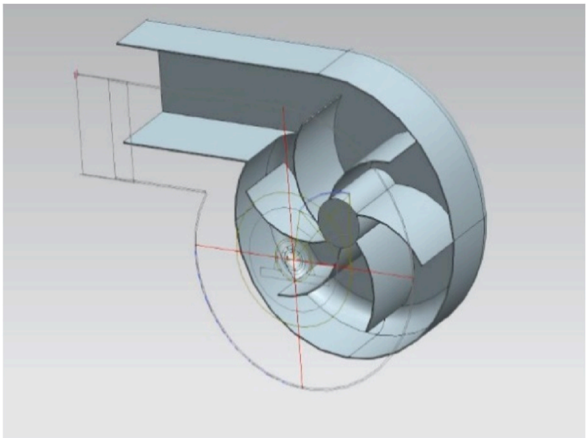

Fig. 3. Three-dimensional model diagram of centrifugal fan.

Table 2
Basic parameters of centrifugal fan.

Project	unit	parameter
Impeller speed n	r/min	1200
Blade inlet width b_1	m	0.20
Blade outlet width b_2	m	0.20
Impeller inner diameter D_1	m	0.30
Impeller outer diameter D_2	m	0.50

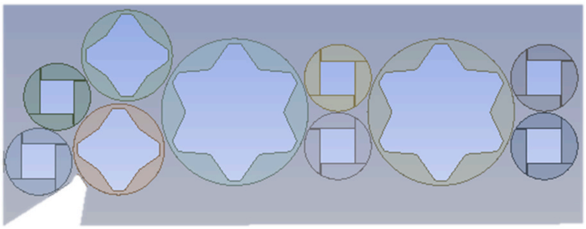

Fig. 4. Computational domain model of multi-stage threshing Unit.

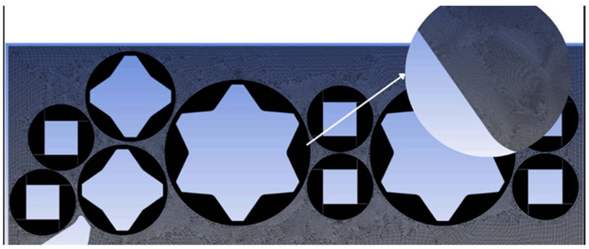

Fig. 5. Meshed grid for multi-stage threshing device.

2.4.1. Selection of input parameters for simulation

To optimize the threshing unit, limiting factors have been selected after multiple simulations and analysis of the simulation results. Five inlets' positions were selected from the front of the threshing unit, each of 50 mm wall length of the device as inlet-velocity. The simulation was carried out for each inlet using 2 factor 4 level Taguchi design separately. The air enters the device in a positive X direction. Different inlet velocities were taken as velocity inlets for each inlet to observe its effect on cleaning. The third most important factor affecting the cleaning performance is the rotation speed of the threshing drums. For simulation, different rotation velocities were used for the main threshing drums to check their effect on the cleaning performance of the combined harvester. The selection of inlet air velocity was based on buckwheat grain's suspension velocity, which ranges from 4.47 to 10.18 m/s. Taking the lowest suspension velocity of buckwheat grains as a reference point, inlet air velocity is selected as a reference to the minimum suspension speed, which ranges from 3 m/s to 4.5 m/s; in 0.5 increments, the rotation velocity of main threshing drums is selected for reference to the experience and related literature, the range is 300–450 rpm in 50 rpm increment.

2.4.2. Boundary condition

The CFD Ansys FLUENT was used to evaluate how the air inlet position and air flow velocity combined with the rotation speed of main threshing drums affects the cleaning performance of buckwheat. The sliding mesh technique was employed for modeling. In this approach, grids adjust their relative positions during calculations based on the angular velocity of the main threshing drum. The threshing drum domain was defined as a dynamic zone with varying rotational speeds utilizing the sliding mesh model. In addition, the Re-Normalization Group (RNG) k-ε turbulence model was utilized. The solution was based on the pressure-based SIMPLE separation algorithm, and a second order up air discretization scheme is used to achieve greater accuracy and the least numerical values [29]. The workplace has been configured at standard atmospheric pressure and all other parameters are left at their default values.

3. Results and discussion

The simulation was conducted for five different inlet positions with four inlet velocities combined with the rotation speed of the main threshing drums. Sixteen simulations were performed for each inlet position, and velocity below the drums was calculated using a line of 50 points postprocessing CFD modeling. Inlet air velocity with the rotation speed of main threshing drums is the optimum combination of inlet position. The ratio of the number of points with high air velocity below the drum to the maximum suspension speed of buckwheat to the number of points with low air velocity below drums to the minimum suspension speed of buckwheat was calculated.

3.1. Simulations result for Inlet_1

According to the above analysis, the inlet-1 was simulated using air velocity ranges from 3 to 4.5 m/s and main threshing drum rotation speeds from 300 to 450 rpm. The input parameters for Inlet-1, along with the corresponding simulation results, are presented in Table 3. According to the results Inlet-1 with the inlet velocity of 4 m/s along with the threshing drum speed of 450 rpm has the highest ratio which is the best combine for better cleaning of threshing unit. The velocity contour for this combination is illustrated in Fig. 6. From figure the air velocity is higher under the main threshing drums due to the rotation effect and decrease gradually while moving to rare end of the threshing unit which satisfy the cleaning conditions.

3.2. Simulations result for Inlet_2

Input parameter and simulations results are shown in Table 4. Based on the results, it is observed that the combination of an inlet velocity of 3.5 m/s and a threshing drum speed of 400 rpm yields the highest ratio. This suggests that this configuration stands out as the optimal choice for achieving better cleaning performance in the threshing unit. The velocity contour for this specific combination is depicted in Fig. 7. As illustrated in the figure, the air velocity exhibits an elevation beneath the first main threshing drums, attributed to the rotational effect. It then gradually diminishes towards the rear end of the threshing unit. This observed pattern aligns with the desired cleaning conditions, reinforcing the effectiveness of the chosen configuration.

Table 3
Input parameters and simulation results for inlet_1.

Inlet_1					
Inlet velocity (m/s)	RPM	Max. velocity Below Drums (m/s)	The number of points with air velocity surpassing the suspension velocity of buckwheat. velocity of buckwheat	No. of Points having low air velocity than suspension velocity of buckwheat	Ratio
3	300	17.34	8	27	0.30
3	350	19.45	9	23	0.39
3	400	22.89	12	19	0.63
3	450	26.04	15	13	1.15
3.5	300	23.56	10	21	0.48
3.5	350	24.94	9	17	0.53
3.5	400	27.09	10	16	0.63
3.5	450	28.55	13	15	0.87
4	300	25.61	9	17	0.53
4	350	23.63	9	18	0.50
4	400	26.17	10	16	0.63
4	**450**	**28.69**	**18**	**13**	**1.38**
4.5	300	25.36	10	18	0.56
4.5	350	25.31	10	17	0.59
4.5	400	26.39	11	16	0.69
4.5	450	29.33	14	15	0.93

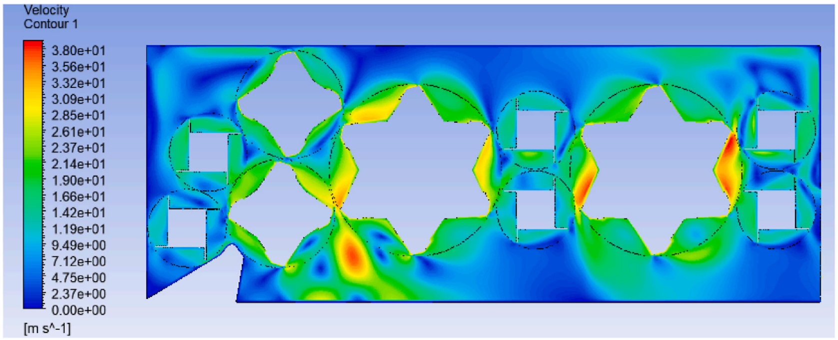

Fig. 6. The velocity contour of the first inlet with air speeds of 4 m/s and 450 rpm of main threshing drums.

Table 4
Input parameters and simulation results for inlet_2.

Inlet_2					
Inlet velocity (m/s)	RPM	Max. velocity Below Drums (m/s)	No. of Points having high air velocity than suspension velocity of buckwheat	No. of Points having low air velocity than suspension velocity of buckwheat	Ratio
3	300	17.47	8	27	0.30
3	350	19.35	8	25	0.32
3	400	22.5	9	21	0.43
3	450	26.51	16	17	0.94
3.5	300	22.95	9	23	0.39
3.5	350	20.55	8	25	0.32
3.5	400	27.84	10	16	0.63
3.5	**400**	**27.61**	**16**	**16**	**1.00**
4	300	26	9	16	0.56
4	350	24.9	10	18	0.56
4	400	26.94	10	17	0.59
4	450	29.22	13	15	0.87
4.5	300	26.09	9	17	0.53
4.5	350	27.19	9	16	0.56
4.5	400	25.97	14	17	0.82
4.5	450	29.64	10	15	0.67

3.3. Simulations result for Inlet_3

Table 5 presents the input parameters and simulation results. Analysis of the data reveals that the combination of an inlet velocity of 3.5 m/s and a threshing drum speed of 450 rpm produces the highest ratio, although the ratio itself is less than 1. Despite this, the configuration emerges as the optimal choice for achieving improved cleaning performance in the threshing unit.

In Fig. 8, the velocity contour for the specified combination is illustrated. The figure reveals an initial surge in air velocity beneath the first main threshing drums, attributed to the rotational effect. Interestingly, this velocity gradually decreases but exhibits a renewed upward trend towards the rear end of the threshing unit. The notable increase in air velocity at the outlet raises concerns, as it has the potential to carry grains along with non-grain materials. Consequently, this particular combination may not be conducive to achieving an optimal cleaning effect.

3.4. Simulations result for Inlet_4

Based on the simulation results for inlet_4, an inlet velocity of 3.5 m/s paired with a threshing drum speed of 450 rpm yielded the highest ratio at 0.93. The comprehensive simulation results are detailed in Table 6.

In Fig. 9, the velocity contour for the aforementioned combination is presented. The contour illustrates that the air velocity attains its highest value below the initial threshing drum and exhibits a decreasing trend further downstream. Notably, at the rear end of the threshing unit, there is a resurgence in air velocity, potentially impacting grain cleaning adversely. Consequently, this specific combination may not be optimal for achieving an effective cleaning effect.

3.5. Simulations result for Inlet_5

The simulation outcomes for inlet_5 is outlined in Table 7. As per the results, the maximum ratio of points with high air velocity compared to the suspension velocity of buckwheat to points with low air velocity is 1. This ratio is achieved with an inlet velocity of

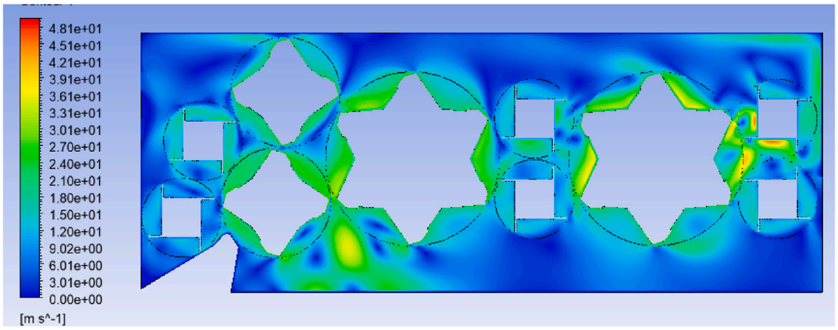

Fig. 7. The velocity contour of the second inlet with air speeds of 3.5 m/s and 400 rpm of main threshing drums.

Table 5
Input parameters and simulation results for inlet_3.

Inlet_3					
Inlet velocity (m/s)	RPM	Max. velocity Below Drums (m/s)	No. of Points having high air velocity than suspension velocity of buckwheat	No. of Points having low air velocity than suspension velocity of buckwheat	Ratio
3	300	17.38	8	25	0.32
3	350	19.23	8	23	0.35
3	400	22.5	10	21	0.48
3	450	25.89	14	17	0.82
3.5	300	24.34	10	23	0.43
3.5	350	19.6	8	24	0.33
3.5	400	27.1	10	17	0.59
3.5	**450**	**27.77**	**15**	**17**	**0.88**
4	300	23.42	9	23	0.39
4	350	24.36	10	17	0.59
4	400	27.66	10	17	0.59
4	450	29.09	9	15	0.60
4.5	300	25.29	9	20	0.45
4.5	350	24.99	10	18	0.56
4.5	400	25.76	14	17	0.82
4.5	450	29.8	9	15	0.60

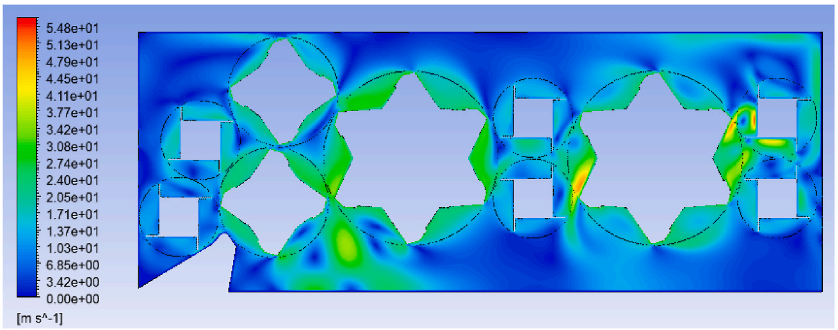

Fig. 8. The velocity contour of the third inlet with air speeds of 3.5 m/s and 450 rpm of main threshing drums.

3.5 m/s and a threshing drum speed of 450 rpm. The corresponding velocity contour is presented in Fig. 10.

The velocity contour illustrates that the air speed is significantly elevated beneath the drums, a factor that could potentially result in blowing grains out of the machine and consequently increasing grain loss.

3.6. Effect of multiple inlets

Fig. 11 represents the velocity contours inside the threshing drum by injecting air through multiple inlets, i.e. inlets_1 and inlet_2 with velocity of 3 m/s. It can be observed that air injecting through multiple air inlets simultaneously increases the air flow below the drums, resulting in a higher turbulence. The space below the drum is considered to be the most critical location in the threshing device

Table 6
Input parameters and simulation results for inlet_4.

Inlet velocity (m/s)	RPM	Max. velocity Below Drums (m/s)	No. of Points having high air velocity than suspension velocity of buckwheat	No. of Points having low air velocity than suspension velocity of buckwheat	Ratio
Inlet_4					
3	300	17.95	8	27	0.30
3	350	19.77	8	23	0.35
3	400	23.47	9	20	0.45
3	450	28.82	15	17	0.88
3.5	300	24.94	10	21	0.48
3.5	350	20.71	8	22	0.36
3.5	400	27.64	9	17	0.53
3.5	**450**	**28.82**	**14**	**15**	**0.93**
4	300	25.73	9	15	0.60
4	350	27.49	9	15	0.60
4	400	28.28	9	13	0.69
4	450	29.75	9	14	0.64
4.5	300	29.75	9	14	0.64
4.5	350	25.86	10	18	0.56
4.5	400	26.68	13	16	0.81
4.5	450	29.8	12	15	0.80

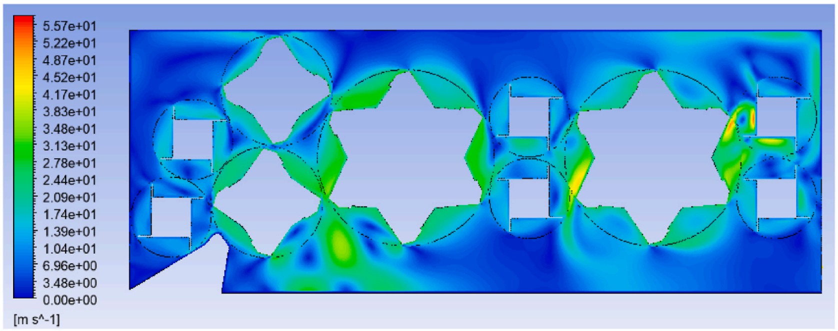

Fig. 9. The velocity contour of the fifth inlet with air speeds of 3.5 m/s and 450 rpm of main threshing drums.

Table 7
Input parameters and simulation results for inlet_5.

Inlet velocity (m/s)	RPM	Max. velocity Below Drums (m/s)	No. of Points having high air velocity than suspension velocity of buckwheat	No. of Points having low air velocity than suspension velocity of buckwheat	Ratio
Inlet_5					
3	300	17.65	7	23	0.30
3	350	19.36	8	23	0.35
3	400	22.35	13	20	0.65
3	450	26.23	15	16	0.94
3.5	300	22.88	9	24	0.38
3.5	350	19.06	8	25	0.32
3.5	400	25.9	11	17	0.65
3.5	**450**	**28.04**	**16**	**16**	**1.00**
4	300	22.92	8	23	0.35
4	350	22.31	8	20	0.40
4	400	24.5	13	18	0.72
4	450	27.64	16	16	1.00
4.5	300	21.97	8	23	0.35
4.5	350	23.95	9	18	0.50
4.5	400	24.77	13	16	0.81
4.5	450	29.97	12	15	0.80

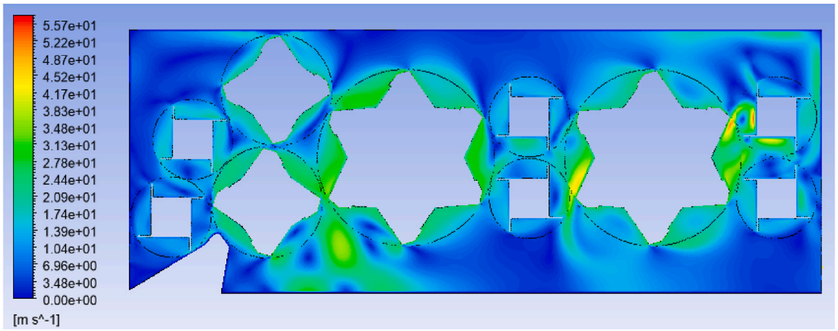

Fig. 10. The velocity contour of the fifth inlet with air speeds of 3.5 m/s and 450 rpm of main threshing drums.

from where the grains are likely to fall down towards the grain collection unit. The elevated velocity and turbulence may lead to the blowing out of grains, which has indeed severe implications for the overall cleaning efficiency. More blowing power requirements cost is another drawback which may lead to increase operational cost of the machine.

3.7. Best cleaning parameter

The distribution of airflow within the threshing device is directly influenced by both the air velocity and the dimensions of the air inlet. Achieving effective grain cleaning necessitates a specific air speed, and it is the intensity of this air speed within the flow field that contributes to the successful outcome of a thorough and clean threshing process. Utilizing simulation results, the criterion for selecting the optimal combination of inlet position, inlet air velocity, and the rotational speed of the main threshing drums for cleaning was determined based on the ratio of points below drums with higher airflow speeds compared to suspension speed to those with lower airflow speeds. This ratio was found to be greater than one. Consequently, the most favorable combination was identified as Inlet_1 with an inlet velocity of 4 m/s and a main threshing drum rotation speed of 450 rpm. Velocity contour result for this specific configuration is depicted in Fig. 12.

Fig. 13 illustrates the pressure distribution for the initial inlet with a speed of 4 m/s and a main threshing drum rotation speed of 450 rpm. The air enters the machine from the left side and immediately faces two drums, which will cause the pressure to rise in this location, as shown in the figure. Behind these drums, the pressure will be lower, which will help in creating a suction effect to drive the air along the machine. Since all drums are rotating, some areas of low pressure will show around the drums, as indicated by the green color in the images. The region under the main threshing drum is particularly noteworthy. The contours reveal a zone of low pressure, generating a high-velocity area that propels some grains below the drum. This phenomenon is integral to the machine's functioning and contributes to the effective separation and cleaning of the buckwheat grain from chaff and other stalks.

4. Conclusions and prospects

In this study, a novel cutting-edge self-cleaning technology was developed to ensure a comprehensive cleaning of the threshing unit. This innovative cleaning system integrates a centrifugal fan powered by a frequency converter motor, allowing precise control over the air speed at the fan's air outlet. Design evaluation was carried out using computational fluid dynamics (CFD) modelling approach. The comparison of different air inlet configurations showed that the inner aerodynamics have a significant effect on the self-cleaning of the threshing unit. Having narrow passage, the velocity of air increases at the drum clearance which can remove the particles. The cleaning efficiency increases by increasing the air inlet velocity; however, a higher inlet air speed can create more turbulence in the cleaning chamber. The optimum cleaning performance was achieved with the inlet configuration as "inlet_1", an inlet

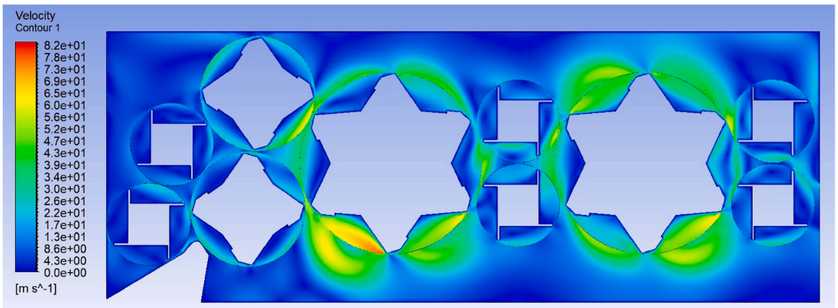

Fig. 11. The velocity contour of air injection through multiple inlets.

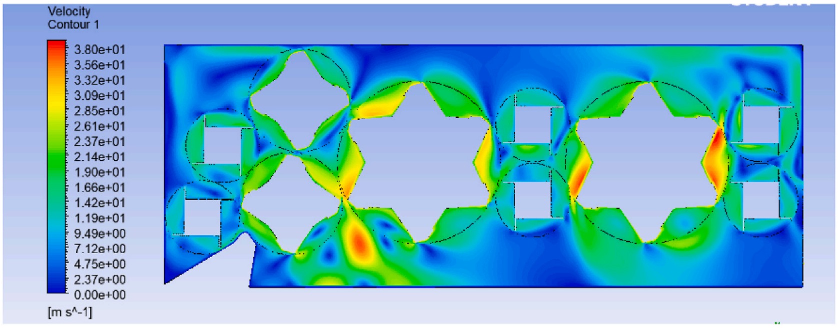

Fig. 12. Velocity contour for inlet_1 with 4ms-1 inlet velocity and 450 rpm rotation speed of main threshing drums.

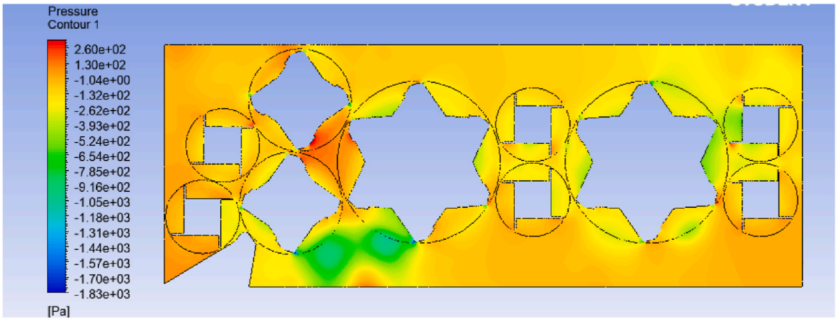

Fig. 13. Pressure contour for inlet_1 with 4ms-1 inlet velocity and 450 rpm rotation speed of main threshing drums.

velocity of 4 m/s and a main threshing drum speed of 450 rpm. It should be noted that the current study was conducted with empty threshing unit and assuming the weight of the straws. Further CFD simulation studies are planned by considering the multiphase interaction of the grains, straws and air to enhance threshing efficiency.

Data availability

The data supporting this study's findings are available from the corresponding author upon responsible request.

CRediT authorship contribution statement

Saddam Hussain: Writing – review & editing, Writing – original draft, Software. **Hu Jianjun:** Supervision. **Chen Yong:** Data curation. **Asad Ali:** Conceptualization. **Haiyan Song:** Writing – review & editing, Data curation. **Decong Zheng:** Supervision. **Muhammad Usman Farid:** Software. **Abdul Ghafoor:** Methodology. **Mukhtar Ahmed:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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