Effect of air-jet impingement parameters on the removing of sunflower seeds from the heads in static conditions

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Abstract: Due to the success of air-jet in food and agricultural sciences, in order to eliminate a number of problems in mechanical methods of removing sunflower seeds from the head, a new method was invented based on impingement jets. In fact, the aim of presenting the air-jet impingement method was not to design this simple machine. But when we started designing the final machine, we realized that we need to take a step back and study the jet parameters in simple and static state. The effect of the seeds' location on sunflower head, reservoir pressure, the angle of impingement, nozzle diameter and the distance between the nozzle outlet and the surface of the sunflower head on the removed area of sunflower head in static conditions were examined. The regions removed by the impingement of the air-jet were photographed and the area of the removed regions was calculated. Response surface methodology was used for designing experiments for all three regions of sunflower head of "Dorsefid" variety. Based on the obtained results of two varieties, on side, middle and central regions, removing seeds using 30°, 60° and 90° angle of impingement is advised respectively. The results indicated that the area of the removed regions was increased with the increase of the nozzle diameter and reservoir pressure. Also the removed area increased with the increase of the distance between the nozzle outlet and the surface of the SH at first, but then decreased. The optimal distance between the nozzle outlet and the surface of the SH ranges between 24 to 28 mm.

Keywords: sunflower (Helianthus Annuus. L), thresher machine, image processing; nozzle diameter, reservoir pressure, angle of impingement, response surface methodology

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1 Introduction

Sunflower (*Helianthus Annuus.* L) is one of the most important oil crops in the world. It is important for human consumption due to the favorable fatty acid compositions of oil. In general, there are two methods for removing sunflower seeds from the sunflower head (SH), including 1) traditional manual method, and 2) mechanical mechanized methods. Traditionally, the farmers rub the sunflower heads (SHs) over a brick, stone, piece of metal, wood, rubber or rub the sunflower heads with each other for its threshing. The efficiency of the traditional manual methods depends on the efficiency and experience of the workers. The efficiency of these methods is very low in general (Goel et al. 2009; Mirzabe et al. 2012).

The mechanical methods of removing sunflower seeds are based on beating, friction and simultaneous beating and friction. The machines for removing sunflower seeds from the head are classified as 1) combined harvester machines 2) stationary thresher machines.

In order to reduce the number of damaged seeds and decrease the power consumption of thresher machines and also increase their efficiency, these machines should be redesigned or optimized based on the mechanical and physical properties of the sunflower heads and seeds; therefore, the physical and mechanical properties of sunflower seeds and heads and also the effective parameters of combines or thresher's performance must be known. Little published literature is available on physical and mechanical properties of sunflower seeds and heads (Mirzabe et al. 2012; Khazaei et al. 2008b; Gupta and Das 1997; Gupta et al. 2007; Gupta and Das, 2000).

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Little published literature is available on sunflower thresher machines and their performance, power consumption and efficiency. Sharma and Devnani (1979) studied the effect of cylinder tip speed and concave clearance of a rasp bar thresher on threshing of sunflowers. Anil et al. (1998)developed a thresher used for cereals into a thresher machine which could be used for sunflower seeds. Bansal and Dahiya (2001) studied the effect of threshing techniques on the quality of sunflower seeds. Sudajan et al. (2002) studied the effects of feed rate, drum, type of drum and drum speed on sunflower threshing. Sudajan et al. (2003) investigated power requirements and performance factors of a sunflower thresher. Sudajan et al. (2005) studied the effect of a number of drum characteristics on rasp-bar drum performance for threshing sunflowers.

In some areas of the world (in many developing countries), due to traditional plantation of sunflower, combined harvester machines cannot be used. Also due to low level of agricultural mechanization, traditional farming, low level of farmers' income, complexity of thresher mechanisms, complexity and difficulty of the settings of the machine and damages to the seeds during the operation with stationary thresher machines, farmers are not interested in using stationary thresher machines.

Despite air-jets impingement and water-jets impingement have many usages in industry, food sciences and agricultural machinery; there is little published literature on application of the air and water-jet impingement for removing arils of pomegranate fruits (Khazaei et al., 2008a; Sarig et al., 1985; Schmilovitch et al., 2014) and extracting the citrus juice and juice sacs (Khazaei et al., 2008c; Nahir and Ronen, 1992; Hayashi et al., 1981; Ando et al., 1988). Results of this literature indicated that air-jet and water-jet impingement methods are efficient methods for removing arils of pomegranate fruits and extracting the citrus juice and juice sacs.

Due to the success of air-jet in removing arils of pomegranate fruits and extracting the citrus juice and juice sacs, in order to eliminate a number of problems in manual and mechanical methods of removing sunflower seeds from the head, a new method was invented based on impingement jets. Thrust force of air-jet impingement can be used to remove the sunflower seeds from their head; when the high speed air flow gets out of the nozzle, the seeds are subject to external forces caused by the high-speed air-jet. The air-jet transfers momentum to the SH and seeds, and generates a force on the head surface; therefore, the seeds will be removed from the head.

Before designing the remover machine of sunflower seeds from the heads based on the air-jet impingement, the effect of the air-jet impingement parameters on removing the seeds from the heads must be examined. Preliminary model of such machine was designed, constructed and evaluated. Effects of the seed location, angle of impingement, distance between nozzle outlet and sunflower head, and rotational velocity of sunflower head on percentage of extracted seeds were examined (Mirzabe et al., 2014).In fact, the aim of presenting the air-jet impingement method was not to design this simple machine. The final machine was to be able to take a sunflower with all its seeds from one head, and deliver the empty flower and separated seeds on the other head of the machine. In fact, the built machine plays an efficient role in recognizing the jet parameters and their effect on the sunflower heads and seeds. But when we started designing the final machine, we realized that the results obtained from the preliminary machine are not enough and we need to take a step back and study the jet parameters in simple and static state.

The aim of the present study is to 1) investigate the effects of air pressure, nozzle diameter, distance between the nozzle outlet and the surface of the SH, angle of impingement between jet and SH surface and sunflower seeds location on the area of removed region of the SH; 2) calculate the theoretical air density, air-jet mass flow rates and theoretical air-jet impingement force in different levels of air pressures and nozzle diameters; 3) calculate the theoretical covered region by air-jet and comparison to experimental removed region by air-jet.

A	Area of nozzle outlet, m^2	**P_0**	Ambient pressure, Pa
AI	Angle of impingement, degree	**PR**	Reservoir pressure, Bar
CR	Central region on sunflower head	**R**	Real gas constant, J K^{-1} mol^{-1}
DNS	Distance between nozzle out let and SH surface, mm	**SH**	Sunflower head
F	Maximum jet force in outlet of nozzle, N	**SHs**	Sunflower heads
ERA	Experimental removed area by air-jet, cm^2	**SR**	Side region on sunflower head
k	Constant specific heats	**T**	Temperature in Kelvin, K
M	Molar mass of air, g/mol	**t**	Temperature in Centigrade, ^oC
ṁ	Mass flow rate in nozzle outlet, kg/m^3	**TCR**	Theoretical covered region by air-jet, cm^2
M_a	Molar mass of dry air, g/mol	**T_s**	Relative temperature of the fluid, K
MR	Middle region on sunflower head	**V_{cr}**	Critical nozzle outlet velocity, m/s
M_u	Much number	**V_l**	Local speed of sound, m/s
M_w	Molar mass of water in the air, g/mol	**x_v**	Mole fraction of water vapor, g/mol
ND	Nozzle diameter, mm	**Z**	Compressibility factor of air
P	Pressure at the nozzle outlet, Pa	**ρ_s**	Supply air density, kg/m^3

2 Material and methods

2.1 Theoretical calculations

2.1.1 Density, mass flow rate and jet force

For removing the sunflower seeds from the SH using air-jet impingement, the seeds are subject to external forces caused by the high-speed air-jet. The air-jet transfers momentum to the SH and seeds, and generates a force on the head surface. Calculation of the momentum, and also the force available from a given jet, requires knowledge of the initial velocity, mass flow rate and impingement force of the jet.

When the jet temperature equals 20 ℃, the effects of air pressure (at 2, 3, 4, 5, 6, 7, 8 and 9 Bar) and nozzle diameter (at 2, 4, 6 and 8 mm) on theoretical supply air density, mass flow rate and jet force were examined. In order to calculate the theoretical mass flow rates and theoretical jet forces in different conditions (different values of air pressure and nozzle diameter) mentioned formulas in Table 1 were used.

Table 1 List of equations were used to calculate air and jet parameters

Formula	Application	References
$F = \dot{m}V_{cr} + (P - P_0)A$	Calculation of maximum jet force in outlet of nozzle from an isentropic jet	(Munoz 2011; Sutton and Biblarz, 2010)
$\dot{m} = \rho_s\ V_l\ A\left(\frac{2}{k+1}\right)^{\frac{k+1}{2(k-1)}}$	Calculation of critical mass flow rate for an ideal gas with constant specific heats	(Fay and Sonwalkar, 1996; Khazaei et al., 2008a)
$V_{cr} = V_l\left(\frac{1+k}{2}M_u\right)^{-\frac{1}{2}}$	Calculation of critical speed of the sound in general stats	(Khazaei et al., 2008c; Mirzabe and Chegini, 2015)
$V_{cr} = V_l\left(\frac{1+k}{2}\right)^{-\frac{1}{2}}$	Calculation of critical speed of the sound when the Much number equals to 1	(Khazaei et al., 2008c; Mirzabe and Chegini, 2015)
$V_l = \sqrt{\frac{kRT_s}{M}}$	Calculation of local speed of sound	(Huber, 2007; Mirzabe and Chegini, 2015)
$\rho_s = \frac{PM_a}{ZRT}\left[1 - x_v\left(1 - \frac{M_w}{M_a}\right)\right]$	Calculation of supply air density (air density in the reservoir)	(Picard et al., 2008; Mirzabe and Chegini, 2015; Giacomo, 1982)
$\rho_s = \frac{PM_a}{ZRT}$	Calculation of supply air density if moisture of the air is ignored	(Picard et al., 2008; Mirzabe and Chegini, 2015; Giacomo, 1982)
$Z = 1 - \frac{P}{T}\ [a_0 + a_1t + a_2t\ ]$	Calculation of compressibility factor of the dry air	(Mendes and Pavlis, 2004)

Note: a_0, a_1 and a_2 are constant factors: a_0 = 1.58123 ×10^{-6}K/Pa, a_1 = -2.93310 ×10^{-8}/Pa, a_0 = 1.10430 ×10^{-10} K^{-1} Pa^{-1}

Molar mass of the air depends on the contents of the atmospheric gases, including the concentration of argon relative humidity of air (Picard et al., 2008). Molar mass of the dry air, based on composition of the dry air was calculated by Picard et al. (2008). They cited that molar mass of the dry air is equal to 28.96546 $\times 10^{-3}$ kg/mol.

2.1.2 Theoretical covered region by air-jet

When the jet temperature equals to 20 ℃, the effects of nozzle diameter (at 4, 6 and 8 mm), angle of impingement (at 30 °, 60 ° and 90 °) and distance between the nozzle outlet and the surface of the SH (at 10, 20 and 30 mm) and theoretical covered region by air-jet impingement were examined. In order to calculate the theoretical covered region by air-jet impingement in different conditions (different values of nozzle diameter, angle of impingement and distance between the nozzle outlet and the surface of the SH), air-jet was simulated in CATIA V5R20 software package.

2.2 Experimental methods

2.2.1 Sampling preparation

Two varieties of sunflowers, namely “Dorsefid” and “Sirena” widely cultivated in Iran, were used in the present work. The “Dorsefid” variety is native of Iran. The varieties were planted on April 27th, 2012 in research farms of the University of Tehran, located in Pakdasht, Tehran Province, Iran (longitude of 35.47 °N, latitude of 51.67 ° E, average annual Precipitation 110 mm from 2000 to 2010, height above the sea level of 1025 m, average annual temperature of 18.0 ℃ from 1993 to 2010). The sunflowers of the two varieties were harvested manually in late September, when SHs were completely matured.

Seeds moisture content was measured after the test. The seeds were cleaned manually to remove all foreign materials. The moisture content of each sample was determined using the standard hot air oven method at $105\pm1^{\circ}C$ for 24 hours (Gupta and Das 1997). Average values of moisture content for “Dorsefid” and “Sirena” varieties was found to be 32.33% and 34.87% (d.b.), respectively. For the varieties dimensions, true densities, bulk densities, porosity, angle of fiction and angle of repose on different surfaces were calculated (Mirzabe et al. 2012).

In order to examine the effect of air-jet parameters on area of the removed region in different locations of seed on SH, the selected SHs are divided into three regions, namely central region (CR), middle region (MR) and side region (SR), as is shown in Figure 1.

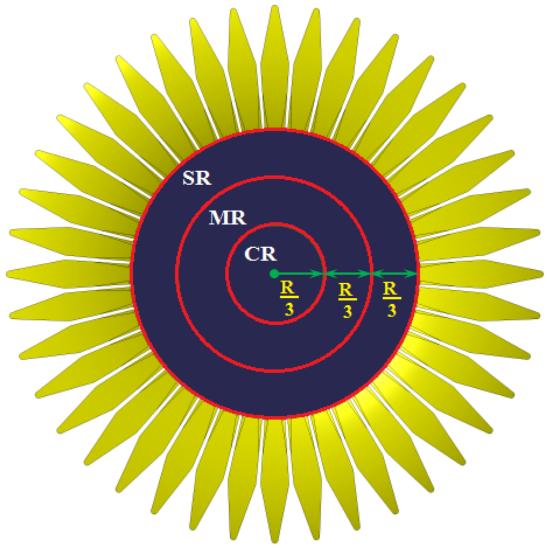


Figure1 Three regions of sunflower head (SH). (1) Central region (CR), (2) Middle region (MR) and (3) Side region (SR)

2.2.2 Experimental setup

A schematic diagram of the experimental setup used to evaluate the effects of operating parameters of air-jet impingement on removing sunflower seeds is shown in Figure 2. Main part of machine consists of frame, holder disc, vertical guide shaft, horizontal guide shaft, changing angle mechanisms, nozzle and switching valve. This setup works as follows:

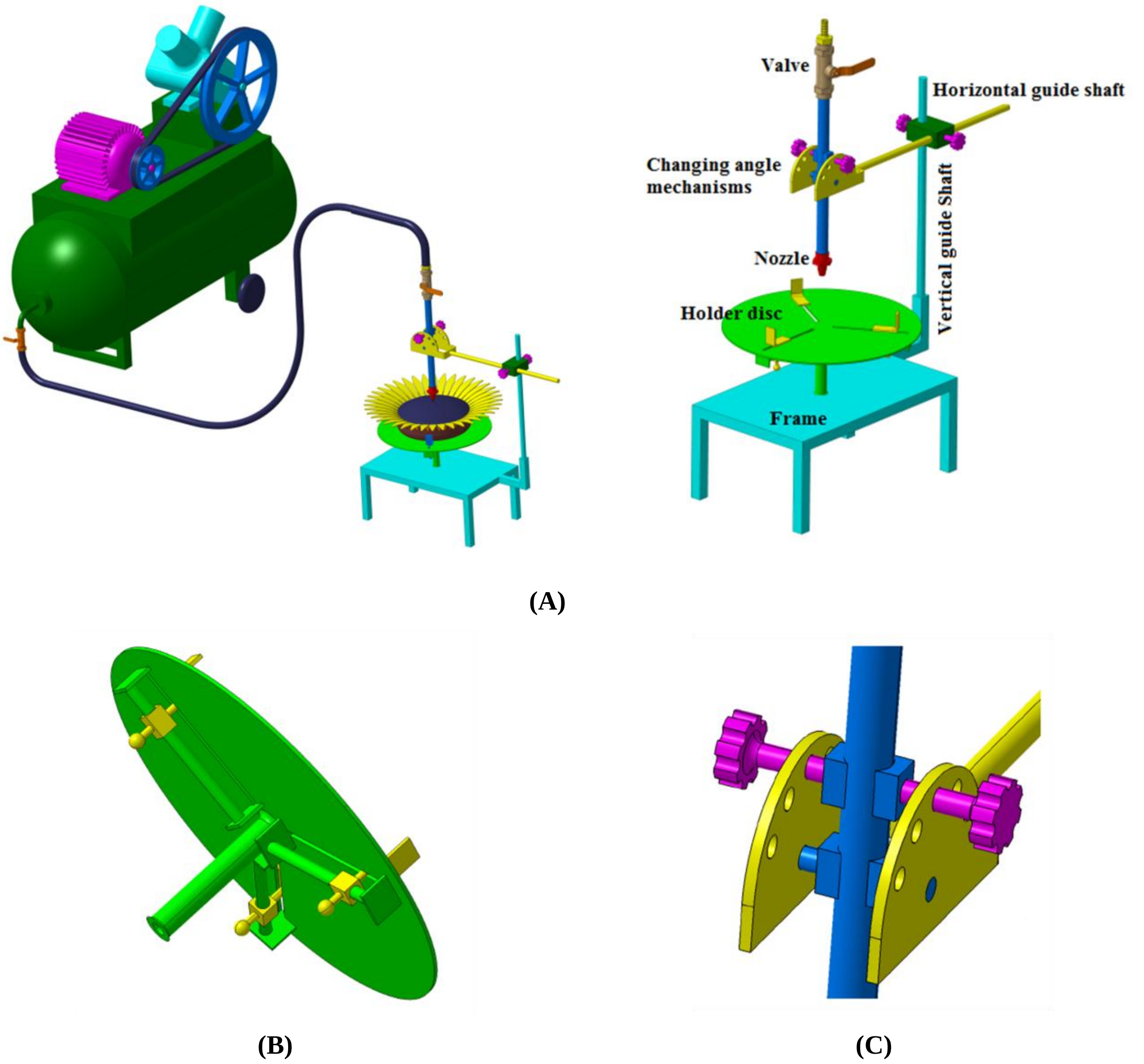


Figure 2 (A) Experimental set up used to evaluate the effects of operating parameters of air-jet impingement on removing sunflower seeds, (B) Schematics of mechanisms used to maintain the sunflower head during the tests, (C) Schematics of mechanisms used to set the angle of impingement

Frame: frame of the machine was a small table that the other parts put on it (Figure 2, A).

Holder disc: in order to hold the SHs during the tests, SHs are put on holder disc. The holder disc was constructed to be capable of holding SHs with diameters from 6 to 36 cm and are shown in the Figure 2, A, and which are zoom in Figure 2, B. For the holder disc to be able to hold the sunflower heads with different diameters, three grooves on the holder disc with 14 cm in length and 5 mm width was created. The angles between the grooves were 120 °. The holder disc was attached to the frame with nut and bolt.

Vertical guide shaft: the distance between the SHs and the nozzle outlet were set using vertical guide shaft. The shaft diameter was 100 mm and its length was 300 mm and welded to the frame.

Horizontal guide shaft: the shaft was used to examine the effect of air-jet parameters on the area of the removed region in different locations of seed on SH. The shaft diameter was 100 mm and its length was 300 mm and welded to the changing angle mechanisms (Figure 2, A).

Changing angle mechanisms: angle of impingement (angle between SH surface and air-jet) was set using changing angle mechanisms (are shown in Figure 2, A, and which are zoom in Figure 2, C). Two semi-circular steel plates with 10 cm in diameter were used. On the each plate, an imaginary 4 cm radius circle was considered and in the center of the imaginary circle a hole with 6 mm diameter was created; also, on the circumference of the imaginary circle six holes with 6.2 mm in diameter were created. The angles between the adjacent holes were 30 °. Then the plates were placed with a distance of 35 mm to each other and parallel to each other, so that the created holes on the plates were placed accurately across each other and were welded together with a small steel plate. On the both sides of the air pipe, two small rods, which were 6 mm in diameter, were welded. At the distance of 40 mm from the center of the small rods, two M6 bolts were welded on the both sides of the air pipe. The small rods were paced in the created hole on the center of imaginary circle. To avoid changes in the angle of impingement, two firming M6 screws were used. By placing the firming M6 screws into the holes (created holes on the circumference of the imaginary circle) and two M6 bolts, changes in angle were avoided.

The pressure of the air is increased in piston compressor; the high pressure flow of the air is transferred to experimental set up using pneumatic hoses. Switching valve is used to connect and disconnect the air flow. All experiments are performed with three repetitions and the duration of each test, i.e. the duration that the switching valve was open and air jet impinged the seeds, was decided to be two seconds. Image processing technique is used to calculate the area of the removed regions.

2.2.3 Image processing setup

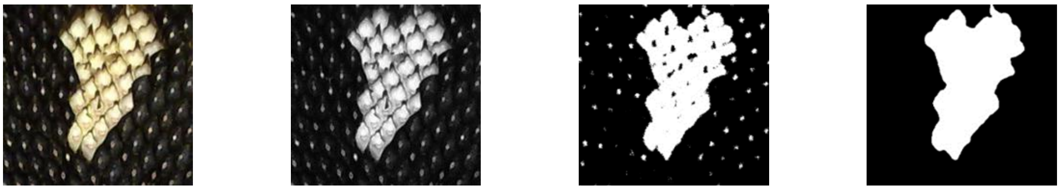
The image processing system consisted of a camera (Canon, IXY 600F, Japan) with 3X IS lens capable of filming up to 120 frames per second (fps) and 12.1 megapixels, USB connection, four white-colored fluorescent lamps (32 W) and a laptop computer (DELL, INSPIRON 1558, China) equipped with Matlab R2012a software package. The camera was mounted on an image processing box (Mansouri et al., 2015b; Mansouri et al., 2015a). Each sunflower head was placed at the center of the camera's field of view and three metal spheres with the same and identified diameters were placed at the side of the sunflower head; then one RGB color images were captured from up view of removed region of sunflower head.

The original color image of each sunflower head (removed region) and each metal sphere was converted to an eight-bit grayscale image. Eight-bit grayscale intensity represents 256 different shades of gray from black (0) to white (255). The eight-bit grayscale images were digitized to binary image by using binary transformation on the basis of all the pixels with a brightness level which was the average of the brightness levels of the three channels (Uozumi et al., 1993; Mansouri et al., 2015b). The threshold value of sunflower heads was determined experimentally (Koc, 2007; Mansouri et al., 2015b). From the grayscale image, pixel values less than 175 were converted to 0 (black) and pixel values higher than 175 were converted to 255 (Koc, 2007; Mansouri et al., 2015b). The threshold level of 175 was determined experimentally. The pixels with value of 255 showed the removed regions of the head and the pixels with value of 0 showed the remainder (Koc, 2007; Mansouri et al., 2015b).

The holes and noise of binary images are filled by morphological closing and opening. The number of the pixels for each metal sphere and each removed region due to impingement air-jet for each image were calculated. The projected area of the each sphere was calculated (projected area equaled to3.1415 R^2). In the last step, the areas of the removed regions of the sunflower head were calculated using the Equation (1):

$$Area\ of\ the\ removed\ region = \frac{Number\ of\ pixels\ of\ removed\ region\ \times Projected\ area\ of\ the\ shpere}{Number\ of\ pixels\ of\ sphere} \quad (1)$$

Examples original in RGB, grayscale image, binarized image and binarized image with removed noise of a removed zone of the sunflower head are shown in Figure 3.



(a) (b) (c) (d)

Figure 3 (a) Original RGB color image of a removed zone, (b) eight-bit grayscale image, (c) two-bit binary image and (d) two-bit binary image with removed noise

2.2.4 Data analysis

For the “Dorsefid” variety the effects of air pressure (at 5, 6 and 7 Bar), nozzle diameter (at 4, 6 and 8 mm), angle of impingement (at 30°, 60° and 90°) and the distance between the nozzle outlet and the surface of the SH (at 10, 20 and 30 mm) on the area of the removed region are studied. Also for the “Sirena” variety the effects of seeds location on SH, air pressure (at 5, 6, 7 and 8 Bar), nozzle diameter (at 2, 4, 6 and 8 mm), and angle of impingement (at 30°, 60° and 90°) on the area of the removed region were studied. It is necessary to note that all the analyzed levels of variable parameters mentioned were selected after preliminary experiments. For example, in those experiments, pressure fluctuated from 4 to 9 Bar. Since, for the “Dorsefid” variety response surface methodology (RSM) was used, and in the method variable levels should be triplex, therefore in the test of the “Dorsefid” triplex variable levels were considered.

To reduce number of tests and optimize the operating parameters of air-jet, for the “Dorsefid” variety response surface methodology was used. Response surface methodology is a collection of mathematical and statistical techniques for empirical model building. By careful design of experiments, the objective is to optimize a response (output variable) which is influenced by several independent variables (input variables). An experiment is a series of tests, called runs, in which changes are made in the input variables in order to identify the reasons for changes in the output response (Box and Draper, 1987; Khuri and Mukhopadhyay, 2010; Myers and Montgomery, 2003).

The mass flow rate and the area of the removed region by air-jet were considered as the response surfaces of the tests; because the purpose was designing and constructing a machine for removing sunflower seeds from the SH with lowest power consumption. It should be noted that when the pressure and nozzle diameter are increased, the mass flow rate and power consumption are increased too; therefore, optimum conditions for removing the seeds from the SH was considered to be the time when the area of the removed region by air-jet and mass flow rate are maximum and minimum, respectively.

The Design Expert 7 software package was used for regression and graphical analysis of the data obtained. In working with Design Expert 7 software and with response surface method, variables and their change levels are defined for the software. The software provides the list of the tests needed to be done. In fact, all the tests need not to be done, and this is one of the advantages of this method. After doing all the determined tests, the obtained results would be entered to the software, and the software does the necessary analyses. The experiments needed to be done for the mentioned variables are shown in Table 2. These experiments were performed for all the regions of the sunflower head, namely, SR, MR, and CR, separately. Variables levels of parameters for conducted test, in each region, are shown in Table 2.

Table 2 Variables levels of parameters for conducted test, in each region

Test NO.	PR (Bar)	AI (Degree)	DNS (mm)	ND (mm)
1	5	30	20	6
2	7	30	20	6
3	5	90	20	6
4	7	90	20	6
5	6	60	10	4
6	6	60	30	4
7	6	60	10	8
8	6	60	30	8
9	5	60	20	4
10	7	60	20	4
11	5	60	20	8
12	7	60	20	8
13	6	30	10	6
14	6	90	10	6
15	6	30	30	6
16	6	90	30	6
17	5	60	10	6
18	7	60	10	6
19	5	60	30	6
20	7	60	30	6
21	6	30	20	4
22	6	90	20	4
23	6	30	20	8
24	6	90	20	8
25	6	60	20	6
26	6	60	20	6
27	6	60	20	6
28	6	60	20	6
29	6	60	20	6

A second order quadratic equation is used to describe the effect of independent variables in terms of linear, quadratic and interactions. The proposed model for the response (ρ) is:

$$\rho = b_0 + \sum_{i=1}^{3} b_i x_i + \sum_{i=1}^{3} b_{ii} {x_i}^2 + \sum_{i=1}^{3} \sum_{j=i+1}^{4} b_{ij} x_i x_j + \varepsilon \quad (2)$$

where, ρ is the predicted response, density; b_0 is the interception coefficient; b_i, b_{ii}, and b_{ij} are the linear, quadratic, and interaction terms; ε is the random error and X_i is the independent variables studied (Yeh, 2003). The significance of the statistical model was evaluated by the F-test analysis of variation (ANOVA).

3 Results

3.1 Theoretical results

3.1.1 Mass flow rate and jet force

The calculated values of density, mass flow rate and maximum impingement jet force of air for different levels of the air pressures and nozzle diameters are reported in Table 3. The data showed that air density increased from 2.378 to 10.728 kg/m^3 as air pressure increased from 2 to 9 Bar. Table 3 also demonstrated that, as expected, the mass flow rate of air increased as the air pressure increased and the nozzle diameter increased.

When the air pressure equals 2 and 9 Bar, with an increase in nozzle diameter from 2 to 8 mm, the mass flow rate increased from 1.484 to 6.695 g per sec and from 23.746 to 107.114 g per sec, respectively. It is evident that whilst initial velocity cannot exceed ambient sonic velocity due to the formation of a shock wave, the mass flow rate of the air-jet continues to increase in proportion to air pressure (Khazaei et al., 2008a).

Table 3 Effect of nozzle diameter and supply pressure on air density, mass flow rate and maximum impingement jet force for critical flows

Pressure, Bar	Density, kg/m^3	Theoretical mass flow rate, g per sec Nozzle diameter, mm				Theoretical impingement force, N Nozzle diameter, mm			
		2	4	6	8	2	4	6	8
5	5.952	3.714	14.857	33.428	59.427	1.164	4.655	10.474	18.621
6	7.145	4.459	17.834	40.127	71.336	1.397	5.588	12.573	22.352
7	8.338	5.204	20.814	46.830	83.254	1.630	6.522	14.674	26.087
8	9.533	5.949	23.795	53.539	95.180	1.864	7.456	16.776	29.824

The theoretical calculated impingement jet forces normal to the surface of the sunflower head are shown in Table 3. For the different nozzle diameters, all the trends were similar. For any given nozzle diameter, the air-jet force is found to increase linearly with the supply pressure as is shown in Table 3. Table 3 also demonstrates that for all the supply pressures considered, the impingement force increased as the nozzle diameter increased. When the air pressure equals 5 and 8 Bar, with an increase in nozzle diameter from 2 to 8 mm, the mean impingement force increased from 1.164 to 18.621 N and 1.864 to 29.824 N, respectively.

3.1.2 Theoretical covered region by air-jet

The calculated values of area of covered region by air-jet impingement for different levels of distances between the nozzle outlet and the surface of the SH, nozzle diameters and angle of impingement are shown in Table 4. The data indicated that the areas of the covered regions by air-jet increased when the nozzle diameters and distance between the nozzle outlet and the impingement surface increased and also increased when the angle of impingement decreased. The results showed that nozzle diameter and distance between the nozzle outlet and the impingement surface are respectively the lowest and the most effective parameters on area of the covered region.

Table 4 Effect of nozzle diameter, Distance between the nozzle outlet and the impingement surface and angle of impingement on theoretical covered region

Nozzle diameter, mm	Distance between the nozzle outlet and the impingement surface, mm	Angle of impingement, Degree		
		30	60	90
4	10	1.331	0.632	0.535
	20	3.055	1.450	1.226
	30	5.485	2.604	2.205
6	10	2.054	0.975	0.826
	20	4.110	1.951	1.652
	30	6.873	3.263	2.762
8	10	2.933	1.393	1.179
	20	5.322	2.527	2.139
	30	8.417	3.996	3.383

3.2 Experimental results

3.2.1 “Sirena” variety

Results of examining the effect of the operating parameters of air-jet impingement including pressure, nozzle diameter, angle of impingement and seeds location on sunflower head on removing sunflower seeds from the head for “Sirena” variety are shown in Table 5. Results indicated that in three regions with increasing reservoir pressure and nozzle diameter, areas of removed regions increased. Results indicated that in SR with increasing the angle of impingement the area of the removed regions decreased; while, in MR and CR with increasing the angle of impingement from 30 to 60° and decreasing from 90 to 60° the area of the removed regions increased (Table 5).

Table 5 Effect of reservoir pressure, angle of impingement, nozzle diameter and location of seed on SH on experimental removed area by air-jet impingement and also different between experimental removed area and theoretical covered region by air-jet impingement

PR, Bar	AI, Degree	ND, mm	Experimental removed area by air-jet impingement (ERA), cm^2			Different between ERA and TCR (Different = ERA – TCR), cm^2		
			Location of seed on SH			Location of seed on SH		
			CR	MR	SR	CR	MR	SR
5	30	4	1.05	2.71	4.17	2.005	0.345	-1.115
		6	1.33	3.38	4.95	2.780	0.730	-0.840
		8	1.67	4.39	6.24	3.652	0.932	-0.918
	60	4	1.28	3.33	3.72	0.170	-1.880	-2.270
		6	1.63	4.11	4.48	0.321	-2.159	-2.529
		8	1.99	5.40	5.60	0.537	-2.873	-3.073
	90	4	1.11	2.42	3.41	0.116	-1.194	-2.184
		6	1.43	3.04	4.08	0.222	-1.388	-2.428
		8	1.75	3.91	5.12	0.389	-1.771	-2.981
6	30	4	1.18	3.00	4.77	1.875	0.055	-1.715
		6	1.52	3.79	5.68	2.590	0.320	-1.570
		8	1.89	4.91	7.17	3.432	0.412	-1.848
	60	4	1.45	3.73	4.24	0.000	-2.280	-2.790
		6	1.83	4.61	5.12	0.121	-2.659	-3.169
		8	2.22	6.05	6.44	0.307	-3.523	-3.913
	90	4	1.23	2.71	3.92	-0.004	-1.484	-2.694
		6	1.61	3.42	4.69	0.042	-1.768	-3.038
		8	1.97	4.39	5.86	0.169	-2.251	-3.721
7	30	4	1.45	3.56	5.75	1.605	-0.505	-2.695
		6	1.83	4.43	6.80	2.280	-0.320	-2.690
		8	2.32	5.73	8.61	3.002	-0.408	-3.288
	60	4	1.74	4.35	5.13	-0.290	-2.900	-3.680
		6	2.26	5.37	6.18	-0.309	-3.419	-4.229
		8	2.73	7.05	7.73	-0.203	-4.523	-5.203
	90	4	1.52	3.16	4.74	-0.294	-1.934	-3.514
		6	1.98	3.97	5.63	-0.328	-2.318	-3.978
		8	2.41	5.10	7.07	-0.271	-2.961	-4.931
8	30	4	1.58	4.26	6.21	1.475	-1.205	-3.155
		6	2.00	5.31	7.37	2.110	-1.200	-3.260
		8	2.53	6.9	9.29	2.792	-1.578	-3.968
	60	4	1.92	5.21	5.54	-0.470	-3.760	-4.090
		6	2.45	6.40	6.64	-0.499	-4.449	-4.689
		8	2.99	8.48	8.34	-0.463	-5.953	-5.813
	90	4	1.66	3.87	5.08	-0.434	-2.644	-3.854
		6	2.15	4.78	6.07	-0.498	-3.128	-4.418
		8	2.65	6.15	7.66	-0.511	-4.011	-5.521

In all tests the distance between the nozzle outlet and the impingement surface was equal to 20 mm.

Maximum area of removed region in the SR was obtained when the reservoir pressure, nozzle diameter and angle of impingement were equal to 8 Bar, 8 mm and 30°, respectively. Minimum area of removed region was obtained when the pressure, nozzle diameter and angle of impingement were equal to 5 Bar, 4 mm and 90°, respectively. Maximum and minimum values of area of removed regions in the SR were equals to 9.29 and 3.41 cm^2, respectively (Table 5).

Maximum area of the removed region in the MR was obtained when the reservoir pressure, nozzle diameter and angle of impingement were equal to 8 Bar, 8 mm and 60°, respectively. Minimum area of the removed region was obtained when the pressure, nozzle diameter and angle of impingement were equal to 5 Bar, 4 mm and 90°, respectively. Maximum and minimum values of area of the removed regions in the MR were equal to 8.48 and 2.42 cm^2, respectively (Table 5).

Maximum area of removed region in the CR was obtained when the reservoir pressure, nozzle diameter and angle of impingement were equal to 8 Bar, 8 mm and 60°, respectively. Minimum area of removed region was obtained when the pressure, nozzle diameter and angle of impingement were equal to 5 Bar, 2 mm and 30°, respectively. Maximum and minimum values of area of the removed regions in the CR were equal to 2.99 and 1.05 cm^2, respectively (Table 5).

A comparison between theoretical covered region by air-jet and area of the removed region showed that in the SR in all cases (different levels of reservoir pressure, angle of impingement and nozzle diameter) values of the area of the removed region were more than the values of the theoretical covered region. In the MR when the reservoir pressure was equal to 5 and 6 Bar and angle of impingement was equal 30° values of the area of the removed region were less than the values of the theoretical covered region; while in the other cases values of the area of the removed region were more than the values of the theoretical covered region (Table 5).

In the CR when the reservoir pressure was equal to 5 Bar, values of the area of the removed region were less than the values of the theoretical covered region. Also when the reservoir pressure was equal to 6, in most cases values of the area of the removed region were less than the values of the theoretical covered region; while, when the reservoir pressure was equal to 7 and 8 Bar and angle of impingement was equal 60 and 90°, values of the area of the removed region were more than the values of the theoretical covered region (Table 5).

3.2.2 "Dorsefid" variety

The results of interaction between operating parameters of air-jet impingement including pressure, nozzle diameter, angle of impingement and distance between the nozzle outlet and the surface of the SH on removing sunflower seeds from the head inside region of the SH showed that maximum and minimum areas of the removed region were equal to 9.66 and 3.66 cm^2, respectively. Maximum area of the removed region were obtained to be when the pressure, nozzle diameter, angle of impingement and distance between the nozzle outlet and the surface of the SH were equal to 7 Bar, 8 mm, 30° and 20 mm, respectively.

Based on optimization performed using Design Expert software package, the best condition for removing sunflower seeds from the SH was when the pressure, nozzle diameter, angle of impingement and distance between the nozzle outlet and the surface of the SH were equal to 7 Bar, 7.49 mm, 30.41° and 27.98 mm, respectively. Also results indicated that in all cases, area of the removed region increased with increasing nozzle diameter and air pressure and decreasing angle of impingement.

Table 6 shows the results of the statistical analysis performed to examine the effect of the operating parameters of air-jet impingement on area of the removed region in side region (SR). ANOVA indicated that pressure, nozzle diameter, and angle of impingement, all the three independent variables significantly influenced area of the removed region (Table 6). In all cases, in the SR, the effects of interaction between the independent variables are not significant.

Table 6 ANOVA results for area of the removed region of sunflower head on SR

Sources of variations	Sum of squares	Degree of freedom	F Values	p-value Probability>F
Model	65.264	14	94.851	< 0.0001**
Pressure of reservoir (A)	4.011	1	81.618	< 0.0001**
Angle of impingement (B)	48.912	1	995.213	< 0.0001**
Distance between nozzle and head (C)	0.012	1	0.254	0.6221
Nozzle diameter (D)	8.467	1	172.281	< 0.0001**
AB	0.432	1	8.796	0.0102
AC	0.008	1	0.170	0.6861
AD	0.025	1	0.508	0.4877
BC	0.003	1	0.054	0.8197
BD	0.302	1	6.144	0.0265
CD	0.000	1	0.000	0.9947
Residual	0.688	14		
Lack of Fit	0.581	10	2.167	0.2373
R-squared	0.9896			
Adjusted R-squared	0.9791			
Pred R-squared	0.9467			

"**" is the significant factor when the P = 0.01 and

The results of the effect of interaction between operating parameters of air-jet impingement on area of removed region in MR of the SH indicated that maximum and minimum areas of the removed region were equal to 8.24 and 3.25 cm^2, respectively. The maximum area of the removed region was obtained to be when the pressure, nozzle diameter, angle of impingement and distance between the nozzle outlet and the surface of the SH were equal to 7 Bar, 8 mm, 60 °and 20 mm, respectively.

Based on optimization performed, the best condition for removing sunflower seeds from the head was when the pressure, nozzle diameter, angle of impingement and distance between the nozzle outlet and the surface of the SH were equal to 7 Bar, 8 mm, 56.68 ° and 25.66 mm, respectively. Results also showed that in all cases, area of the removed region increases with increasing nozzle diameter and air pressure.

With increasing angle of impingement and distance between the nozzle outlet and the surface of the SH from 30 to 60 ° and 10 to 20 mm, respectively, the area of the removed region increased. But with the increasing angle of impingement and distance between the nozzle outlet and the surface of the SH from 60 to 90 ° and 20 to 30 mm, respectively, the area of the removed region increased.

The results of the statistical analysis performed to examine the effect of air-jet parameters on area of the removed region in MR of SH are shown in Table 7. ANOVA indicated that pressure, angle of impingement, nozzle diameter, distance between the nozzle outlet and the surface of the SH, all the three independent variables significantly influenced area of the removed region (Table 7). In all cases, in the MR, the interaction effects of the independent variables were not significant.

Table 7 ANOVA results for removed area of sunflower head on MR

Sources of variations	Sum of squares	Degree of freedom	F-values	p-value
Model	35.223	14	79.260	< 0.0001**
Pressure of reservoir (A)	9.899	1	311.854	< 0.0001**
Angle of impingement (B)	0.346	1	10.915	0.0052
Distance between nozzle and head (C)	1.444	1	45.498	< 0.0001**
Nozzle diameter (D)	10.373	1	326.793	< 0.0001**
AB	0.004	1	0.137	0.7166
AC	0.021	1	0.649	0.4340
AD	0.144	1	4.525	0.0517
BC	0.001	1	0.019	0.8926
BD	0.005	1	0.168	0.6882
CD	0.000	1	0.003	0.9538
Residual	0.444	14		
Lack of Fit	0.442	10	72.631	0.0004*
R-squared	0.9875			
Adjusted R-squared	0.9771			
Pred R-squared	0.9285			

"**" is the significant factor when the P = 0.01 and "*" is the significant factor when the P = 0.05

The results of the same tests in CR showed that maximum and minimum areas of the removed region were equal to 4.06 and 1.54 cm^2, respectively. The maximum area was obtained to be when the pressure, nozzle diameter, angle of impingement and distance between the nozzle outlet and the surface of the SH were equal to 7 Bar, 8 mm, 90 °and 20 mm, respectively.

Based on optimization carried out, the best condition for removing sunflower seeds from the SH was when the pressure, nozzle diameter, angle of impingement and distance between the nozzle outlet and the surface of the SH were equal to 6.24 Bar, 7.90 mm, 86.10 ° and 24.50 mm, respectively. Also the results showed that in all cases, the area of the removed region increased with the increasing nozzle diameter and air pressure and increasing angle of impingement.

With the increasing of the distance between the nozzle outlet and the surface of the SH from 10 mm to 20 mm, the area of the removed region increased. But with the increasing distance between the nozzle outlet and the surface of the SH from 20 mm to 30 mm, the area of the removed region increased.

The results of the statistical analysis carried out to examine the effect of air-jet parameters on area of the removed region in CR of SH are shown in Table 8. ANOVA indicated that pressure, nozzle diameter and angle of impingement, all the three independent variables significantly influenced the area of the removed region (Table 8). In all cases in the central region, the interaction effects of the independent variables were not significant.

Table 8 ANOVA results for area of the removed region of sunflower head on CR

Sources of variations	Sum of squares	Degree of freedom	F-values	p-value
Model	14.543	14	8.529	0.0001**
Pressure of reservoir (A)	2.386	1	19.591	0.0006*
Angle of impingement (B)	4.938	1	40.546	< 0.0001**
Distance between nozzle and head (C)	0.000	1	0.000	0.9987
Nozzle diameter (D)	4.914	1	40.347	< 0.0001**
AB	0.062	1	0.507	0.4881
AC	0.000	1	0.000	0.9933
AD	0.024	1	0.200	0.6617
BC	0.000	1	0.000	0.9989
BD	0.051	1	0.416	0.5295
CD	0.000	1	0.000	0.9989
Residual	1.705	14		
Lack of Fit	1.705	10	1256.120	< 0.0001**
R-squared	0.8591			
Adjusted R-squared	0.7091			
Pred R-squared	0.3957			

"**" is the significant factor when the P = 0.01 and "*" is the significant factor when the P = 0.05

In order to examine the effect of the air-jet parameters on the area of the removed region, the area of the removed region was modeled using Design Expert software package. To model the area of removed region, quadratic equation was used, because of the difference in significance and lack of fit between the quadratic equation on one hand and third-degree and fourth-degree equations on the other hand was very small. Quadratic model is simpler than the other ones and has a smaller number of coefficients. Coefficients of the models of the area of removed region for SR, MR and CR are shown in Table 9.

Table 9 Obtained coefficients for equations of relationship between independents variable and area of the removed region in different locations

Sources of variations	Side region	Middle region	Central region
Pressure of reservoir (A)	0.61807	-0.46875	0.82222
Angle of impingement (B)	-0.00022	0.14799	-0.01091
Distance between nozzle and head (C)	0.21306	0.35015	0.11789
Nozzle diameter (D)	0.35098	-0.66963	-1.29809
AB	-0.01096	-0.00110	0.00414
AC	0.00457	-0.00717	-0.00015
AD	0.03950	0.09475	0.03900
BC	0.00009	0.00004	0.00000
BD	-0.00458	-0.00061	0.00188
CD	-0.00004	-0.00026	-0.00001
A^2	0.02409	0.08483	-0.07132
B^2	0.00020	-0.00120	-0.00003
C^2	-0.00606	-0.00857	-0.00292
D^2	0.00896	0.05065	0.10598
Constant coefficient	0.05234	-2.60167	0.14385

3.3 Discussions

3.3.1 Theoretical results

The obtained results indicated that with increasing the reservoir pressure, jet force increased; theoretically (based on mentioned equations in Table 1), it can be explained as follows: as the current in nozzle outlet is supersonic, increase in the air reservoir pressure results in the increase in velocity of the air in nozzle outlet. Increase in air velocity in nozzle outlet results in increase in mass flow rate which results in increase in impingement jet force.

The results indicated that with the increasing of nozzle diameter, jet force increased; theoretically, it can be explained as follows: increase in the nozzle diameter causes the cross section of the nozzle outlet to increase. Increase in the cross section of nozzle outlet causes an increase in mass flow rate and, therefore, an increase in air-jet force in nozzle outlet. Increase in the air-jet force in nozzle outlet causes an increase in air-jet force on impingement surface.

With increasing the distance from the nozzle outlet, the cross section of the air-jet increases, because the air-jets were expanded as frustum. Therefore, when the distance between the nozzle outlet and the surface of the SH increases, area of the covered region by air-jet will increase.

3.3.2 Experimental results

The experimental results indicated that in the same condition (identical pressure, identical nozzle diameter, identical angle of impingement and identical distance between the nozzle outlet and the surface of the SH), the area of the removed region in side region and central region was the highest and the lowest; respectively; because for each head, seeds located on the side region of the head reach maturity before the seeds located on the middle region of the head (Mirzabe and Chegini, 2015). Also, seeds located on the middle region of the head reach maturity before the seeds located on the central region of the head.

Physiological maturity of sunflower heads starts from the side region to the central region. So when the sunflower head matures there are immature seeds in central region which are still absorbing nutrition from the plant; therefore, in most cases in the central region, maturity does not happen completely and so, picking force of the seeds in central region is more than the side and middle region and value of picking force on middle region is more than the side region (Mirzabe et al., 2014; Mirzabe and Chegini, 2015).

ANOVA indicated that the results of all the three models were significant and lack of fit of the models for SR was not significant (Tables 6, 7 and 8). Therefore the presented models for SR can predict the area of the removed regions precisely.

Based on the ANOVA results, reservoir pressure, angle of impingement and nozzle diameter are independent variables which significantly influence the area of the removed region for SR, MR and CR of sunflower head. ANOVA results indicated that the distance between the nozzle outlet and the surface of the SH is an independent variable which significantly influences the area of the removed region for MR of sunflower head. In all cases in the SR, MR and CR, the effects of interaction between the independent variables were not significant.

3.3.3 Comparison between experimental and theoretical results

Based on the theoretical results, with increasing nozzle diameter and reservoir pressure, mass flow rate, jet momentum, jet force and area of the removed region will increase; the experimental results confirmed the theoretical results.

Based on the theoretical results, with the increasing of the distance between the nozzle outlet and the surface of the SH, area of the covered region increases; the experimental results showed that with the increasing of the distance between the nozzle outlet and the surface of the SH, the area of the removed region increases at first, but then decreases. In fact when the distance from the nozzle outlet increases, area of the covered by air-jet increases but jet force decreases; therefore, it cannot be said that the area of the removed region increases with increasing distance from nozzle outlet, because the jet force decreases.

Comparison between experimental results of "Dorsefid" variety and theoretical results showed that for SR in all cases, for MR in 27 cases out of 29 cases and for CR in 18 cases out of 29 cases, the values of the area of the removed region were more than the area of the theoretical covered region by air-jet. Also experimental results of "Sirena" variety showed that in the SR and MR in most cases the values of the area of the removed region were more than the area of the theoretical covered region. It means that in removing sunflower seeds from the head, in addition to vertical flows impinged to the SH surface, the horizontal flows exit parallel to the surface, which results in removing seeds from the SH.

Theoretical results indicated that with increasing angle of impingement, the area of the covered region by air-jet increases. In the side region, the experimental results confirmed the theoretical results; but in the middle and central regions, with increasing angle of impingement, the removed region increases, but then decreases. Arrangement of the seeds on the SHs and distance between adjacent seeds can be an influential factor on suitable angle of impingement.

4 Conclusions

The effect of some of the most important parameters of air-jet impingement parameters on removing sunflower seeds were examined in static condition. Results indicated that in the same condition, area of the removed region in side region and central region were the highest and lowest; respectively and in all tests, no seeds were observed to have been damaged due to air-jet impingement. ANOVA results indicated that reservoir pressure, angle of impingement and nozzle diameter, as independent variables, had a significant influence on area of the removed region for SR, MR and CR ($P = 0.01$). In all cases, in all regions, the effects of interaction between the independent variables were not significant (P = 0.05).

Theoretical values of area of covered region by air-jet impingement for different levels of distances between the nozzle outlet and the surface of the SH, nozzle diameters and angle of impingement were calculated. The data indicated that areas of the covered regions by air-jet increased when the nozzle diameters and distance between the nozzle outlet and the impingement surface increased and also increased when the angle of impingement decreased. Also the theoretical covered region and the area of the removed region was compared together; results showed that in the side region in all cases values of the area of the removed region were more than the values of the theoretical covered region, while, in the central region in most cases values of the area of the removed region were less than the values of the theoretical covered region.

In present work all the test were done in the static condition; while, in the final thresher machine, sunflower heads or nozzles must be movement as linear, rotational or a combination of linear and rotational motion. Based on the theory, with increasing linear or rotational velocity of sunflower head or nozzle, focus of jet on coverage by jet will decrease; therefore, in the same condition, in the final machine area of covered region will less than the static condition. So, in order to increase percentage of removed seeds, in the final machine, jet force (in other words pressure or nozzle diameter) must be increased.

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