Design and Performance of an Air Shaker for Citrus Fruit Removal

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ABSTRACT

AN air shaker for citrus fruit removal was designed, constructed, and field tested between 1973 and 1975. The main components of the shaker were three 1.2 m (48 in.) diameter vane-axial fans which were belt driven by two engines and were trailer mounted on a live, steerable axle. The shaker weighed 8,522 kg (18,919 lb) and delivered an air volume flow rate of 85 m^3/s (180,000 cfm) with a power input of 242 kW (325 hp).

Air pressure measurements are presented to characterize the air shaking pattern. In all field performance tests abscission chemicals were applied to the citrus fruit to reduce the bonding strength of the fruit to the tree. Fruit removal capacities of the air shaker ranged up to 3.4 kg/s (152,856 lb/hr) at 80 to 100 percent removal efficiency. In general, when the fruit bonding strength was uniformly reduced to 22.4 N (5 lb) or less, the air shaker would remove 90 to 95 percent of the fruit at a rate of not less than 5.7 kg/s (45,000 lb/hr).

INTRODUCTION

Research work to determine the design requirements for mechanical citrus harvesters has been underway in Florida since the late 1950's. One essential step in harvesting is to remove the citrus fruit from the tree. Many devices have been investigated, one of which is the air shaker. Its main advantages are that (a) no physical attachments to the tree are required, allowing a continuous down-the-row operation, (b) a high percentage of fruit can be removed at a fast rate when the fruit bonding strength has been uniformly reduced to about 22.4 N (5 lb) by an abscission chemical, and (c) the machine reliability of the concept is inherently high. The main problems with the air shaker are its high power requirements, large capital investment, instability on sloping terrain, poor mobility in Florida sand, heavy weight, and dependence on an abscission chemical for satisfactory performance (Whitney and Patterson 1972) (Whitney 1972). The objectives of the research described in this paper were to design, construct, and field test an air shaker which would alleviate these problems.

DESIGN OBJECTIVES

The major design objectives for the air shaker were as follows:

1 Limit total power input for air generation to approximately 224 kW (300 hp) and minimize losses in air delivery system. Total air volume and velocity at the discharge should be approximately 85 m^3/s (180,000 cfm) at not less than 55 m/s (122 mph) and be capable of delivering an air shaking pattern for a tree height up to 6 or 7 m (18.3 to 21.3 ft).

2 Shaker to be mounted on a single, live (powered), steerable axle and should not require more than the average 45 kW (60 hp) grove tractor for towing. The tractive effort of the tractor-shaker combinations should be capable of negotiating most sandy grove terrain in Florida.

3 Center of gravity height should be low to maximize stability on rolling terrain.

4 Minimal time should be required to change shaker-tractor combination from grove operation to road travel and vice versa. Overall height and width for road travel should not exceed legal limits. Overall width in the grove should be minimized to allow operation in narrow row middles.

5 Machine construction should be simple and durable enough to lend itself to manufacturing and field use by interested companies and citrus growers.

CONSTRUCTION

The air shaker was constructed at the Agricultural Research and Education Center at Lake Alfred in 1973. It consisted of three, 1.22 m (48 in.) diameter, vane-axial fans (Joy Manufacturing Company*, Axivane Model 48-26-1/2 BD) which had adjustable pitch blades and were belt driven by two engines (Figs. 1 and 2). Each fan was driven by eight-5V section V-belts. The bottom engine powered the two bottom fans and provided power for all accessories while the top engine powered only the top fan. With this arrangement, the air shaker could be used for fruit removal in its road travel configuration on trees not exceeding 4.25 m (14 ft) in height. Two hydraulic cylinders raised the top fan for field operation or lowered it for road travel. This required less than 10 min by one operator.

The air shaker was mounted on a live, steerable axle which could be hydraulically steered 20 deg to the left or right. The axle had 16.5 x 19.5 tires and a tread width and overall width of 1.98 m (78 in.) and 2.39 m (94 in.), respectively. A traction assist of approximately 13.4 kN (3000 lb) was available by engaging the torque of a hydraulic motor into the differential of the axle with a manually-operated jaw clutch. Hydraulically-driven fruit sweepers were mounted in front of the two air shaker tires and in front of the tires of the towing tractor to push fruit out of the path of the tires.

A dual vane pump, belt driven by the bottom engine, supplied hydraulic oil at 1.5 l/s (24 gpm) to the primary

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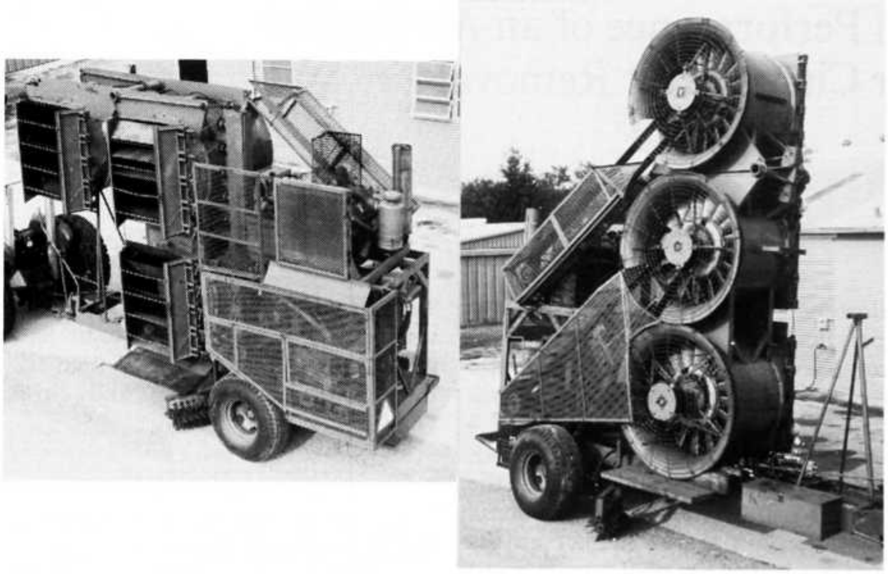

FIG. 1 Left—left rear view of air shaker with top fan down for road travel. Right—right front view of air shaker with top fan up for field operation.

circuit and 0.6 l/s (9 gpm) to the secondary circuit. The primary circuit provided oil to the hydraulic motor driving the air-manipulating plates and the traction assist. The secondary circuit provided oil to operate the cylinders for raising and lowering the top fan, to steer the axle, and to power the hydraulic motors driving the fruit sweepers in front of each tire.

The conversion of engine power to air power to shake the tree was maximized in several ways. First, the fans were belt driven from the engines. Second, efficient fans were selected for the air volume flow rate and pressure in the design objectives. Third, losses between the fan rotor and the point of air discharge were minimized. This was accomplished by making the path of air flow relatively straight and constant in cross-sectional area (Fig. 3) and by making the air manipulating plates like air foils with the diameter of the large or shaft end of each air foil less than 15 percent of the spacing dimension between them. The annulus area of each fan (between inside and outside casing) and its transition discharge were each 0.85 m^2 (9.33 ft^2).

To minimize the width of the air shaker, the length of the outer casing of the fans was reduced from a nominal 1.22 m (48 in.) to 0.84 m (33 in.) and each transition was 0.61 m (24 in.) in length (Fig. 3). This required the transitions to converge horizontally at a total included angle of 45 deg. The width of the air shaker was also minimized by displacing the radiator of the bottom engine to the side of the engine and centering it over the air shaker axle. The maximim profile width of the air shaker (disregarding the axle) was 2.03 m (80 in.)

The total weight of the air shaker was 8522 kg (18,919 lb). Its center of mass was positioned 0.48 m (19 in.) in front of the axle so that approximately 940 kg (2087 lb) was on the hitch and 7582 kg (16,832 lb) was supported by the axle when the machine was level and the top fan up. The hitch weight increased to about 1400 kg (3108 lb) when the top fan was lowered for road travel. The lateral position of the center of mass was important because of the weight transfer on the axle from one wheel to the other as a result of the thrust of the fans. This thrust or momentum force can be calculated (Baumeister and Marks 1969) as follows:

$$F = DQV = DAV^2$$

Where

- F = momentum force of air in direction of air flow, N (lbs)
- D = density of air, kg/m^3 ($slugs/ft^3$)
- V = Average velocity of air flow, m/s (ft/sec)
- A = cross-sectional area through which air flows, m^2 (ft^2)
- Q = volume flow rate of air, m^3/s (ft^3/sec)

Based on air pressure measurements and the fan manufacturer's performance curves, values assumed in the equation for all three fans were, Q = 85 m^3/s (180,000 cfm), V = 58 m/s (130 mph) and D of standard air is 1.2 kg/m^3 (0.0023 $slugs/ft^3$). This yielded a total thrust force of 5916 N (1329 lb) at 3.12 m (123 in.) above ground (height of middle fan). Air delivery was to the left so that the thrust was to the right and had to be resisted by a weight transfer from the left to the right tire on the air shaker.

The center of mass (8522 kg) of the air shaker was positioned 0.13 m (5 in.) to the left of the longitudinal center line to achieve a compromise on the balance of weight on the tires with

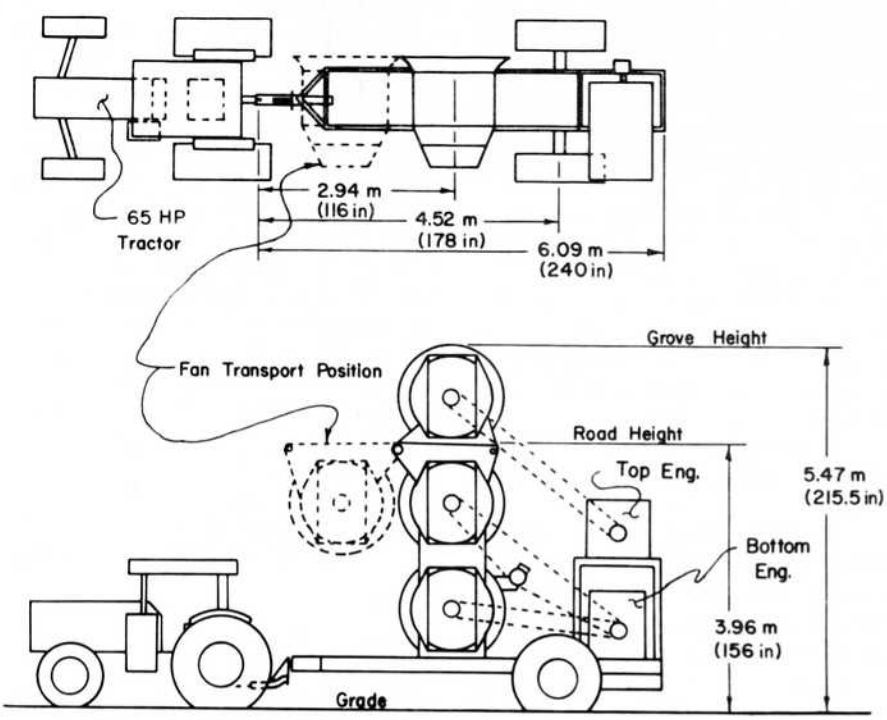

FIG. 2 Schematic top and side views of towing tractor and air shaker showing placement of axial fans, engines and belt drives.

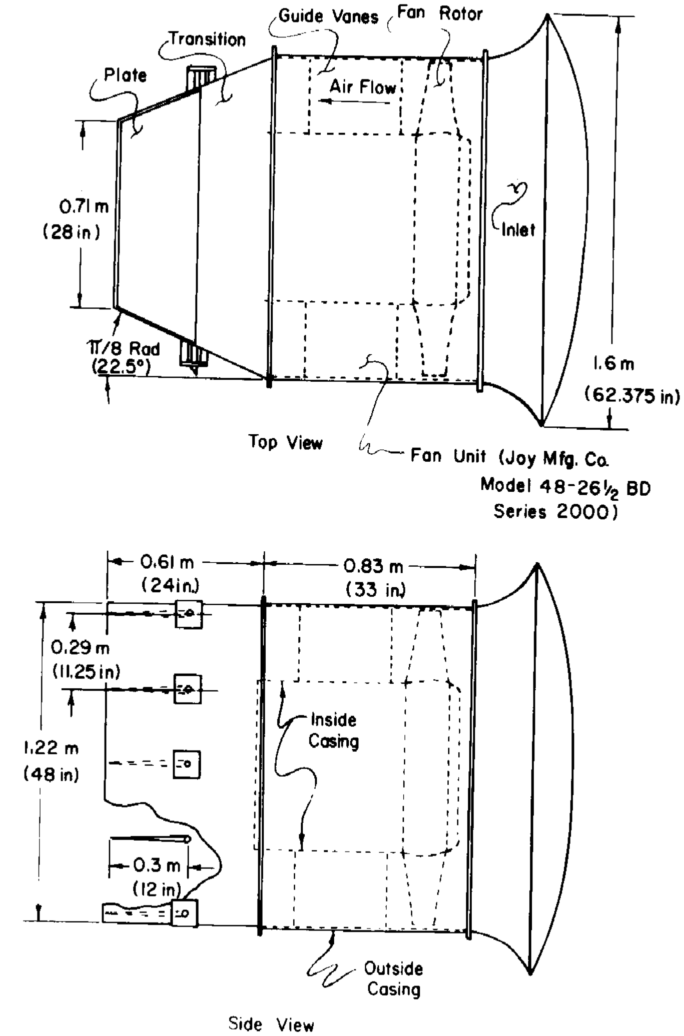

FIG. 3 Schematic top and side views of fan-transition unit with air-manipulation plates.

or without the fans operating. With the top fan up and no fan thrusts, weights on the left and right tires were approximately 4382 kg (9728 lb) and 3200 kg (7104 lb), respectively. When all three fans were operating at full thrust, the left and right tire weights were approximately 3431 kg (7616 lb) and 4151 kg (9213 lb), respectively.

The center of mass height above ground was 1.96 m (77 in.). With no fan thrusts, the theoretical tipping angles about the hitch-tire line on the right and left side of the air shaker were 27 and 21 deg, respectively.

The air shaking pattern emanating from the discharge on the air shaker was produced with a set of 15 upstream pivot plates, five per fan (Whitney and Schultz 1975). The plates were trapezoidal in shape to fit the transition and were 0.3 m (12 in.) wide (parallel to direction of air flow), 0.71 m (28 in.) long on the downstream side, and 0.97 m (38 in.) long on the upstream side where the pivot shaft was mounted (Fig. 3). The phase angle between driving disks, which were driven with miter gears off a vertical shaft, was 25 deg and the arc of plate oscillation was set at 100 deg.

AIR MEASUREMENTS

Initial observations of the air shaker in removing oranges from the tree indicated that greater shaking energy was required in the top portion of the tree. To adjust for this difference in required energy, the pitches of the fan blades were set so that the top and bottom fans delivered the most and least volume flow rate of air while the middle fan delivered an intermediate amount. With the fans rotating at 188 rad/s (1800 rpm), and the plates oscillating at 1 cps, the static pressures between the fan rotor and plates averaged 750, 1000 and 1250 Pa (3, 4 and 5 in. water) for the bottom, middle, and top fans, respectively. Because the plates varied the area and configuration of the fan discharges, the static pressures cycled sinusoidally at an amplitude of about 750 to 1000 Pa (2 to 3 in. water). Based on fuel consumption records, pressure measurements, and fan manufacturer's specifications, the top, middle, and bottom fan delivered 30.5 m^3/s (65,000 cfm), 28.2 m^3/s (60,000 cfm), and 25.9 m^3/s (55,000 cfm), respectively, with a total power of 242 kW (325 hp).

The type of air pattern emanating from the discharge has been discussed by Whitney and Schultz 1975. Figs. 4, 5, and 6 illustrate some representative characteristics that were measured by a pressure transducer and recorded on a storage oscillopscope. Turbulence in the air patterns caused the transducer to sense a wide band of pressures and the average pressures within the band have been plotted.

Fig. 4 depicts the pressures recorded on the discharge center line at a horizontal distance of 0.6 m (2 ft), 1.8 m (6 ft), and 3.1 m (10 ft) from the discharge and a vertical distance from 1.2 m (4 ft) to 4.3 m (14 ft) above ground level. The upstream pivot plates were held stationary as shown on the figure and the focal point (plates converging) of air was located at 2.8 m (9 ft) above ground level. Two characteristics can be noted here. First, the peak pressure associated with the focal point did not decrease significantly with increased distance from the discharge. Second, the ratio of focal point peak pressures to vertically adjacent pressures increased with increasing distance from the discharge.

Fig. 5 shows tht pressures recorded on the discharge center line at 2.8 m (9 ft) above ground level with the plates oscillating at 1 cps. The focal point pressure pattern was moving vertically at 4.6 m/s (10 mph). Average peak pressure readings of the focal point were on the order of 2 Pa (8 in. water). The two characteristics noted above in Fig. 4 can also be seen in Fig. 5.

Fig. 6 displays the focal point pressure profile developed in a horizontal plane at 2.8 m (9 ft) above ground level with the plates operating at 1 cps. Basically, this profile is what the tree would be subjected to as the air shaker passed by the tree. The air pattern diverges at angle of approximately 50 deg. To a great extent, this large angle of horizontal divergence was a result of the plates converging or forcing the air together in the vertical plane.

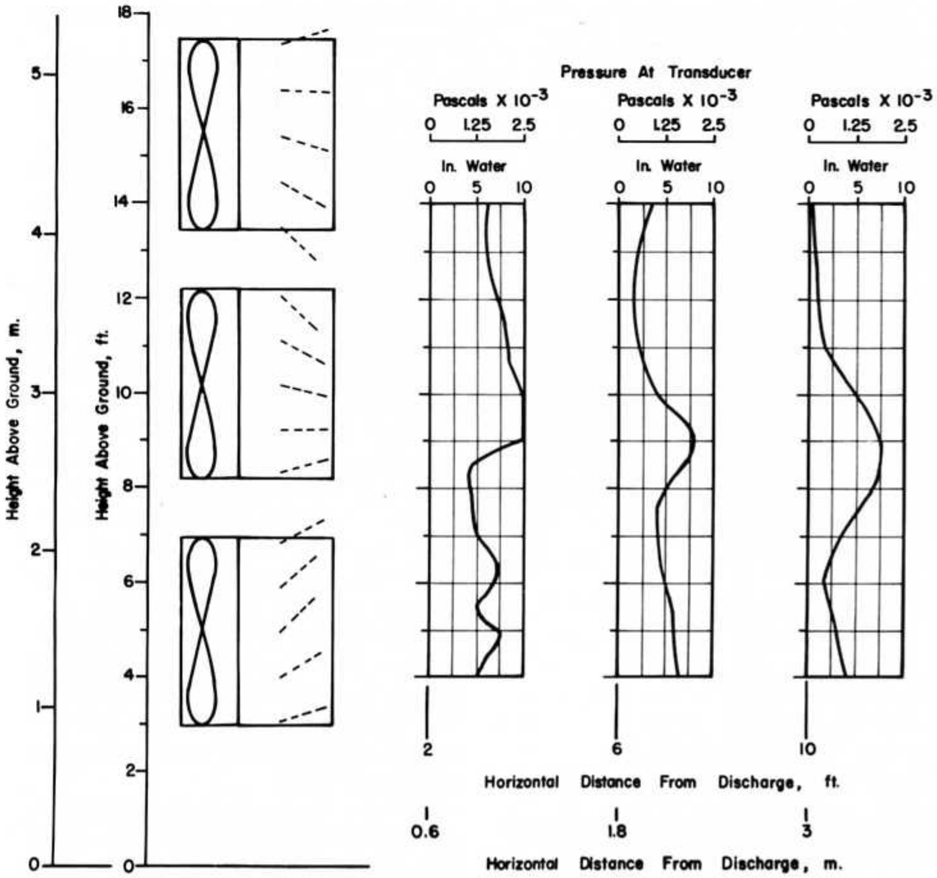

FIG. 4 Air pressure measurements between 1.2 m (4 ft) and 4.3 m (14 ft) above ground and at 0.6 m (2 ft), 1.8 m (6 ft), and 3 m (10 ft) from discharge with air-manipulating plates (dotted lines) stationary.

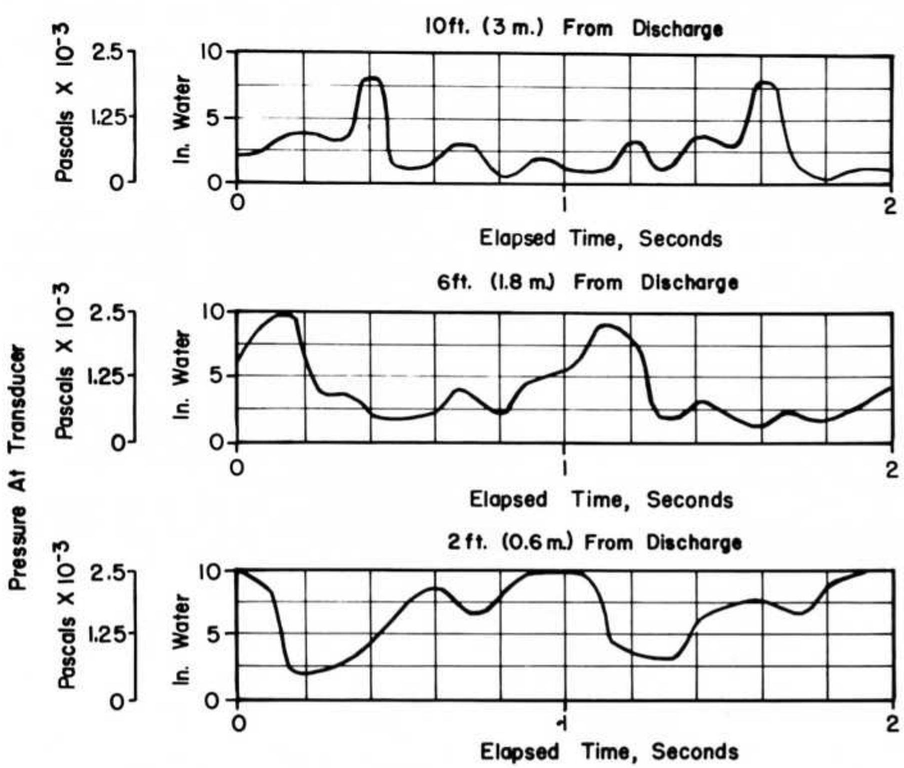

FIG. 5 Air pressure measurements at a point 2.8 m (9 ft) above ground and 0.6 m (2 ft), 1.8 m (6 ft), and 3 m (10 ft) from discharge with air-manipulating plates oscillating at 1 cps.

FIELD PERFORMANCE

During the 1973-75 period, several field tests were conducted in early and midseason oranges. In each test, an abscission chemical was applied to reduce the bonding strength of the fruit, after which the air shaker made one pass on each of two sides of the tree row to remove the fruit. Data recorded were percent preharvest fruit drop, range of percent fruit removal, fruit removal rate, and mass of fruit removed per unit of energy (fuel) consumed.

Table 1 summarizes the field performance data. Test 1 was conducted on trees 3.6 m (12 ft) to 4.3 m (14 ft) high. Only the two bottom fans on the air shaker were operated. Fruit loosening by the abscission chemical was not uniform and the air shaker achieved less than 85 percent removal. Samples of the fruit left by the air shaker indicated a fruit bonding strength of 36 N (8 lb).

Test 2 was conducted in trees up to 7.6 m (25 ft) high. Most of the fruit left by the air shaker was above a 5.5 m (18 ft) to 6.1 (20 ft) height in the tree and was too high for the air shaking pattern to effectively reach. A high percentage of the total fruit was removed in the first of two passes.

Tests 3 through 5 were conducted on trees at a fairly uniform height of 5.5 m (18 ft). Test 3 had very ideal fruit loosening in that the fruit bonding strength was uniformly reduced to below 22 N (5 lb). As the results indicate, percentage fruit removal, removal rate, and mass of fruit removed per unit of energy (fuel) consumed were all high.

Tests 4 and 5 were conducted in the same grove, the main difference being that Test 4 had 1 percent preharvest drop vs. 25 percent for Test 5. With the higher preharvest drop (Test 5), the fruit removal percentage was somewhat higher, and the removal rate and fruit removed per unit of energy (fuel) consumed were almost doubled.

In all field tests, the air shaker was towed with a tractor weighing 4505 kg (10,000 lb) with 49 kW (65 hp) (PTO) and was operated by one man. The tractor and the air shaker were capable of moving up a sandy 7 percent slope with the 13.4 kN (3000 lb) of traction assist of the powered axle on the air shaker. The live (powered) axle was an essential part of the air shaker and the 13.4 kN (3000 lb) was adequate in all groves in which

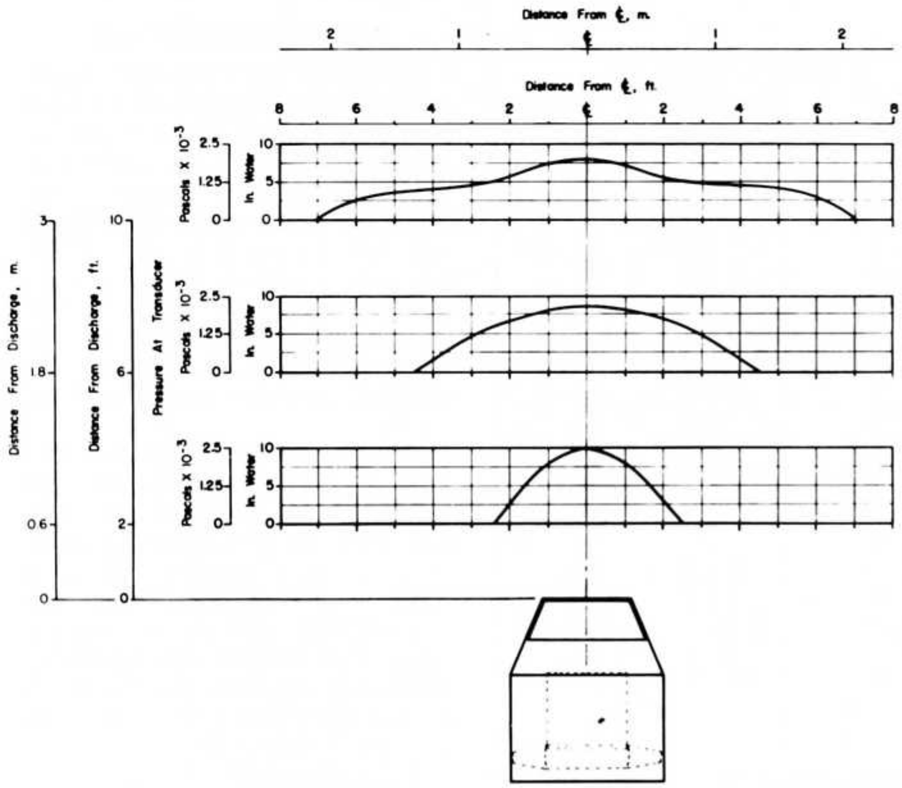

FIG. 6 Air pressure measurements on a horizontal line 2.8 m (9 ft) above ground and 0.6 m (2 ft), 1.8 m (6 ft), and 3 m (10 ft) from discharge with air-manipulating plates oscillating at 1 cps.

tests were conducted and was usually needed to turn at the row ends. The flotation provided by the two 16.5 x 19.5 tires on the air shaker was marginal in some groves. Although the air shaker was never precariously close to tipping over, the height of the center of gravity with the top fan up was probably too high to be considered safe for the average operator.

In general, the air shaker performed satisfactorily in trees that were not over 5.5 m (18 ft) high and when the fruit bonding strength was uniformly reduced to less than 22.4 N (5 lb). Such a reduction in fruit bonding strength usually caused a preharvest fruit drop of 10 percent or more. Under these conditions, 90 to 95 percent of the fruit could be removed at a rate of not less than 5.7 kg/s (45 000 lb/hr) and at least 0.04 kg of fruit could be removed per J of fuel energy (0.09 lb/Btu).

TABLE 1. FIELD PERFORMANCE TESTS WITH THE AIR SHAKER* IN EARLY AND MIDSEASON ORANGES

Test no.	Mass of fruit removed, kg	(lb)	Percent preharvest drop	Range of percent fruit† removal	Fruit removal rate† kg/s	(lb/hr)	Mass of fruit removed/fuel consumed‡, kg/J	(lb/Btu)
1	25,000	55,000	5	80-84	3.4	26,928	0.04	0.09
2	206 000	437,320	10	80-100	4.3	34,056	0.03	0.07
3	98 000	217,560	20	96-99	19.3	152,856	0.13	0.30
4	50,000	111,000	1	90-95	5.7	45,144	0.04	0.09
5	64,000	142,080	25	95-100	11.0	87,120	0.07	0.17

*Air manipulating plates operated at 1.3 cps.
†Includes preharvest drop, but not lost time for turning at row ends.
‡J and Btu represents the high heating value of the fuel consumed by the engines.

SUMMARY

An air shaker for citrus fruit removal was designed, constructed, and tested to alleviate some of the more pronounced problems (such as high power requirements) with existing air shakers. The unit was trailer-mounted on a live, steerable axle, weighed 8522 kg (18,919 lb), and delivered an air volume flow rate of 85 m^3/s (180,000 cfm) with a power input of 242 kW (325 hp). When towed by a 49 kW (65 hp) tractor in sandy groves, a drawbar pull of 13.4 kN (3,000 lb) was required from the live axle. The center of mass was 2 m (77 in.) above ground and was considered too high to be safe for the average operator and conditions.

The air shaker was capable of developing air blast (pulse) pressures of 2 Pa (8 in. water) at 3.1 m (10 ft) from the discharge. The air pattern diverged at 50 deg and covered a height of 5.5 m (18 ft).

In fruit removal tests, abscission chemicals were applied to the citrus fruit to reduce the bonding strength of the fruit to the tree. Preharvest fruit drop ranged from 1 to 25 percent. Fruit removal capacities of the air shaker ranged up to 3.4 kg/s (152,856 lb/hr) at 80 to 100 removal efficiency. In general, when the fruit bonding strength was uniformly reduced to 22.4 N (5 lb) or less, the air shaker could remove 90 to 95 percent of the fruit at a rate of not less than 5.7 kg/s (45,000 lb/hr).

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