model by defining c_{sD}, the "diffusive" oil concentration present in the solid (6), as $c_s = c_L^* + (c_{sD} - c_L^*) \exp(-K_D t)$. In fact, when K_D is low enough (even lower than the values obtained in [6]), c_s is a function of the time almost unaffected by the concentration of the liquid c_L^*.

Actually, a more rigorous model that took into account the oil concentration gradients within the solid particles and the different transport properties of the chemical species involved (lipids and phospholipids) could allow a closer fitting of the experimental results.

The results of the present investigation indicate that the rate-limiting step of the extraction is the removal of the last portion (diffusive) of the oil of the seed. This step could be improved by increasing the residence time, or the temperature in the last phase of the extraction. So that satisfactory extraction efficiencies (residual oil less than 1.5% with extraction ratios R in the range 4-5) could be attained even with very simple immersors (mixer-settler or semicontinuous extractor).

ACKNOWLEDGMENTS

This work was supported by ENI, Rome. Technical assistance was provided by F. Grillo, A. Gubbiotti, S. Angelici and B. Renotti. E. Proietti collaborated in the preparation of the report.

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[Received August 9, 1982]

Almost Complete Dehulling of High Oil Sunflower Seed

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ABSTRACT

An almost complete dehulling (hull residue lower than 3%) of sunflower seeds, before oil extraction, reduces to a minimum both the transfer of pigments from hulls to the flour and the content of fiber in the finished product. In this paper some results of our work on the dehulling of high-oil seeds with an air-jet impact huller are presented. The effectiveness of dehulling has been evaluated as a function of characteristics of the seed (variety, moisture and so forth) and of operative parameters (impact velocity, etc.). The optical analysis of the impact of the seeds on the target was made by means of high-speed cinematography (about 8000 frames/sec) to have a better view of the phenomenon and to measure the parameters of energy involved. The use of proper seed monentum, which is a function of the characteristic of the seed, can allow selective hull breaking with minimum kernel breakage. Almost complete hull-free kernels from high-oil sunflower seeds were obtained by means of a continuous dehuller-separator pilot plant.

INTRODUCTION

The scope of this work was to determine the optimum conditions for the production of almost complete hull-free kernels from sunflower seeds. This work is part of a more extensive research program aimed to develop a technology for the production of food-grade sunflower flour. For producing food-grade flour, an almost complete dehulling (residual hulls less than 2-3%) is required to minimize the transfer of pigments from the hulls to the flour and the fiber content in the finished product (1-3).

Partial dehulling of the seed, up to about 10-12% of residual hulls, is quite common in the oil industry (4-7) and presents the following advantages: decreased volume of product to defat; decreased erosion of the presses; better quality oil (lower wax content); better quality of the extracted flour (increase in the protein content).

Industrial applications of complete dehulling of the seeds are unknown. An important contribution on this subject was reported by The Food Protein Research and Development Center, Texas A & M University, which carried out research with the aim of producing hull-free kernels (3). The results of this study, and those of other researchers (8-11) show the technical difficulties and the low yields occurring in the dehulling of high-oil sunflower seed. To try to overcome these difficulties, research mainly devoted to the dehulling of high-oil seed with an air-jet impact huller, has been carried out in the present work. The effectiveness of dehulling, in a once-through laboratory device, and in a continuous dehuller-separator pilot plant, has been measured as a function of the characteristics of the seed (variety, moisture and so forth) and of the operative parameters (impact velocity and so forth).

EXPERIMENTAL PROCEDURES

Laboratory Tests

Once-through dehulling tests have been performed using a laboratory air-jet impact huller manufactured by Hydromecanique et Frottements (HF) (12,13). This huller consists of a seed-sucking section (Ventury effect), an acceleration tube and a metal target tilted at an angle to the axis of the tube (Fig. 1). Proper air (Q) and seed flow rates (W) are fed to the huller for a certain time (t). The outgoing product is collected and the following fractions are separated by hand and analyzed by direct weighing: percentage of hulls (H); percentage of whole or broken kernels; percentage of fines (F) (broken kernels with diameter less than 2 mm); percentage of partially dehulled seeds and percentage of undehulled seeds.

The dehulling efficiency (E), is defined as the percentage of dehulled seed and is evaluated, as $E = H \times r$, r being the

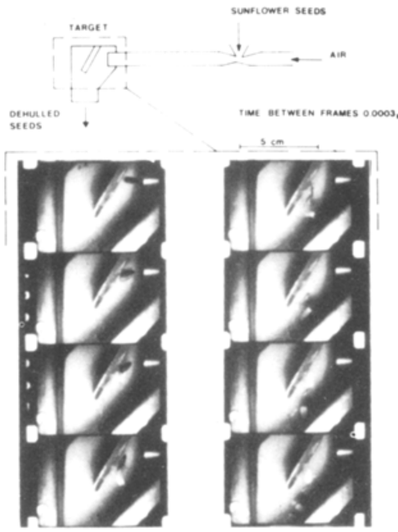

FIG. 1. Laboratory air-jet impact dehuller. High-speed cinematography of the impact.

ratio of seed weight to hull weight in the whole seed.

An optical analysis of the impact of the seeds on the target was also carried out by means of high-speed cinematography. The movie camera, a Hitachi NAC 16-S, was used at speeds up to 8000 frames per second. Frame records were read on a Hitachi NAC-S Film Analyser, allowing the evaluation of the velocity and the position of the seed at the exit of the acceleration tube, the characteristics of the impact and the velocity components of the fragments of broken seeds. A better view of the whole phenomenon and a measurement of the energetic parameters involved was obtained in this way. The tests were repeated by varying seed characteristics (cultivar, moisture content, particle size and density) and operative parameters (air pressure and flow rate, seed flow rate and impact angle).

Three high-oil varieties (Airelle, Luciolle and Cernianka) and 4 high-oil hybrids (Romsun HS90, Inra 6501, Remil and Primasol) grown in the south of Italy (Puglia) were tested. Each sample was characterized by analyzing (Table I): (a) the moisture content of the whole seed and the hand-separated hull and kernel (weight loss measured according to AOCS method Ac 2-41 [14]); (b) the seed/hull weight ratio (direct weight measure); (c) the oil content of the whole seed (petroleum ether extraction according to AOCS method Ac 3-44 (14); (d) the bulk density of the whole seeds (weight, measure according to ASTM standard Method D 1895-69 [15]); (e) the actual density of the single seeds (compressibility measure of the air in the interspace among seeds [16]).

Continuous Pilot-Plant Tests

A continuous production (100-150 kg/hr) of almost complete hull-free kernels was obtained by means of an integrated dehuller-separator system, the dehuller having the same characteristic as the laboratory apparatus (Fig. 2). The outgoing product of the dehuller was seived: the fine kernels were treated in an air classifier and the coarse kernels in a vibrating, fluidized table. The unhulled seeds, separated on the table, were recycled to the same dehuller. Once steady-state conditions were attained, samples of the outgoing and recycled streams were collected for analysis. The performance of the system was evaluated by measuring the kernel recovery (R, % w) and the residual hulls (H) in the kernel stream. Commercial-grade seeds were used for these tests.

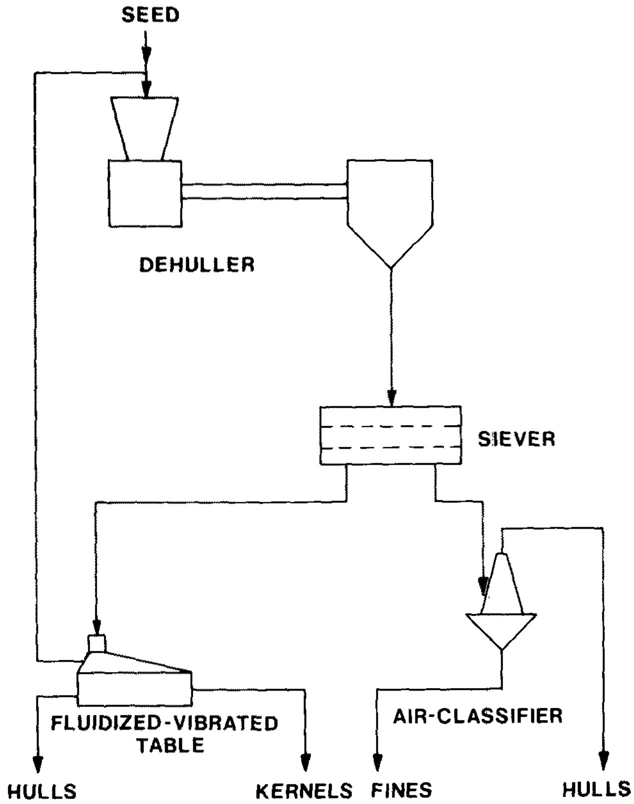

FIG. 2. Continuous pilot-plant dehuller.

RESULTS AND DISCUSSION

Seed Variety

Specific seed characteristics strongly affect the degree of dehulling. Confectionery seeds can be dehulled much more easily than high-oil seeds. However, within the high-oil varieties, a perceptible variation in dehulling effectiveness was found (Fig. 3). Characteristics of the tested seeds are shown in Table I. The seeds that are easier to dehull (INRA, AIRELLE, etc.) have a lower apparent and actual density. This observation is understandable in terms of a greater air space between the hull and the kernel. Light and scanning electron micrographs of different sunflower seeds actually show a large difference in this air space, which is very large for confectionery seeds (17). From a practical point of view, a simple bulk density measurement allows an approximate prediction of the dehulling characteristics of commercial-grade seeds. In particular, seeds with a bulk density higher than 0.4 kg/L are difficult to dehull.

Moisture Content

A decrease in the moisture of the seed increases the percentage of dehulled seed (E) but also the quantity of the fine kernel (F). Attempts to make the hull brittle with a fast thermic treatment have been reported giving variable results (3,9,10). Actually a drying degree can be determined that takes the whole seed humidity to the optimum, where the dehulling is maximum and the quantity of fines kernels produced is minimal. To find this value, Lusas (3) suggests minimizing the sum of the unhulled seeds (U=100-E) and the fine kernels (F). From the results of our laboratory tests, an optimum humidity of ca. 3% was evaluated according to this criterion (Fig. 4).

For a continuous working plant, the optimum refers to the operative conditions that maximize kernel recovery and

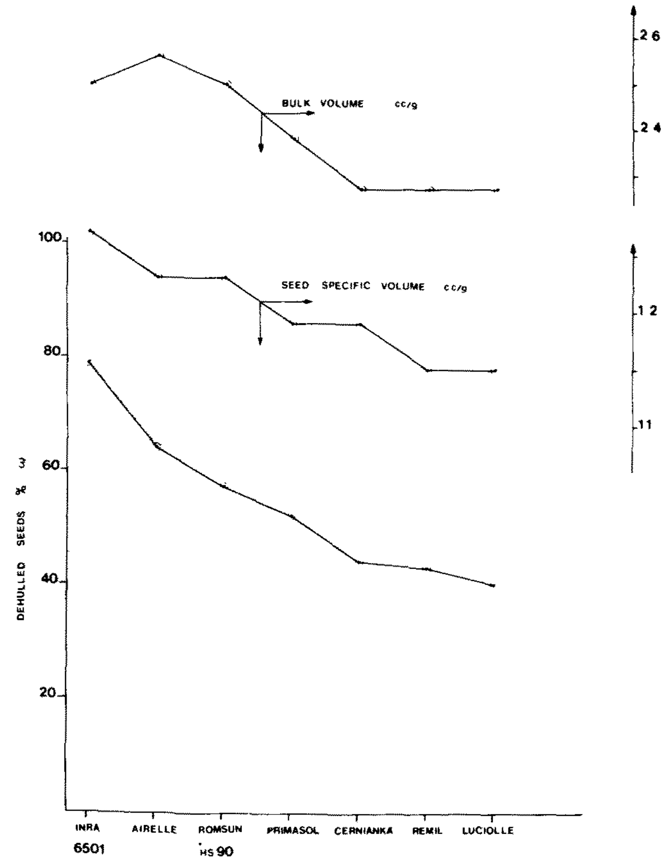

FIG. 3. The percentage of dehulling, bulk and specific volume for different sunflower seed cultivars (Table I).

is to be determined by considering the performance of the integrated dehulling-separation system. This optimum shifts to lower or higher humidity, depending on higher or lower efficiency of the separator for recovery of fine kernels. In the present investigation, for instance, the best condition shifted from 3% in laboratory tests (U + F = min.) to 4-5%, in continuous pilot-plant tests (R = max), because of the low efficiency of the divice for recovering fine kernels.

Dynamic Parameters

The main geometric and dynamic parameters affecting the performance of an air-jet impact huller are the following: pressure and air flow rate, seed flow rate, length of the acceleration tube and impact angle. Pressure and air flow rate determine the available energy. This energy is split in the kinetic energies of the air and of the seeds. The velocity of the seeds increases along the acceleration tube approaching the air speed. The final velocity that the seeds actually attain at the outlet of the tube is less than the air velocity and depends on the length of the acceleration tube and on the seed flow rate. A simplified mathematical approach to the phenomenon can be performed by taking into account the energy balance between the seed input section and a current section of the acceleration tube, and the force balance on the seed:

$$D\, v_1^3\, S_1/2 = Dv^3\, S/2 + w\, u^2/2$$
$$m_s\, (du/dt) = K\, (v\text{-}u)^2$$
$$K = C_D \cdot A_s \cdot D/2,$$

where v and u are the air and the seed speeds, D the air density, w the seed flow rate, m_s the mass of a single seed, S_1 and S the input and the current section, C_D the drag coefficent and As the seed projected area normal to the flow. The above relationships were solved by assuming: (a) instantaneous positioning of the seed in the air stream (the seeds tend to put their axis along the air flow direction in order to minimize the friction); (b) constant drag coefficient of the seed C_D = 0.4 (16); (c) negligible pressure drop along the acceleration tube; (d) negligible air density change.

The results presented in Figure 5 show great sensitivity of u to the air flow rate (Q) and to the length of the acceleration tube (1). A lower effect results from a variation of the drag coefficient (C_D) from 0.3 to 0.5, of (m_s) from 0.04 g to 0.08 g and of S_1 of the acceleration tube from 0.1 cm^2 to 0.2 cm^2.

The kinetic energy of the seed coming out of the acceleration tube is indicated in Figure 5, for m_s = 0.06. An approximate curve of the dehulling efficiency vs the kinetics energy of the seed can be obtained from the results of the present investigation (Table II), and the conditions for a dehulling efficiency level could be identified (Fig. 5). The soundness of this model was tested by comparing the predicted velocity values with the experimental ones measured by means of high-speed cinematography (Table II). The agreement of the results is good enough even if the optical analysis of the phenomenon shows that hypothesis (a) is not always verified: a percentage of the seeds (ca. 50-70%) leaves the acceleration tube still not positioned because the time required to attain equilibrium conditions is longer than the residence time of seeds in the tube. The seed breaking force (F) and work (A) depend on the direction of the applied force. Assuming the shape of the seed to be schematized as an asymmetric ellipsoid with diameters *a*, *b*, and *c*, the direction of the force may be: (a) parallel to the principal axis, *a* (force applied to the tip

TABLE I

Characteristics of Tested Seeds

Cultivars	Seed mositure (%)	Hull mositure (%)	Kernel mositure (%)	Oil (%)	100 seeds weight (g)	Bulk density (g/cc)	Actual density (g/cc)	Seed/hull weight (r)
Airelle[a]	7.8	12.9	5.2	43.2	5.7	0.39	0.81	3.3
Luciolle[a]	7.3	12.2	5.7	45.6	5.7	0.44	0.87	3.8
Romsun HS 90[b]	6.6	11.5	5.3	46.5	6.1	0.40	0.81	3.9
Inra 6501[b]	8.6	12.6	6.0	41.0	4.8	0.40	0.79	2.8
Remil[b]	7.9	13.2	5.9	47.5	5.9	0.44	0.87	3.5
Primasol[b]	6.8	12.5	4.6	48.8	4.8	0.42	0.84	3.5
Cernianka[a]	6.5	11.4	4.9	51.4	5.4	0.44	0.84	3.6

[a]Variety.
[b]Hybrid.

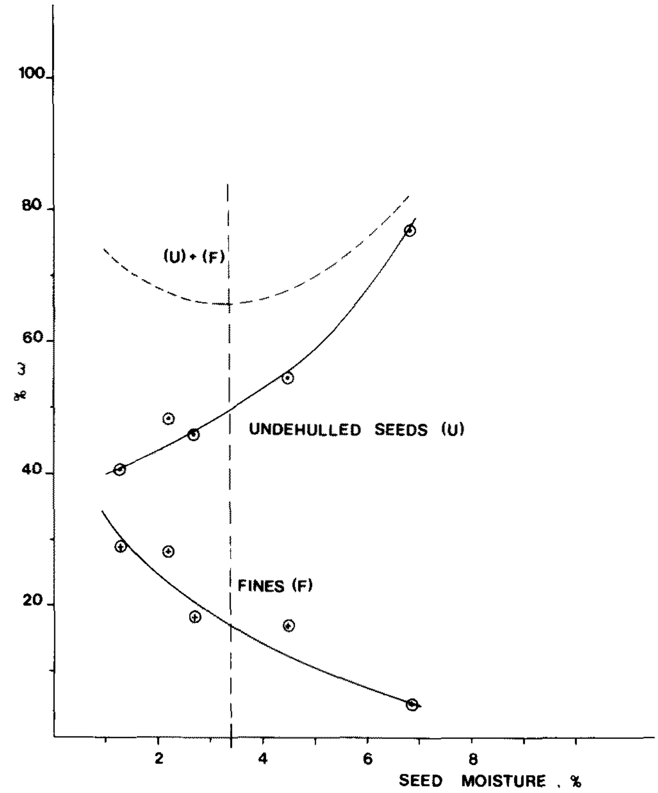

FIG. 4. Percentage of unhulled seeds and fine kernels (<2 mm) as a function of the seed moisture.

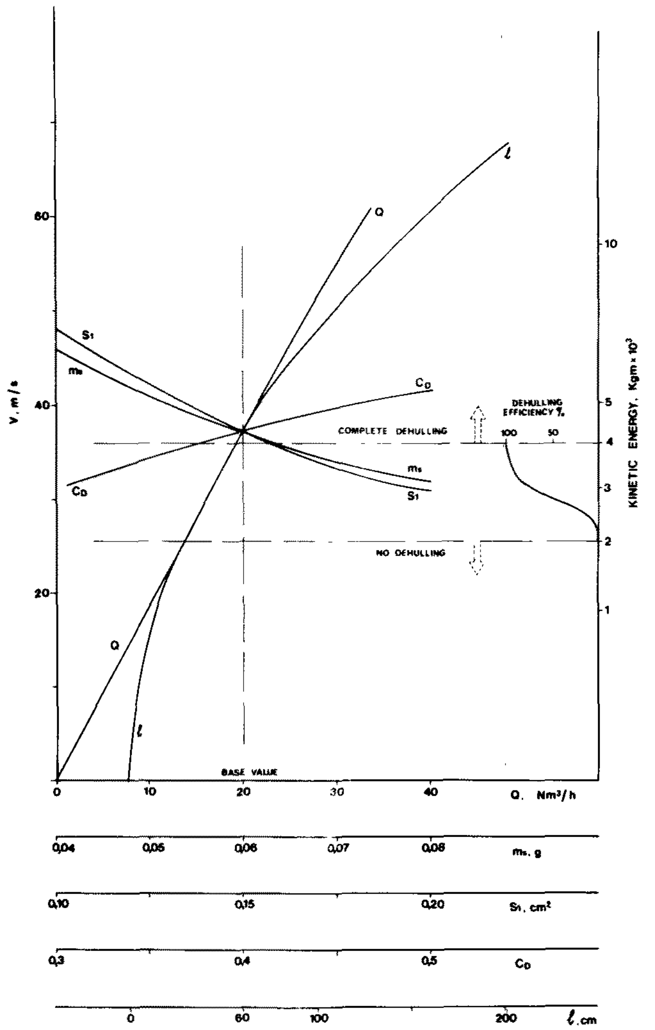

FIG. 5. Sensitivity analysis of the seed velocity to the main parameters of the dehulling system.

of the seed); (b) parallel to the average axis, *b* (force applied to the sharp corner side of the seed); (c) parallel to the lowest axis, *c* (force applied to the flat side of the seed). Experimental static values of F and A for different varieties of sunflower seed and for each of the 3 above mentioned situations were presented by Popova (10) and Morrison (17) (Table III). From these measurements, the minimum amount of energy appears to be supplied for the seed breaking in case (a) (force applied along the principal axis, *a* of the seed). For this reason, the relative seed-target positioning caused by the air stream in the jet huller, seems to be very useful for improving the breaking efficientcy. However, a proper impact angle, different from 90°, is required to allow the broken seeds to be discharged without interaction with the incoming ones. Under these conditions, we observed that, in spite of less breaking energy, seeds positioned along the principal axis were not broken, whereas under the same conditions, unpositioned seeds were broken. The reason appeared to be the different characteristics of the impact: in the first case the seeds slide on the target and save a motion component in the initial direction; unpositioned seeds, on the contrary, lose the whole initial momentum and break. Values of (F) and energy (Ec) were evaluated from the velocity component of the seeds before the impact, by estimating the impact time from the high-speed cinematography records (Table II). These values, corresponding to dynamic conditions, were compared with published static values of (F) and (E) (Table III); the difference is not very high, and is presumably caused by the

TABLE II

Dynamic Parameter Evaluation for Sunflower Seeds Breaking[a]

Air flow rate (ST M³/H)	Seed velocity: Experimental (M/S)	Seed velocity: Expected (M/S)	Dynamic parameters: Force[b] (kg)	Dynamic parameters: Energy[c] (kgm. 10^{-3})	Dehulling efficiency (%)
14	25	26	2.4	1.9	0 – 5
16	30	30	2.9	2.8	45 55
20	35	37	3.4	3.7	95 100
30	52	55	5.1	8.3	100

[a]Seed characteristics: variety, Romsun HS 90; moisture, 6.6%; mass, 0.06 g. Operative parameters: air input section, S1 = 0.15 cm²; seed flow rate, W = 30 kg/hr; tube length, L = 60 cm.
[b]Based on the experimental velocity; impact time roughly evaluated as 1/16000 s.
[c]Based on the experimental velocity; total kinetic energy dissipated.

TABLE III

Comparison Among Breaking Parameters for Sunflower Seed

Variety	Direction of force	Cracking force (kg)	Seed compression (mm)	Seed compression (%)	Cracking work (kgm. 10^{-3})	Dehulling efficiency (%)	Reference
High oil							
Vniimk 8931	Axis (A)	4.3	0.95		2.4	100	Poppva et al. (10)
Vniimk 8931	Axis (B)	8.5	1.70		8.2	100	Popova et al. (10)
Vniimk 8931	Axis (C)	10.0	1.25		4.8	100	Popova et al. (10)
Interstate 3113	Axis (A)	3.37		25.6			Morrison et al. (17)
Sputnik	Axis (A)	4.68		16.8			Morrison et al. (17)
Romsun HS90	Unoriented	2.4			1.9	0 – 5	Present investig.
Romsun HS90	Unoriented	2.9			2.8	45 – 55	Present investig.
Romsun HS90	Unoriented	3.4			3.7	95 – 100	Present investig.
Romsun HS90	Unoriented	5.1			8.3	100	Present investig.
Low oil							
Kruglik A-41	Axis (A)	6.5	0.60		2.1	100	Popova et al. (10)
Kruglik A-41	Axis (B)	8.8	1.70		7.1	100	Popova et al. (10)
Kruglik A-41	Axis (C)	9.8	1.20		4.2	100	Popova et al. (10)
Interstate 923	Axis (A)	4.28		13.1		100	Morison et al. (17)

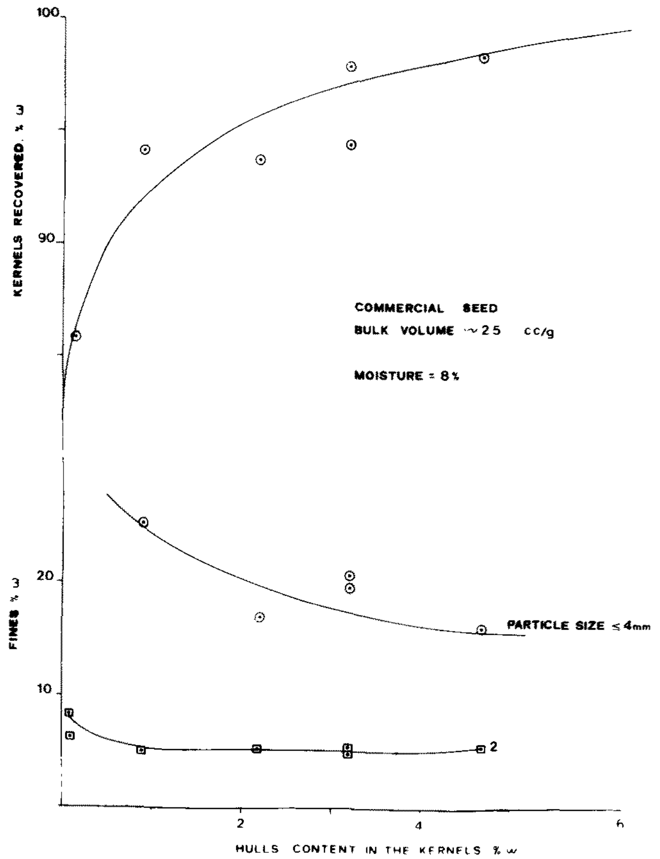

FIG. 6. Kernel recovery and fine kernel formation as a function of the hull content in the final product.

simplifying hypothesis adopted and the different characteristics of the tested seed.

Performance of Continuous Plant

The performance of the integrated system dehuller-separator was expressed as kernel recovery (R) as a function of the residual hulls in the kernel stream (H). A single curve, R = f (H), was obtained for each type of seed tested and each set of operative parameters. An example of this curve is shown in Fig. 6 for a seed with a bulk density of 0.4 kg/L. If a high percentage of residual hull is accepted (H = 6%); the kernel recovery is very high (R = 99.5%). On the contrary, the production of almost complete hull-free kernels gives rise to high kernel losses (R=85%). On the other hand, the production of food-grade sunflower flour requires a product with residual hull of less than 3% (2). This value of (H) corresponds to a kernel recovery of ca. 95-97% in the example shown.

In conclusion, the use of proper seed momentum variation, which is a function of the characteristics of the seed, can allow selective hull breaking with minimum fine kernel production. Under these conditions, hull-kernel-seed separation is facilitated, allowing the production of almost complete hull-free kernels.

ACKNOWLEDGMENTS

This work was supported by ENI, Rome. Prof. G. Russo and Mrs. C. Zucchini, Industrial Chemistry Institute, University of Naples, provided expert technical assistance in the high-speed cinematography analysis.

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[Received August 9, 1982]