A CONTINUOUS FLOW PARTICULATE MEDIUM GRAIN PROCESSOR

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A new machine utilizing the principle of particle-particle heat transfer to dry food grains by conduction heating was designed and a prototype constructed. In this machine, sand was first heated and then metered into a closed annular space along with a regulated mass of grain corn. The two granular media were then thoroughly mixed for a controlled time period and later separated. Heated grain was dispersed into holding tanks and the particulate medium (sand) was recirculated for reheating. The machine was built to accomplish all the above steps in a continuous flow operation. Results indicated that the steady-state temperature conditions are easily achievable at a heating efficiency of 81%. On an average 3–4% of moisture was removed from grain corn processed at an initial moisture content of 30% wet basis.

INTRODUCTION

The major factors of any efficient drying process are the optimal utilization of the heat and mass transfer mechanism. The conventional dryers available on the market follow a convective drying process using air. A convective heat transfer process is considered less efficient than a process utilizing conduction heating. Thus, it would be desirable to find an alternative heat transfer method to replace air drying. Particle-particle heat transfer mechanism (Raghavan et al. 1974) could be one such option. This paper outlines the design and operation of a particulate medium grain processor developed at Macdonald College of McGill University (Pannu 1984).

LITERATURE REVIEW

Although a number of experimental solid medium grain drying units have been built and tested, none is available on the market, implying that more research and development work is required in this field. The market is ready for a newer machine which can accomplish the grain drying operation more efficiently.

Akpaetok (1973) built a small prototype dryer (Akp 1) to study the effect of hot sand on the heating process and moisture loss involved in the drying of corn. Preheated sand and moist corn were transported into the elevated end of the drum for mixing of the two products. Residence time of the mixture was controlled by the drum angular velocity and its angle of inclination. Akpaetok reported moisture losses of 7–8%. Raghavan and Harper (1974) tested a continuous flow prototype dryer (Rag 1) to dry grain corn using salt as the heat transfer medium. Test results indicated a loss of 9% in this study.

Tessier and Raghavan (1984) tested a newer version of a particulate bed dryer (Rag 2) and used hot sand to dry high moisture yellow dent grain corn. This machine was also capable of processing 700 kg/h of grain corn similar to Rag 1. However, as opposed to a maximum moisture loss of 7 and 9% reported by Akpaetok (1973) and Raghavan and Harper (1974), respectively, the magnitude of maximum moisture loss reported was only 4% in this machine.

Several other researchers have experimented with the principle of particle-particle heat transfer to dry rice, oilseeds and wheat. Among them, Khan et al. (1973) demonstrated rice drying and par-boiling with the use of hot sand as the drying medium. In this machine, the best rice quality was obtained at a sand temperature in the range of 150–180°C.

Lapp and Manchur (1974) investigated the drying of rapeseed using a continuous flow unit. They found that for a sand bed temperature of 220°C there was neither contamination nor decrease in the oil quality. A moisture loss range of 2.5–6.7% for a contact time of 30 s was reported in this study. Further, Lapp et al. (1975, 1976) found that there was no damage to the baking and germination quality when wheat was dried at 105°C for 120 s with a sand to wheat ratio of less than 6:1. Subsequent work by Mittal et al. (1982) on this dryer indicated that a sand to wheat ratio of 4.5:1 removed the most moisture for an initial sand temperature of 105°C and a residence time of 60 s; fuel and drying efficiencies were 41 and 61%, respectively.

All of the above researchers indicate that a hot particulate medium can be used to dry cereal grains. However, there seems to be little agreement on the optimal sand to grain mass ratio, percentage points of grain moisture loss, temperature of the particulate medium or the residence time of the grain within the dryer. Values range from 2:1 to 20:1 for medium to grain mass ratio, from 2 to 9% for moisture loss (grain corn), from 105 to 275°C for the medium temperature and from 4 to 300 s for the residence time.

MACHINE DESIGN

In the design of a machine that can successfully process large volumes of grain by immersing it in a hot particulate medium, the following parameters were considered:

(1) Inlet temperature of the heated medium.

(2) Heat losses.

(3) Control of the mixing process and heating time.

(4) Ability to separate grain from the medium.

(5) Effective recirculation of the medium.

(6) Ease of handling the product.

Preliminary designs and calculations led to a machine shown in Figs. 1 and 2. It consists of three conical sections: inside conical drum (Cone-1) for heating the medium, outer conical drum (Cone-2) for mixing of the two media and their subsequent transportation to the separation section, and the last conical drum (Cone-3) for recirculation.

The Inside-conical-drum was equipped with a torsion device made up of four steel rods welded to the inside surface of the minor diameter with a steel sleeve at its center. On the other end, the drum was held in place by eight steel rods (ribs) fixed to a ball bearing assembly unit. A 44-kW propane burner protruding into the central section through a hollow shaft was installed along with the regulatory valves. Several buckets were attached to the inside wall of the inside conical drum (Cone-1)

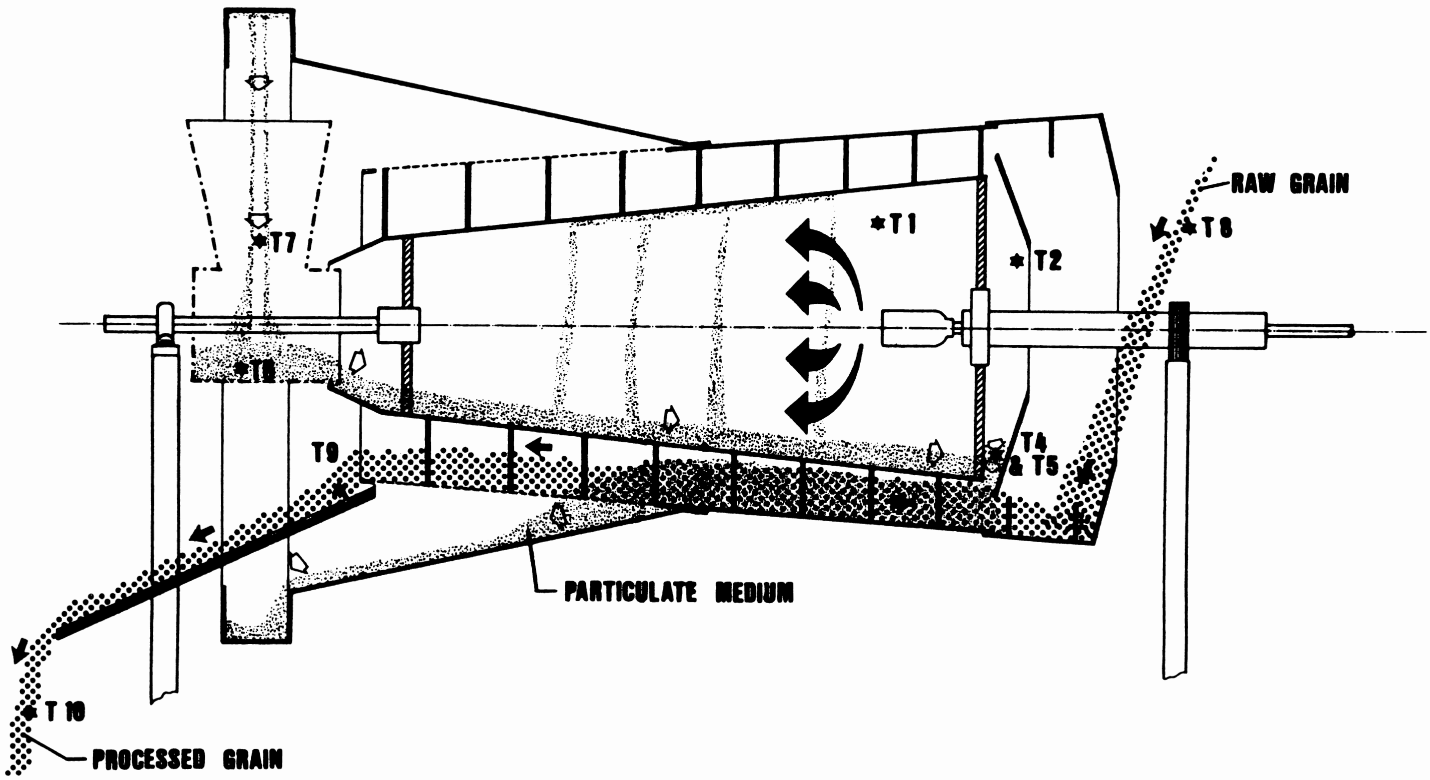

Figure 1. A schematic diagram of the machine showing the thermocouple locations and the flow-path of the particulate medium and product to be processed.

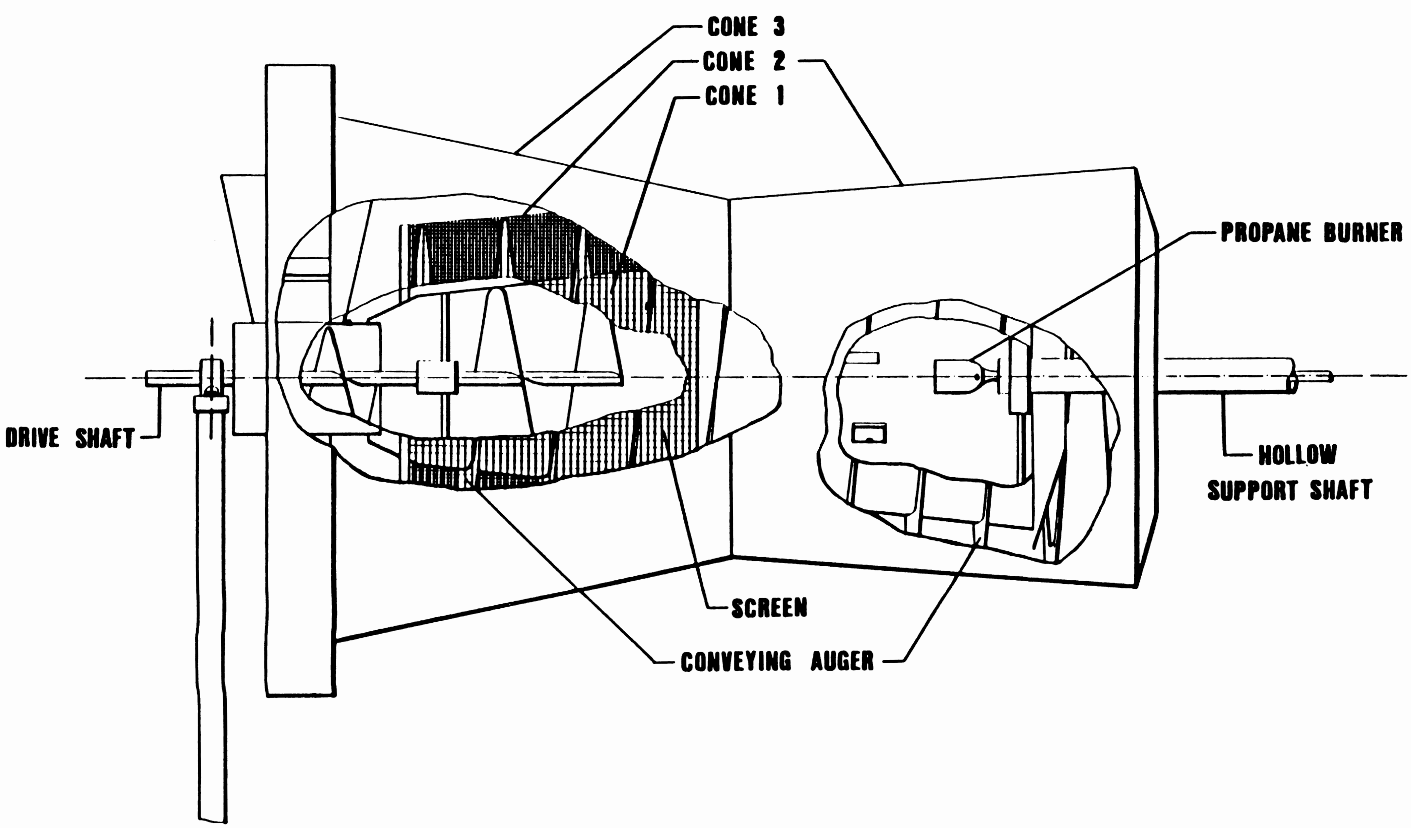

Figure 2. An overall view of the processor with cut sections.

TABLE 1. RESULTS OBTAINED FROM THE 15 TRIAL-RUNS CONDUCTED USING THE PROTOTYPE MACHINE

No.†	SGMR‡	m/c speed (rpm)	GRAIN: Res. time (s)	GRAIN: Flow rate (t/h)	TEMPERATURE (°C): Sand Hot	Sand Cold	Grain Raw	Grain Hot	Grain moisture (% lb): Raw	Loss without aeration
1	2.68	16.2	34.8	0.52	250	125	0	96	18.2	1.25
2	2.93	17.5	32.1	0.49	249	117	7	84	32.9	1.48
3	3.40	16.2	34.8	0.41	222	101	1	82	31.5	1.78
4	3.64	23.9	23.1	0.51	198	111	12	80	30.4	1.23
5	4.11	15.0	36.5	0.33	204	110	3	87	27.4	2.44
6	4.49	24.8	22.0	0.45	205	121	7	90	32.0	2.75
7	4.97	16.2	34.8	0.28	208	126	10	92	32.6	3.05
8	5.43	15.0	36.5	0.25	191	108	0	91	28.8	2.52
9	6.08	22.6	24.6	0.28	201	122	0	89	34.5	3.79
10	6.52	24.8	22.0	0.31	192	133	9	87	32.2	3.25
11	7.10	22.6	24.6	0.24	235	157	1	102	35.8	5.32
12	7.73	23.9	23.1	0.24	238	174	11	100	30.4	3.69
13	8.42	24.8	22.0	0.24	188	127	0	86	31.8	2.89
14	5.01	16.2	34.8	—	203	137	9	97	32.3	2.95
15	—	16.2	34.7	—	187	109	11	90	32.4	2.99

†Sets 1 to 13 were conducted using medium sand (sieve no. 55). Set 14 was conducted using coarse sand (sieve no. 30). Set 15 was conducted using fine sand (sieve no. 65). Contact time = (res. time) × 5/9.

‡ SGMR, calculated sand to grain mass ratio; m/c speed, machine rotational speed; res. time, grain residence time in the processor.

covering approximately one-half of its length. These fixtures directed sand particles through the hot section of the flame several times before being discharged out of the heating zone.

Before installing the outer conical drum (Cone-2) an auger was constructed around Cone-1 (Fig. 2). The conveying auger consisted of 11 complete flights, out of which the first seven were encased by sheet metal and the remaining four were covered by a 3.2-mm (⅛-in) hole steel wire mesh screen with a 84% open area. The part adjacent to the smaller diameter of the outer conical drum acts as the primary separator and the opposite end serves as the product entrance section. It can be observed that the outer conical drum is designed to perform a three-stage operation — dealing with product inlet, mixing the two media to enable particle-to-particle heat transfer and finally the separation of the two products.

The last conical drum (Cone-3) serves a dual purpose: first, it acts as a collector and second, it carries the fine granular particles to one central point of discharge. The drive shaft of the drum also acts as a conveying auger to transport the heating medium back into the inside-conical-drum.

The outside of the machine was insulated with 80-mm-thick R-10 glass wool batts to minimize heat losses. The machine was equipped with a 0.75-kW single phase, variable-speed DC motor for obtaining the desired rate of rotations.

PROCESSOR PERFORMANCE

The grain processor was experimentally evaluated on its performance in relation to heat input, grain feed-rate, contact or mixing time and moisture loss. Results obtained from 15 trial-runs conducted using the prototype machine are presented in Table I.

Heating

Initially, when the machine was fired, the ball bearing assembly unit got excessively hot and the flame inside the heating chamber was yellowish in color implying that the combustion process was incomplete. Therefore, a few modifications were made to the machine to ensure complete combustion of the gaseous fuel.

The 10 iron constantan (Type J) thermocouples installed on the machine as shown in Fig. 1 are fixed in place and not affected by the machine's rotation. The temperature readings were monitored through a Doric 205 data logger at 1-min intervals when the machine was operating. T1 measured the temperature of the hot gases inside the heating zone, T2 the temperature of the hot gases exiting outwards and T3 the ambient or room temperature.

Thermocouples T4 to T7 monitored the temperature of the particulate medium at different locations inside the machine. T4 and T5 provided the temperature of the sand particles just before entering into the mixing stage. T6 and T7 indicated the temperature of the sand prior to its re-entry into the heating section. Lastly, thermocouples T8 to T10 recorded the temperature variation of the grain corn along its flow path.

The temperatures registered for a typical data set are presented in Table II. It can be seen that after approximately 6 min the sand particles attained a steady temperature (T-4) of about 250°C. All the test results conducted on this machine indicated that once the grain processing operation had commenced there was very little fluctuation in the inlet temperature of the sand. The sand at the recirculation end registers a further increase before dropping down to a steady temperature value. This effect is due to heat transfer taking place between the machine and the sand particles before equilibrium temperature conditions are finally achieved.

Grain feed-rates were varied between 0.24 and 0.52 t/h for a multitude of grain moisture, sand temperature and grain residence time conditions. The results of the preliminary experiments demonstrated that it is possible to heat-treat large volumes of grain corn in this prototype machine.

Grain and Medium Flow Characteristics

A plot of grain residence time vs. the machine angular velocity is presented in Fig. 3. It can be observed that the curve is very close to a linear fit. This is true because the internal helix advances the grain forward by a distance equivalent to one pitch for every rotation. However, as the angular velocity increases it can be seen that the curve shifts upwards, indicating that the grain particles tend to prolong their stay in the processor. The best fit line was drawn and the following solution was found to fit the data.

$$t_g = 81.08 \exp(-0.5\,\omega) \quad (1)$$

$$1.6 < \omega > 2.6$$

where, ω is the angular velocity in rad/s.

TABLE II. TEMPERATURES OBTAINED IN A TYPICAL RUN ARE PRESENTED IN CENTIGRADE FOR THERMOCOUPLES T-1 THROUGH T-10

Time†	T-1‡	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9	T-10
13:39:00	486	140	16	99	102	18	19	4	—	—
13:40:00	384	135	16	131	136	20	19	4	—	—
13:41:00	352	148	17	168	175	41	64	4	—	—
13:42:00	374	167	17	199	205	76	98	4	—	—
13:43:00	410	188	18	231	230	106	114	5	—	—
Start										
13:43:47	384	193	18	238	241	122	141	3	—	—
13:44:00	399	194	18	248	246	126	145	2	—	—
13:45:00	376	198	19	250	253	132	135	1	103	—
13:46:00	391	202	20	252	250	125	128	0	111	—
13:47:00	391	202	20	251	250	122	125	0	109	96
13:47:51	385	203	20	246	248	120	123	—	104	96
Stop										
13:49:00	109	133	20	146	153	126	128	13	—	98

† Time: hour:minute:second.
‡ T-*n*, thermocouple number as defined in the text.

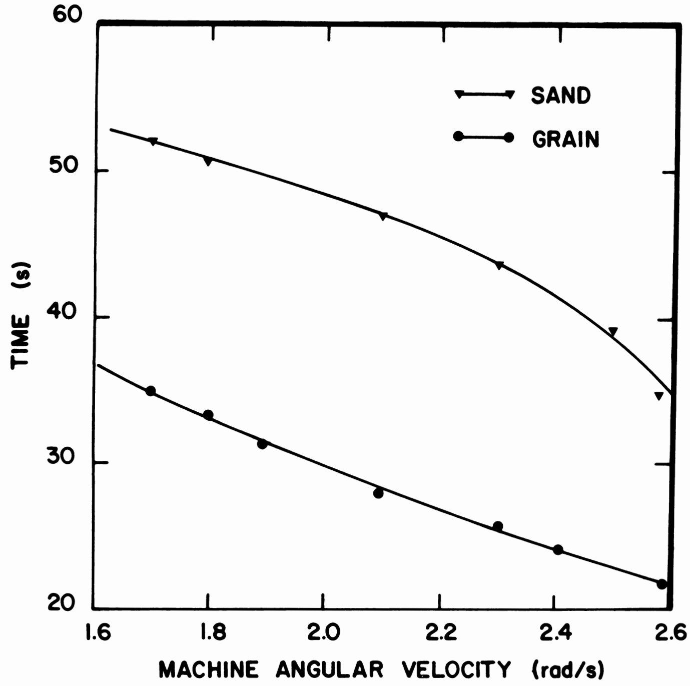

Figure 3. Grain and sand residence time in the machine at varying machine angular velocities.

A second numerical solution to predict the time required by the sand particles to complete one cycle was developed to calculate the recycle time of the sand particles:

$$t_s = 53.05 + 10.56/\tan(\omega) \qquad (2)$$

$$1.6 < \omega > 2.6$$

Figure 3 shows the experimentally determined values for sand recycle time vs. the machine rotational speed.

It is interesting to note that the two curves behave differently. As the machine angular velocity increases it is expected that the grain kernels stick to the side of the mixing/heat transfer drum (Cone-2), thus prolonging their stay. On the other hand, the sand particles after falling through the screen are carried forward at an accelerated rate from Cone-3 into Cone-1 thereby reducing the sand recycling time. Further, it is also expected that the slope of both Cone-1 and Cone-3 would accelerate the forward motion of the sand particles as the angular velocity increases.

It was noted that the separation process was complete and the recirculation was good for machine angular velocities between 1.6 and 2.6 rad/s. However, outside these limits it was observed that the sand particles overflowed in the cylindrical bucket elevator and substantial sand losses were recorded when the rotational speed was decreased below 1.26 rad/s. Increasing the rotational speed beyond 2.6 rad/s resulted in the sand particles being carried upwards at an accelerated rate and being discharged beyond the range of the fixed funnel.

Moisture Removal

For relatively high grain mass flow rates and a short contact time (12.2–19.3 s), the moisture removed varied between 1.2 and 5.3% on a wet basis. These results compared very favorably with those reported by Tessier and Raghavan (1984), Lapp and Manchur (1974), Lapp et al. (1975, 1976) and Mittal et al. (1982).

The experimentally determined drying efficiency (ratio of latent heat of lost water to heat input to sand) for this machine ranged between 11 and 26%, whereas the heating efficiency (ratio of total heat transferred to corn to the heat input to sand) varied between 69 and 90%. When a hot particulate medium, such as sand, is used to dry cereal grains most of the heat transferred by the medium goes to raise the temperature of the grain kernel instead of evaporating the moisture. Therefore improvements are required in terms of finding a suitable medium to enhance mass transfer characteristics in addition to the superior heat transfer property.

CONCLUSIONS

(1) Steady-state temperature conditions were easily achieved and maintained for continuous flow processing operations in the prototype machine.

(2) Temperatures can be regulated to suit any heat-treatment requirements.

(3) The heat transfer process (sand to grain) has an efficiency between 70 and 90%.

(4) The machine needs a medium which can enhance mass transfer properties for vigorous drying applications. But the machine with sand as the medium can serve extremely well as a heat treater and processor.

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