



**Figure 9.16.** Rotary-drum type of koji-making apparatus used for rice solids culture by *A. oryzae*. All operations (washing, cooking, inoculation, loosening of solids, water spraying, cooling, air circulation, filling, and exhausting) can be done in this apparatus. (With permission, from N. Toyama, *Biotechnol. Bioeng. Symp.*, Vol. 6, pp. 207–219, 1976, John Wiley & Sons, Inc., New York.)

agitation/rotation speeds. At low agitation rates, oxygen transfer and  $\text{CO}_2$  evolution rates become limiting. Therefore, an optimal range of agitation rate or rotation speed needs to be determined. Similarly, there is a minimum level of moisture content ( $\sim 30\%$  by weight) below which microbial activity is inhibited. At high moisture levels ( $>60\%$ ), solid substrates become sticky and form large aggregates. Moreover, moisture level affects the metabolic activities of cells. Optimal moisture level needs to be determined experimentally for each cell–substrate system. For most of the koji processes, the optimal moisture level is about  $40\% \pm 5\%$ . Particle size should be small enough to avoid any oxygen– $\text{CO}_2$  exchange or other nutrient transport limitations. Porosity of the particles can be improved by pretreatment to provide a larger intraparticle surface to volume ratio for microbial action.

Most of the SSF processes are realized using a rotary-tray type of reactor in a temperature- and humidity-controlled chamber where controlled-humidity air is circulated through stacked beds of trays containing fermented solids. Figure 9.17 depicts a rotary-tray chamber for koji fermentations. Rotary-drum fermenters are used less frequently because of the shear sensitivity of mycelial cells.

## 9.6. SUMMARY

Bioreactors using suspended cells can be operated in many modes intermediate between a batch reactor and a single-stage chemostat. Although a chemostat has potential productivity advantages for primary products, considerations of genetic instability, process flexibility, and process reliability have greatly limited the use of chemostat units. The use of cell recycle with a CSTR increases volumetric productivity and has found use in large-