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SYSTEMATIC REVIEW OF SOLIDS MIXERS AND THEIR PERFORMANCES

by 6408

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I. INTRODUCTION

Although solids mixing is a basic operation in many different industries, it has received little treatment in the literature as compared with other types of mixing. Barclay (3), Clump (14), Fischer (18), Gray (23), Moran (34), Scott (39) and Work (48) have described some solids mixers, according to their mode of operation. Yet no complete and systematic survey about constructions and details of machines has been made. Consequently this author attempted to review all solids mixers available on the market, which are classified into batch and continuous types.

There are many types of equipment available for mixing solid particles, or powders. However few quantitative performance data can be found. Attempts were thus made by the author to collect all probable experimental results observed by investigators on mixers used for blending solids and discuss their performances from figures based on a single expression, i.e., standard deviation against number of revolutions of the mixer according to the type of mixing machine. The performance data of different solids mixers were compared based on three criteria (a) state of best mixture, (b) rate of mixing, and (c) appearance of final mixture. There are many mixers not yet studied because of the difficulty of sampling and testing as well as costs.

Experiments concerning factors affecting both degree and

rate of mixing were done separately by some authors. In this investigation, attempts were therefore made to summarize the results from these separate reports.

Recently a survey and general review of solids mixing was carried out by Yamaguchi (49) as well as by Fan, Chen and Watson (17). Bourne (5) surveyed the mixing of pastes and non-newtonian fluids in addition to powders and included some discussion about scale-up rules and methods but found no theoretical basis established for the development of scale-up laws for the mixing of powers.

II. MIXING EQUIPMENT

Mixers are used to mix two or more materials into an adequate mixture which depends on the characteristics of the components, of the equipment and the conditions of operation.

Solids to be mixed are usually dry powders, free-flowing materials and plastics. The mixing and blending of solids play an important role in numerous industries such as food industry, chemical industry, glass industry, polymer industry, pharmaceutical processes, sand foundry, etc. Because of the special requirements of each industry and different mixing performance of the varous materials, there are many different forms of solids mixers.

Solids mixing equipments are often classified into two major groups, batch mixers and continuous mixers, according to their operations. It appears that batch mixing is used more often than the continuous because of the more flexible characteristics of the former.

Three types of mixing mechanisms exist according to Lacey's classification (32):

a) convective mixing

b) shear mixing

c) diffusive mixing

Commercial mixers combine two or more of these actions to obtain mixing.

A variety of batch and continuous mixers are described in

detail in this work. Names, manufacturers, predominating mechanisms, applications, features or advantages, major parts of each mixer and mixing action are included. Construction of each type of mixer made by different companies is shown after respective description of the mixers.

A. Batch Mixers

1. Planetary Mixer (Fig. 1)

Name of Mixer: AMF Glen Dual Ratio Mixer

Manufacturer: American Machine and Foundry Company

Predominating Mechanism: Shear

Applications:

- food products
- pharmaceuticals
- abrasives
- cosmetics and toiletries

Features or Advantages:

- off-mixer loading
- variable-speed control
- easy cleaning
- bowls and agitators both completely removable from the mixer

Major Parts of Mixer:

- mixing bowl
- agitators or beaters
- bowl trucks

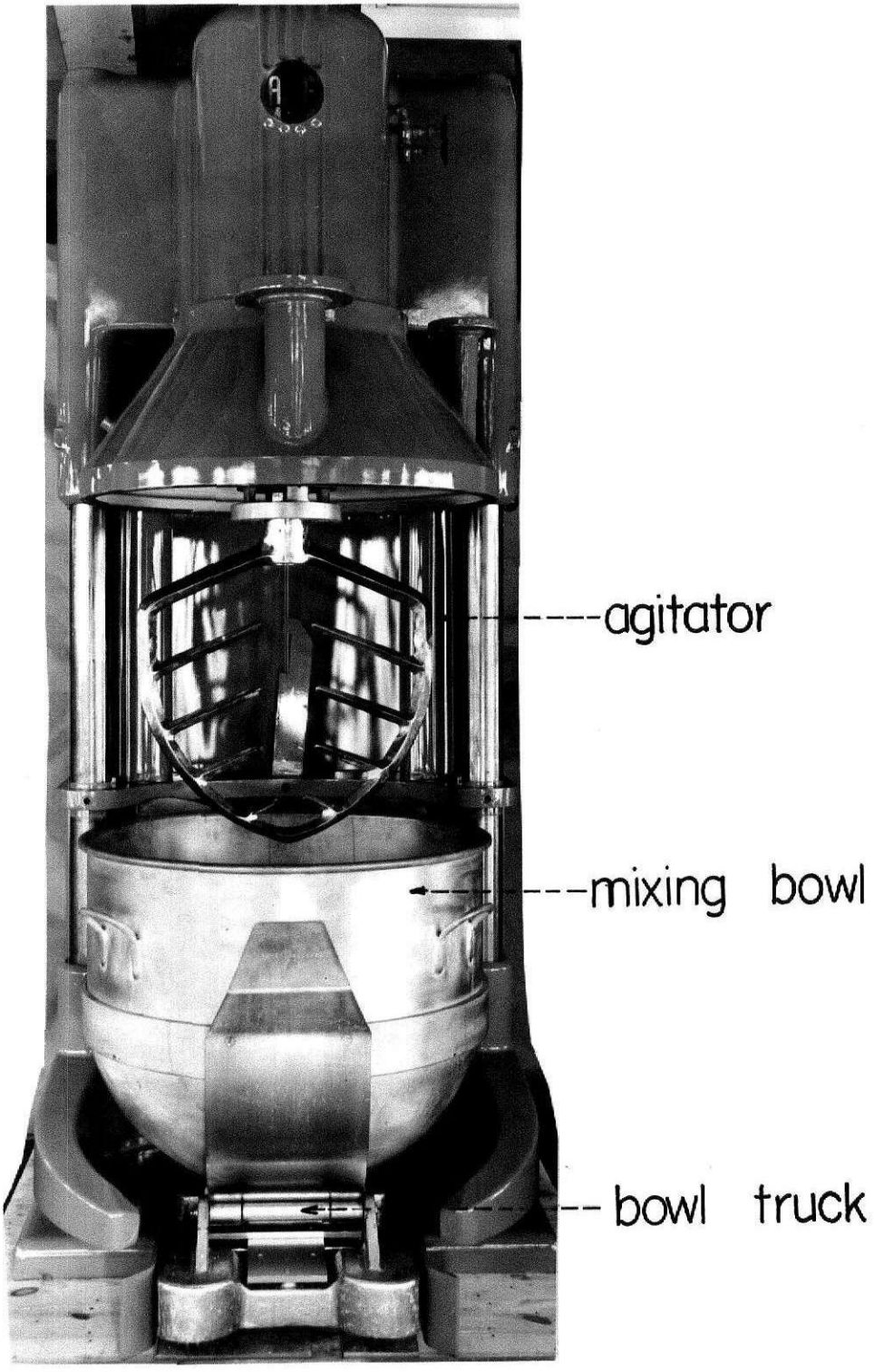


Fig. 1. Planetary Mixer (By courtesy of American Machine & Foundry Company)

Mixing Action:

Rapid and positive mixing is caused by planetary mixing action. Several special and vertical agitator designs help insure thorough incorporation of all the ingredients in the mix.

2. Blade Mixer

a. Helicon Mixer (Fig. 2)

Name of Mixer: Cone-vertical Mixer

Manufacturer: Atlantic Research Corporation, Mechanical Products Division

Predominating Mechanism: Shear and convection

Applications:

processing high viscosity materials such as pseudoplastic solids, pastes, resins, gelled fuels, or rubber compounds

Features or Advantages:

mixing at precisely controlled temperature under positive pressure or vacuum

equal efficiency with variable batch size

vessel configuration providing maximum ratio of exposed surface area to mix volume

adjustable blade-to-vessel clearance providing great flexibility of application

Major Parts of Mixer:

helicone blades

discharge slide valve

cone bowl

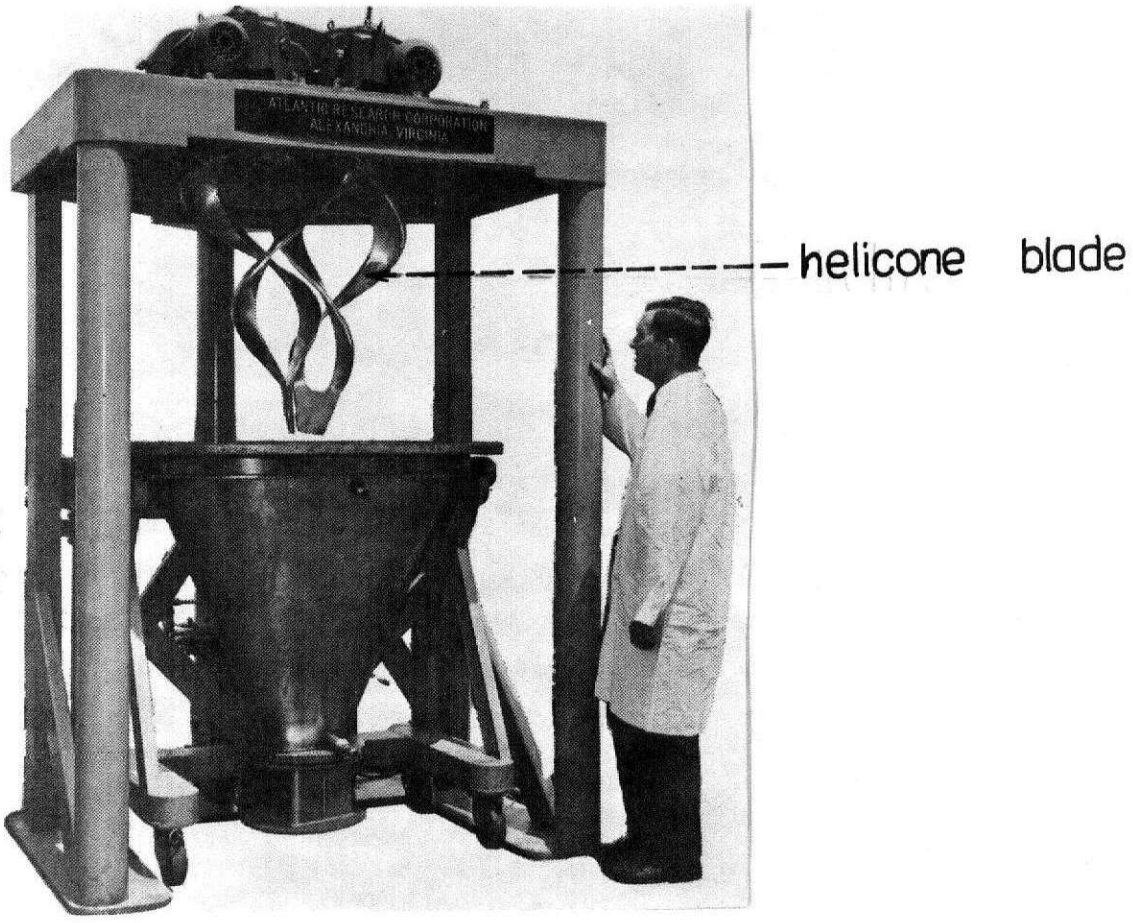


Fig. 2. Helicone Mixer (By courtesy of Atlantic Research Corporation)

Mixing Action:

Two helicone blades rotating in opposite direction provide driving force for top-to-bottom mixing and for dividing and recombining action within the intermeshing cones of the bowl. Blade action discharges the mixture from the mixer through a unique slide valve with minimum hold-up.

b. Double-arm Mixer (Fig. 3)

Name of Mixer: Double Shaft Mixer

Manufacturer: Paul O. Abbe Inc.

Predominating Mechanism: shear and convection

Applications:

chemical processing industries -- mixing of solids prior to the introduction of liquids

Features or Advantages:

leakproof

temperature control

designed for pressure or vacuum operation

sanitary construction

Major Parts of Mixer:

double-blades (sigma blades or dispersion blades)

bowl

Mixing Action:

The double blades with overlapping or tangential arrangements force the materials down in the center of the bowl and to move up at the sides blending ingredients to

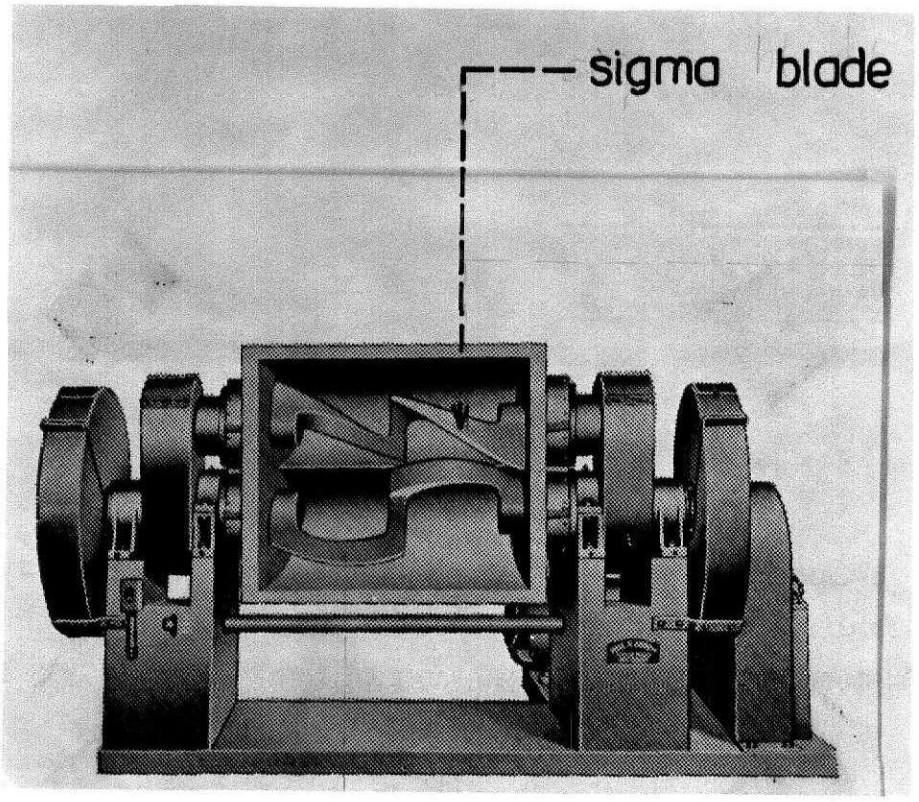


Fig. 3. Double-arm Mixer (By courtesy of Paul O. Abbe Inc.)

a uniform mixture. When tangential blades are used, it is customary to operate at differential speeds.

3. Paddle Mixer

a. Pan-type compulsory Mixer (Fig. 4)

Name of Mixer: Cyclo-mixer

Manufacturer: PCM, Division of Koehring Company

Predominating Mechanism: shear

Applications:

concrete products -- pipe, block, prestressed, precast, flooring, walls, panels, etc.

contractors -- dams, tunnels, silos, missile sites, or bridges

Features or Advantages:

delivering highest quality product

smooth and round for easy cleaning

low maintenance

space saving design

Major Parts of Mixer:

plow-like mixing paddles rotated by a central spinner unit

Mixing Action:

Dynamic mixing action imparts total agitation to the mass. Arrangement is designed so that a combination of angles, spacing, shape and velocity of paddles provides a forced mixing action. There is no reliance on gravity or limitation of centrifugal force which cause a more efficient mixing action than that of drum type mixer or mill.

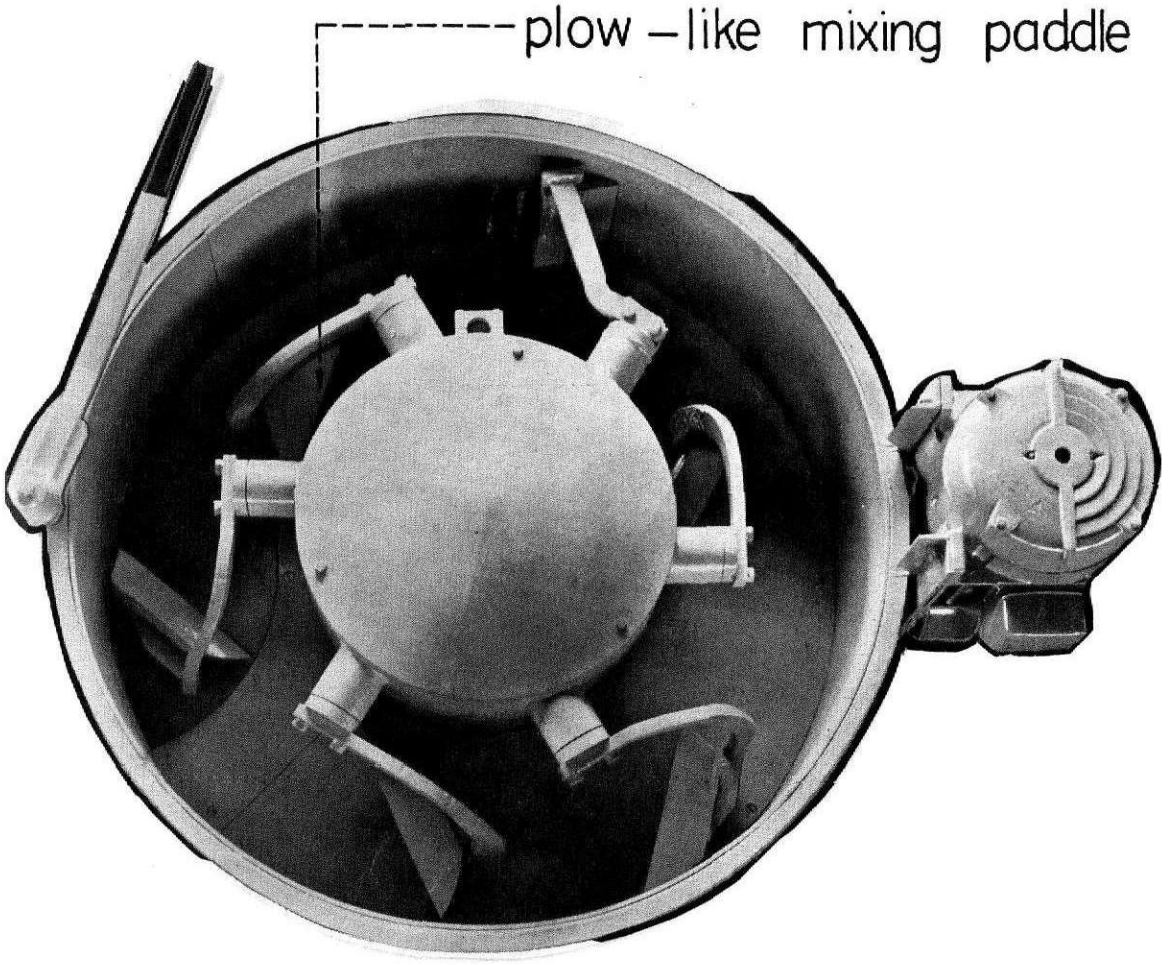


Fig. 4. Pan-type Compulsory Mixer (By courtesy of PCM, Division of Koehring Company)

b. Marion Mixer (Fig. 5)

Name of Mixer: Marion Mixer

Manufacturer: Rapid Machinery Co.

Predominating Mechanism: shear and diffusion

Applications:

wide range of applications -- including most kinds of industries

Features or Advantages:

close blade tolerance assuring accurate mixing and thorough discharge of materials

easy cleaning

ease of maintenance

dependability and lack of obsolescence

Major Parts of Mixer:

curved, canted paddle blades

discharge gate

Mixing Action:

The curved, canted paddle blades scoop, lift and tumble materials. The paddle blades overlap each adjacent blade, insuring no unmixed pockets. All materials are kept moving at all times and crossblending action occurs in an axial direction. The paddle blade also creates a cavity, into which material flows to create a turbulent upward and downward action. The mixing action is intense, yet gentle and does not tend to break up particles or to damage normal materials.

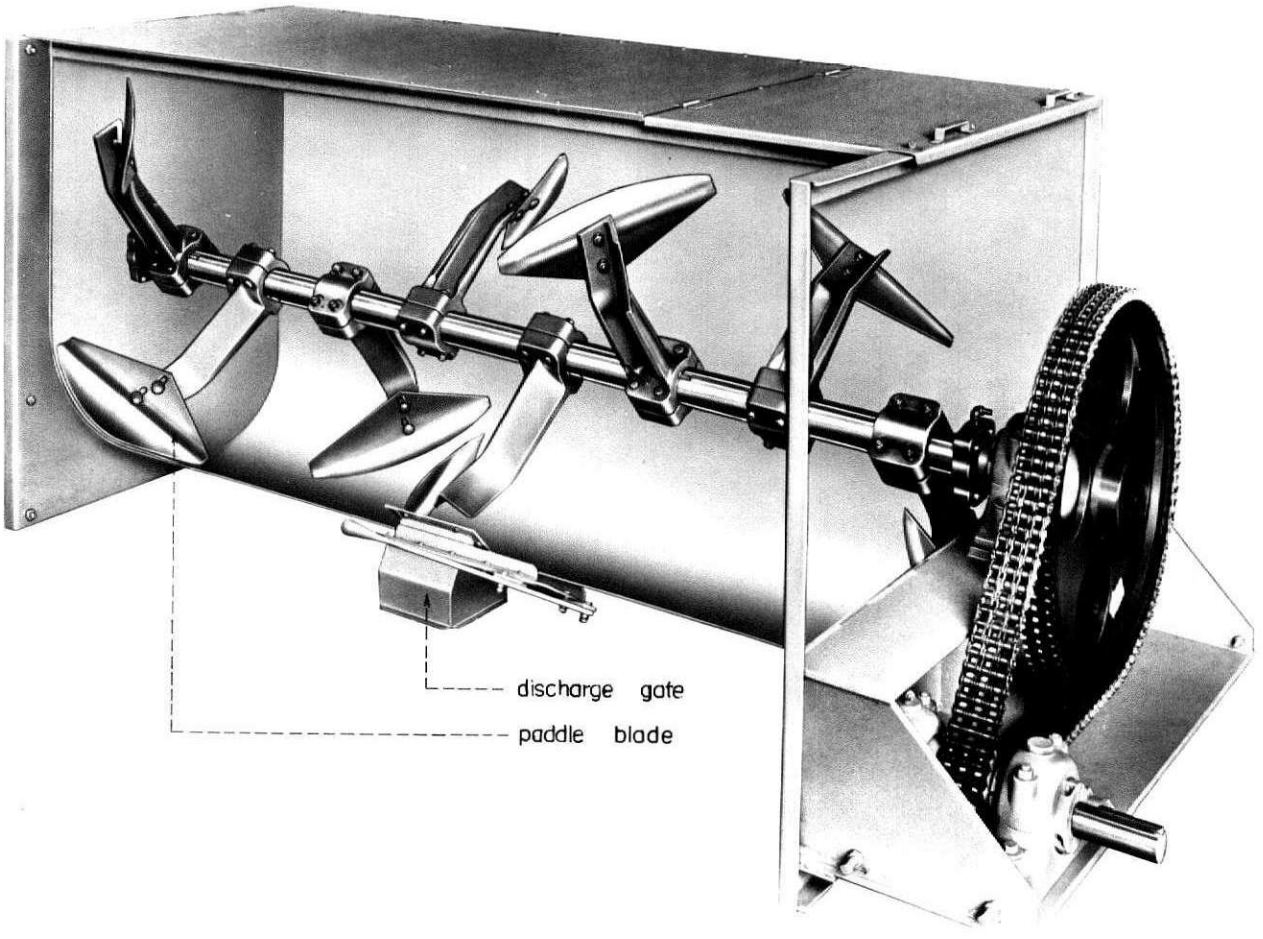


Fig. 5. Marion Mixer (By courtesy of Rapid Machinery Co.)

4. Drum Mixer (Fig. 6)

Name of Mixer: Sturtevant Rotary Dry Batch Mixer

Manufacturer: Sturtevant Mill Company

Predominating Mechanism: shear and diffusion

Applications:

blending dry, free-flowing granular materials

Features or Advantages:

economy

self-cleaning design and dust proof

low maintenance

indluding injector spray systems to coat or moisturize ultra-dry materials during mixing

Major Parts of Mixer:

mixing drum

inlet/outlet gate

Mixing Action:

Materials enter chamber through chute, and are picked up by scoops and cascaded from chamber top. Revolving drum and swining chute force ingredients to mix with circular, vertical and lateral mixing actions. Mixture is automatically discharged when chute is in proper position.

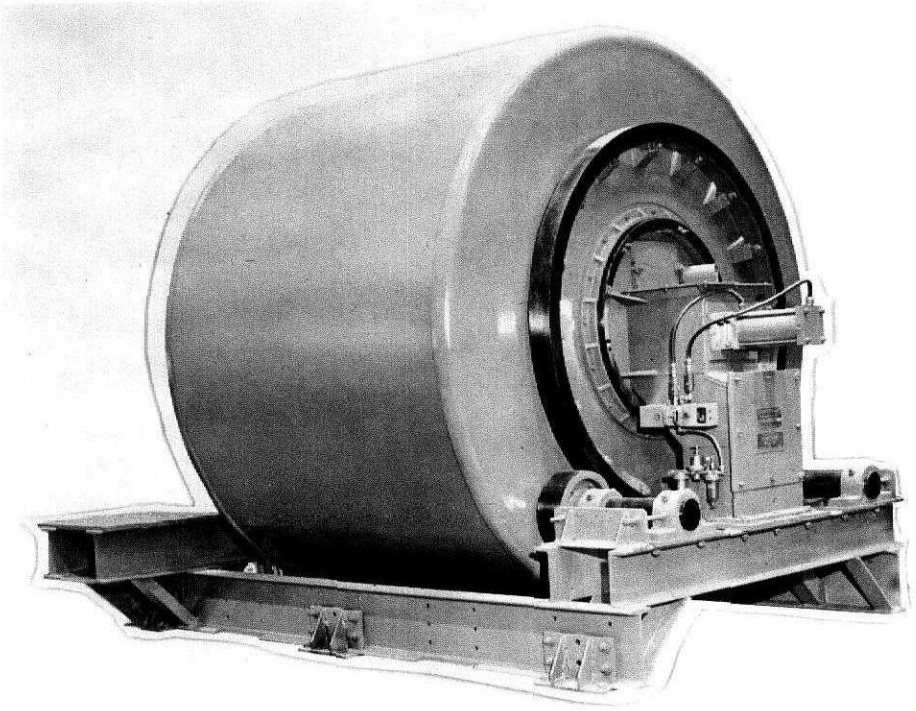


Fig. 6. Drum Mixer (By courtesy of Sturtevant Mill Company)

5. Tumbler

a. Double Cone (Fig. 7)

Name of Mixer: Double Cone Blender

Manufacturer: Komline-Sanderson Engineering Corp.

Predominating Mechanism: shear

Applications:

homogeneous and heterogeneous blending of dry materials

Features or Advantages:

efficient and genrle mixing action with complete discharging of materials

easy cleanability

low maintenance and low power costs

Major Parts of Mixer:

two cones joined to a relatively short cylindrical section

Mixing Action:

As the mixer rotates, continuous rolling and interfolding of materials cause the mixing action. The dispersion disc can be used to disperse uniformly minute additive materials or solid fats or pastes into the dry materials. Agitating elements may be mounted on the axis of rotation to break down lumps and reduce the segregation effect. For difficult materials, deflection cones occupying dead spots are used to increase particle velocity in the trunnion area and make a more uniform velocity across the width of shell.

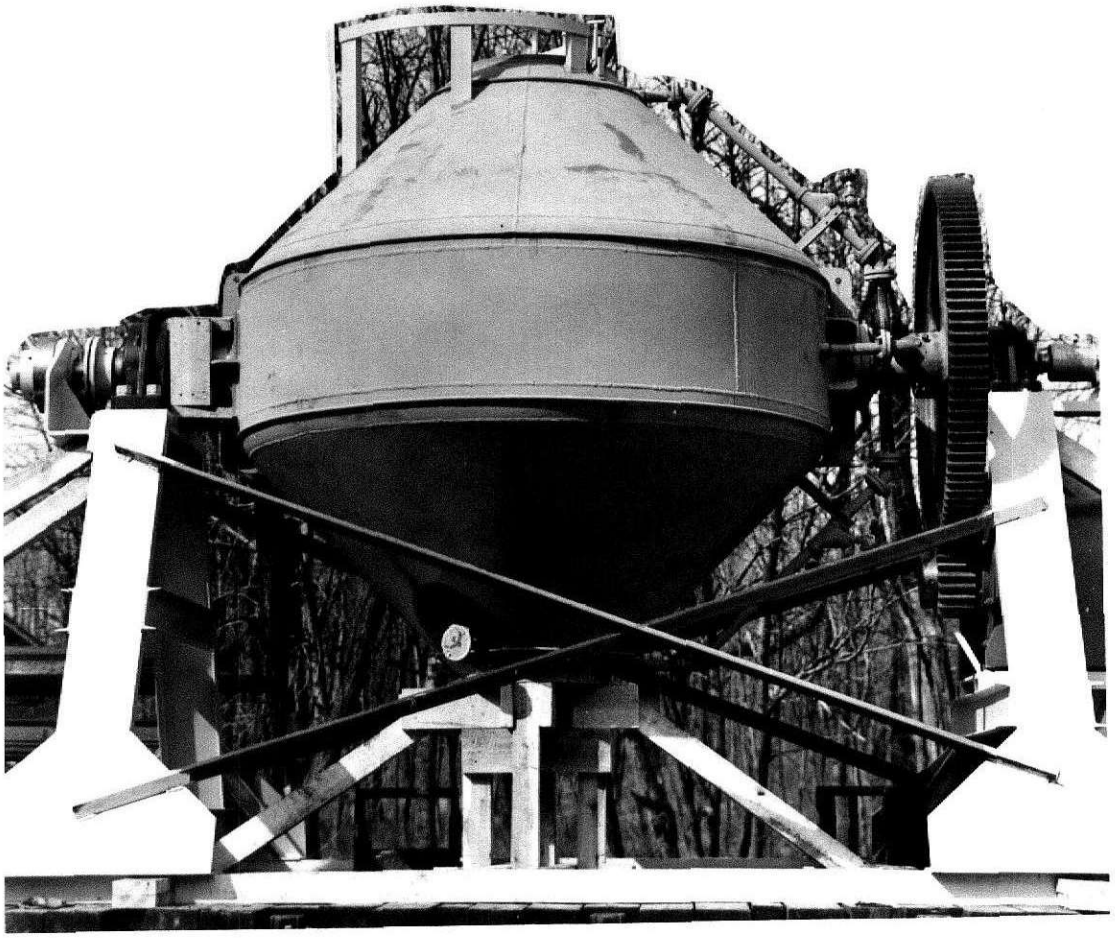


Fig. 7. Double Cone (By courtesy of Komline-Sanderson Engineering Corp.)

b. Twin-shell Mixer (Fig. 8)

Name of Mixer: P-K Twin Shell Solids-Solids Blender

Manufacturer: The Patterson-Kelley Co., Inc.

Predominating Mechanism: shear and diffusion

Applications:

blending of dry, and free flowing materials

features or Advantages:

precise and gentle blending

vacuum or atmospheric operation

nonsymmetrical shape about the axis of rotation to cause better mixing than that of other tumblers

complete discharge

easy cleaning

low maintenance and low installed cost

Major Parts of Mixer:

two opposed simple cylinders formed into a "V"

central discharge valve at the bottom

Mixing Action:

Solids are tumbled and intermeshed to give a fast and precise mixing. A removable intensifier bar can be placed at the axis of rotation to break up agglomerates.

6. Muller (Fig. 9)

Name of Mixer: Muller-type Mixer

Manufacturer: Clearfield Machine Comp.

Predominating Mechanism: shear

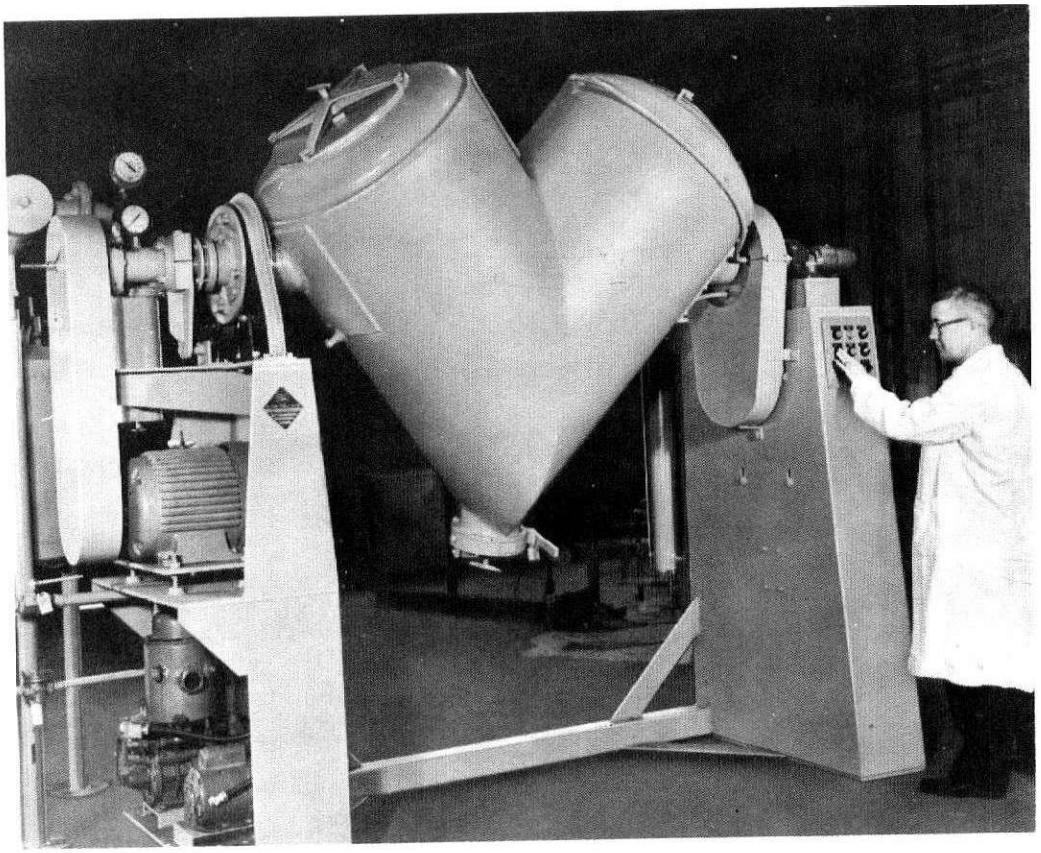


Fig. 8. Twin-shell Mixer (By courtesy of the Patterson Kelley Co., Inc.)

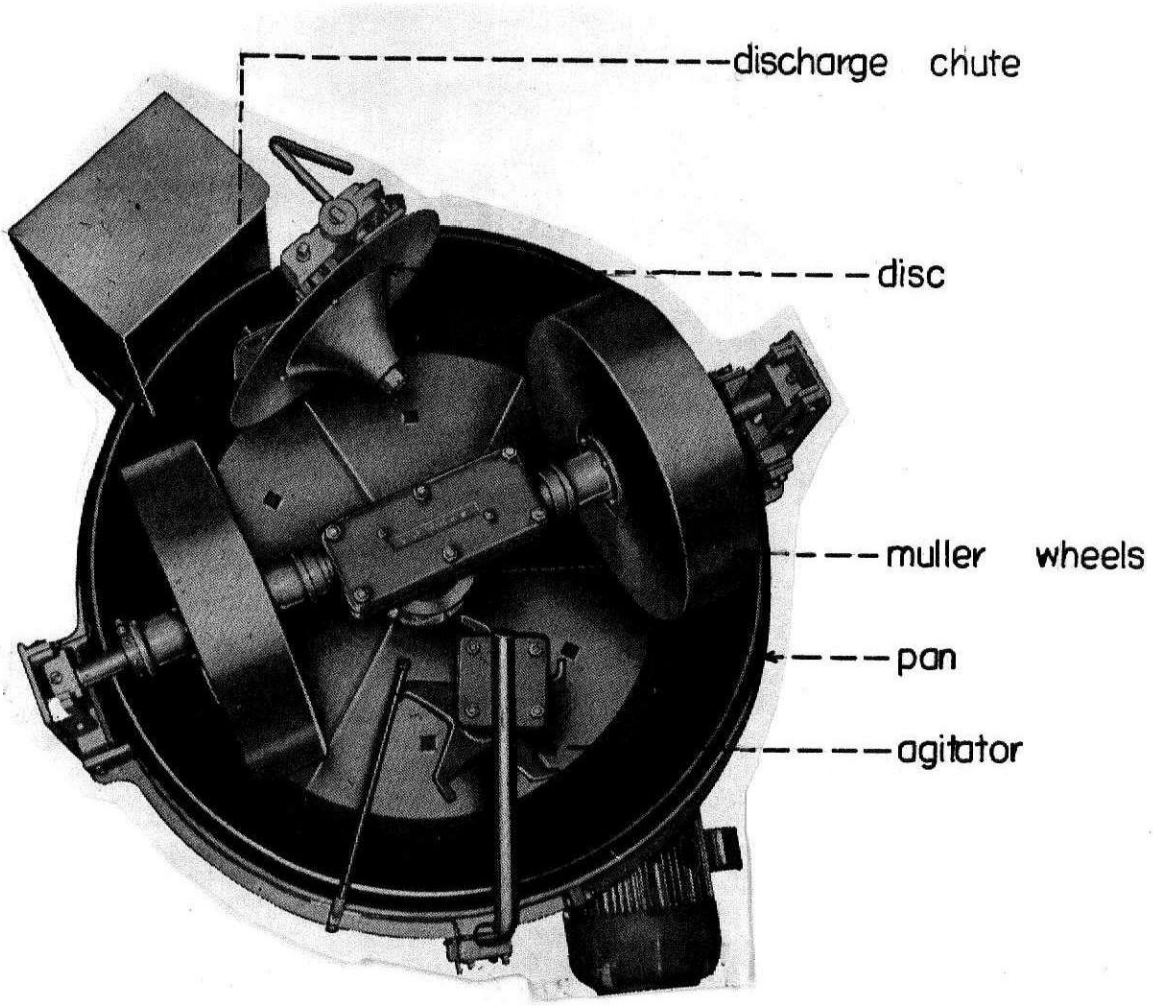


Fig. 9. Muller (By courtesy of Clearfield Machine Comp.)

Applications:

foundry sand (primarily)

chemical industry

glass industry

refractories

paint and pigments

ceramic

floor and wall coverings

electrical procelain

powder metallurgy

Features or Advantages:

mulling -- more uniform coating of sand grains with wetted bond

reduction -- the breaking down of lumps

size control -- maintenance of grain size and structure

tempering -- more efficient dispersion of moisture at the fastest possible rate

aeration -- the introduction of air into the sand mass, making it easy to ram in the mold and permeable for the escape of hot gases when the casting is poured

flowability -- without the use of other auxiliary equipment to develop this characteristic

capacity -- the production of the maximum quantity sand in the least possible time

bond saving -- more uniform coating of sand grains requires

less bond

economy and convenience

protection -- safety of workmen against health and accident hazards

cooling without auxiliary equipment

batch or continuous mixing -- batch mixing changing into continuous mixing by using deflector and disc plow to control the spiral action pattern of centrifugal force; the discharge disc, in addition to having an aerating and disintegrating effect, having the function of mulling time control

Major Parts of Mixer:

agitator

mullers

disc

pan

Mixing Action:

Two muller wheels, whose elevation is usually adjustable, roll on a bed of material while the pan revolves in the opposite direction. Sliding, twisting and grinding can then be obtained simultaneously. The disc, with edge conforming to the curvature of the rim, scrapes and directs the material in the path of the rollers. The agitator gives an additional stirring and beating action and also trys to move the substance off the bottom of the pan.

7. Mill (Fig. 10)

Name of Mixer: Cylinder Mixer

Manufacturer: Paul O. Abbe Inc.

Predominating Mechanism: shear

Applications:

blending dry free-flowing materials or dry, free-flowing materials with agglomerates

Features or Advantages:

able to grind, mix, and disperse dry or wet products in the one machine, without mechanical adjustments of any kind

fast and efficient mixing

temperature control

continuous operation obtained with special design

Major Parts of Mixer:

grinding media -- pebbles or steel balls

mill ends supports

Mixing Action:

Tumbling accompanied by a grinding action.

8. Ribbon Mixer (Fig. 11)

Name of Mixer: Patterson Ribbon Mixer

Manufacturer: Patterson-Ludlow Division, Bauner Industries, Inc.

Predominating Mechanism: convection and diffusion

Applications: Mixing dry powders, granular materials or plowing pastes

Features or Advantages:

specially engineered paddles also furnished for specific

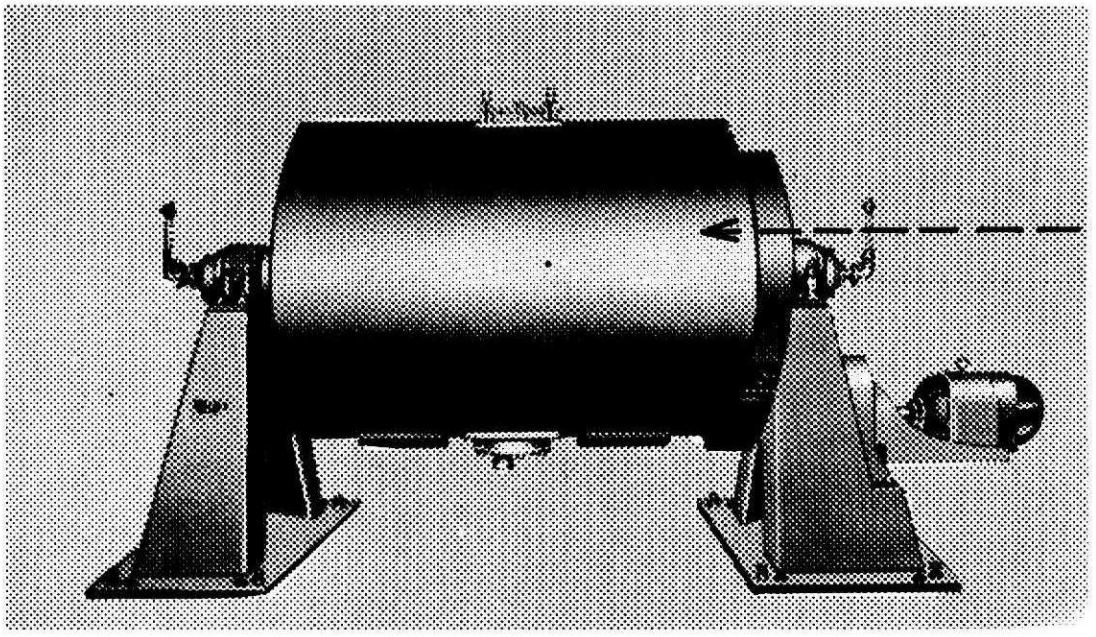


Fig. 10. Mill (By courtesy of Paul O. Abbe Inc.)

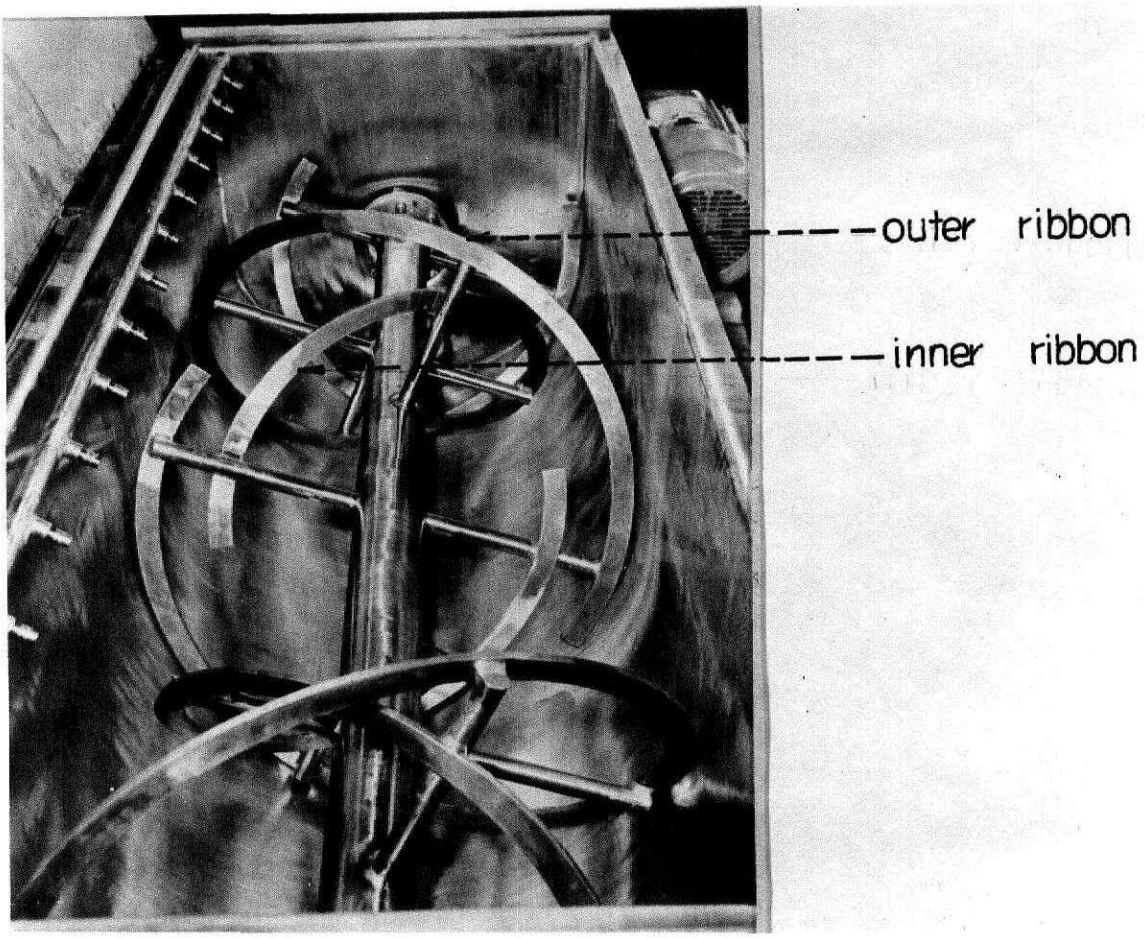


Fig. 11. Ribbon Mixer (By courtesy of Patterson-Ludlow Division, Bauner Industries, Inc.)

mixing problems and different ribbon agitator designs available for every mixing need

temperature control

Major Parts of Mixer:

ribbon agitator

static and U-shaped bowl

Mixing Action:

The materials are rolled, folded, reversed in direction, vertically displaced and laterally displaced and achieve maximum mixing action. In addition, the shearing action in the interface between the oppositely pitched ribbon provides a mild kneading. The ribbons are designed so that the outer ribbon conveys from the end towards the center whereas the inner ribbon conveys from the center towards the end. The diameter, pitch and width of each ribbon are accurately proportional to prevent localized product accumulation or reaggregation.

9. Vretical Spiral Mixer (Fig. 12)

Name of Mixer: Super-twin Mixer

Manufacturer: Prater Industrial Products Inc.

Predominating Mechanism: convection and diffusion

Applications:

industrial mixing applications where the materials to be mixed exhibit free-flowing proterties such as dried blood pulverized meat meal, soybean meal, plastics, chemical and

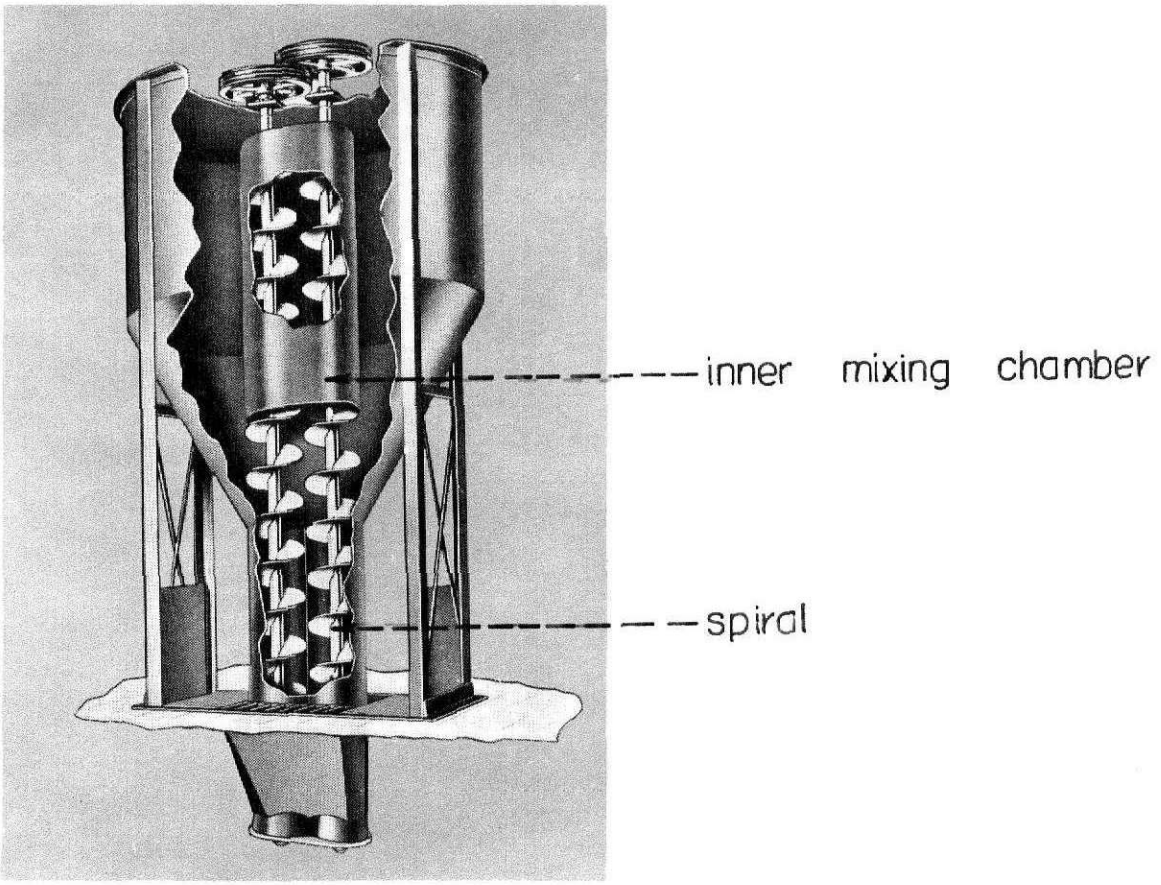


Fig. 12. Vertical Spiral Mixer (By courtesy of Prater Industrial Products Inc.)

pharmaceutical product, cleaning compounds, etc.

blending polystyrene and polyethylene pellets with dry flaked or powdered materials in almost any ratio

Features or Advantages:

less floor space

low power consumption

fast, thorough mixing action

shortest possible mixing time

operated at full or partial capacity

mounted on four legs or suspended from overhead

Major Parts of Mixer:

two spirals

inner mixing chamber

Mixing Action:

The materials are lifted from the conical bottom to the top by the twin screws and then sprayed out and descend slowly through the bed of material. Because of the differential speed between the two spirals, the materials being mixed are caused to move in three directions simultaneously, vertically downward in the main body of the mixer, vertically upward in the inner mixing sleeve, and horizontally between the two spirals. This continuous movement, together with the constant dividing and reassembling of the individual particles of the mixture, produces an intimate intermingling and mixing action.

10. Nauta Mixer (Fig. 13)

Name of Mixer: Day Nauta Mixer

Manufacturer: The J. H. Day Company

Predominating Mechanism: convection and diffusion

Applications:

blending dry powders, granular materials, creams or pastes

Features or Advantages:

exceptional mixing accuracy with no segregation even for the blending of the materials of sidely differing densities

shorter mixing time -- one third to one half the time required by most conventional mixers

gentle mixing action and low power consumption

easy addition of liquids -- piped to the top of the mixer or jet-sprayed into the mix at the bottom of the Nauta mixer if necessary

mixing of partial or full batches with no reduction in efficiency fast, complete discharge and easy cleaning

Major Parts of Mixer:

conical tank

screw agitator

Mixing Action:

The screw flight agitator rotates on its own axis and orbits the periphery of the conical tank setting up three distinct intermixing currents in the batch at the same time. Lifts and spirals the materials upward, mixes on a large spiral around the tank, and provides gravity flow

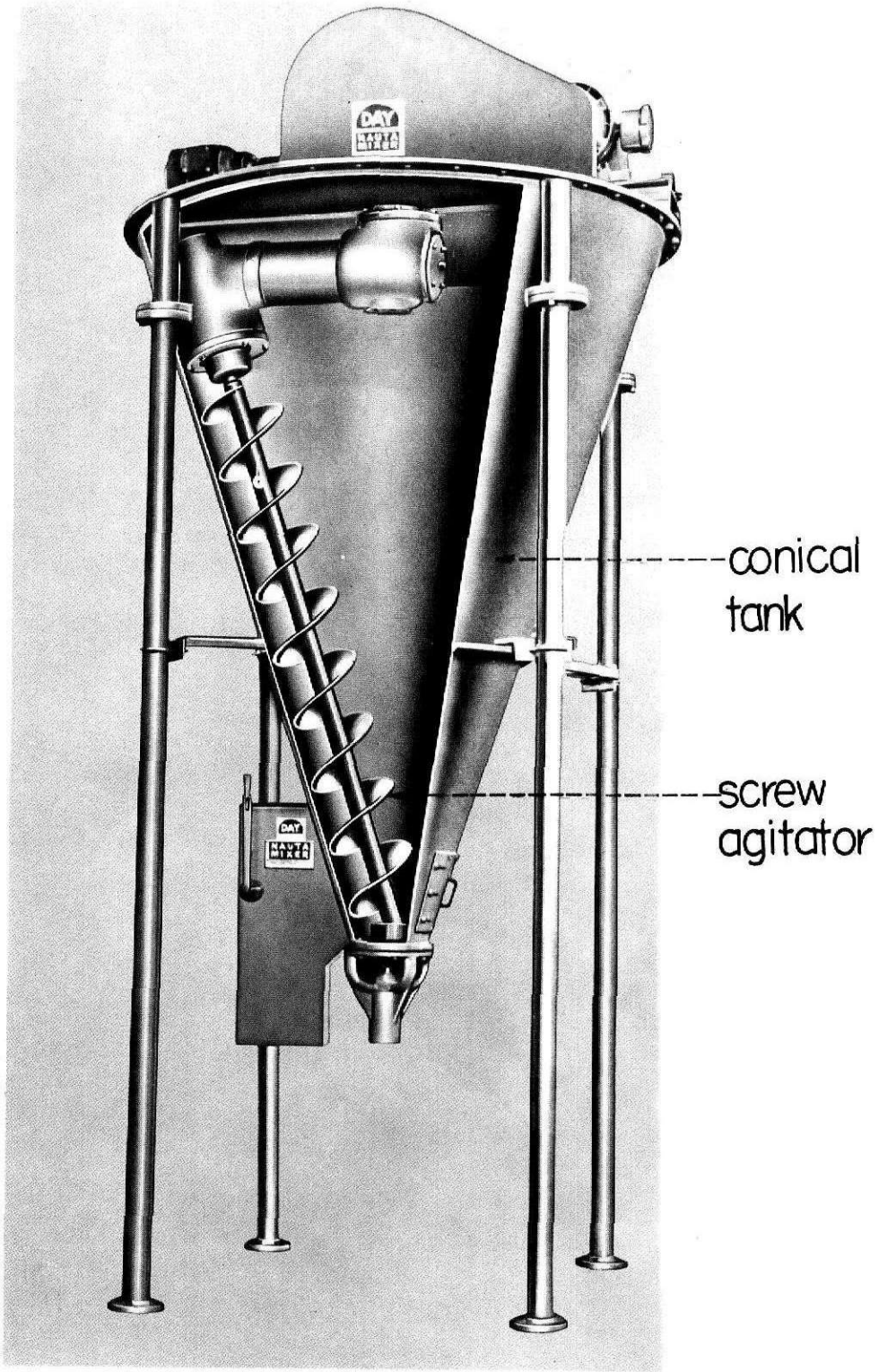


Fig. 13. Nauta Mixer (By courtesy of the J. H. Day Company)

down the side of the tank. These result in the most intimate intermingling of all ingredients. Dry materials are charged into the mixer through the top and discharged at the bottom. The Nauta mixer is also available in the twin-cone design with two orbiting spiral agitators, the Day Combimixer, which permits mixing larger quantities while conserving plant headroom. The axial and orbiting motions of the two agitators, along with the additional intermixing currents occurring through the juncture of the two tanks, provides for greater blending action than the single Nauta Mixer. Combimixer can be used as a continuous mixer with the use of proportional feeding.

11. Banbury Mixer (Figs. 14a and 14b)

Name of Mixer: Banbury Mixer

Manufacturer: Farrel Company, Division of USM Corp.

Predominating Mechanism: shear

Applications:

rubber industry

plastics

asphalt

Features or Advantages:

dewatering and devolatizing of rubbers and a variety of plastics

i) The floating-weight action squeezes out much of the liquid which is then drained or pumped out of the

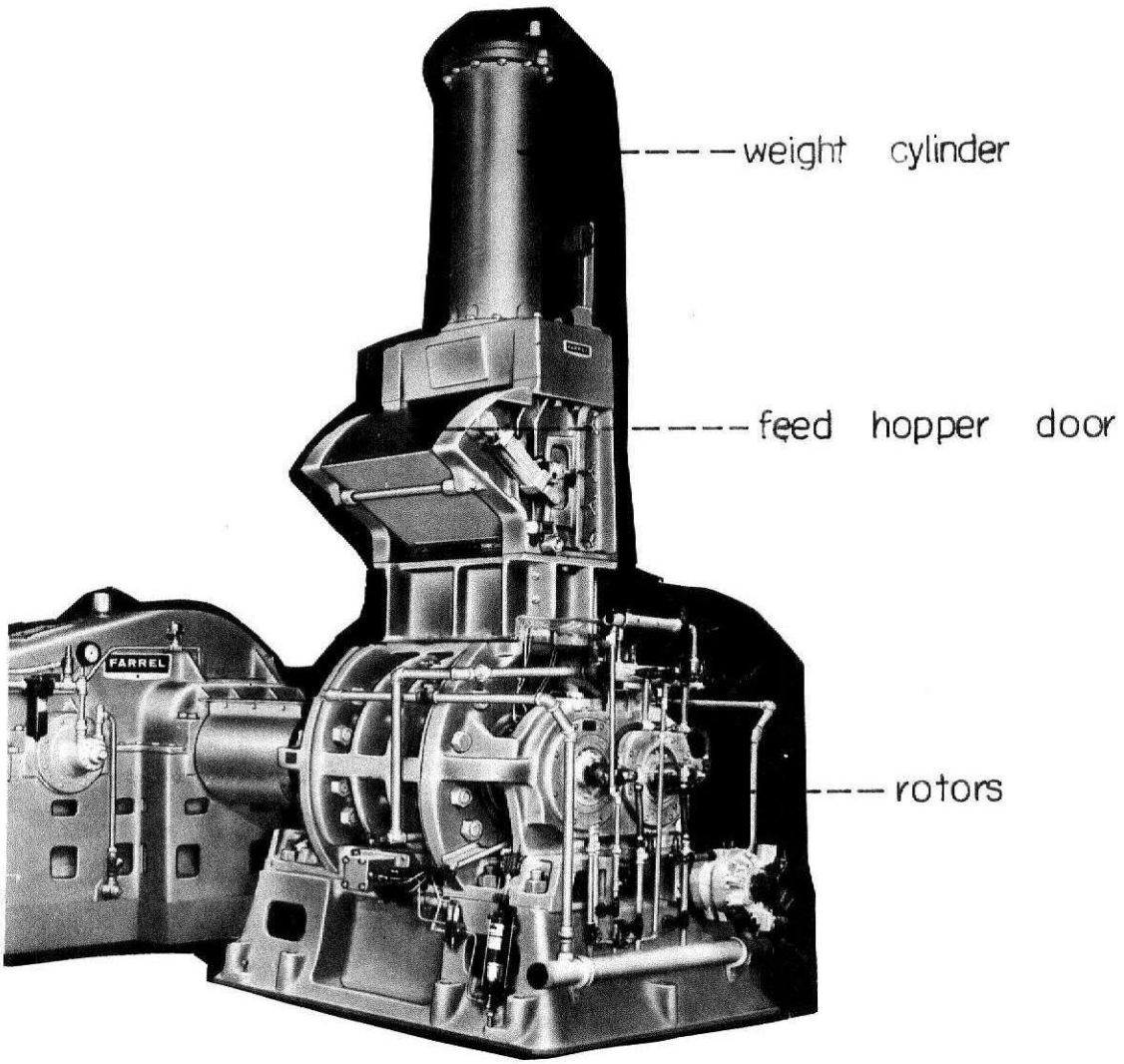
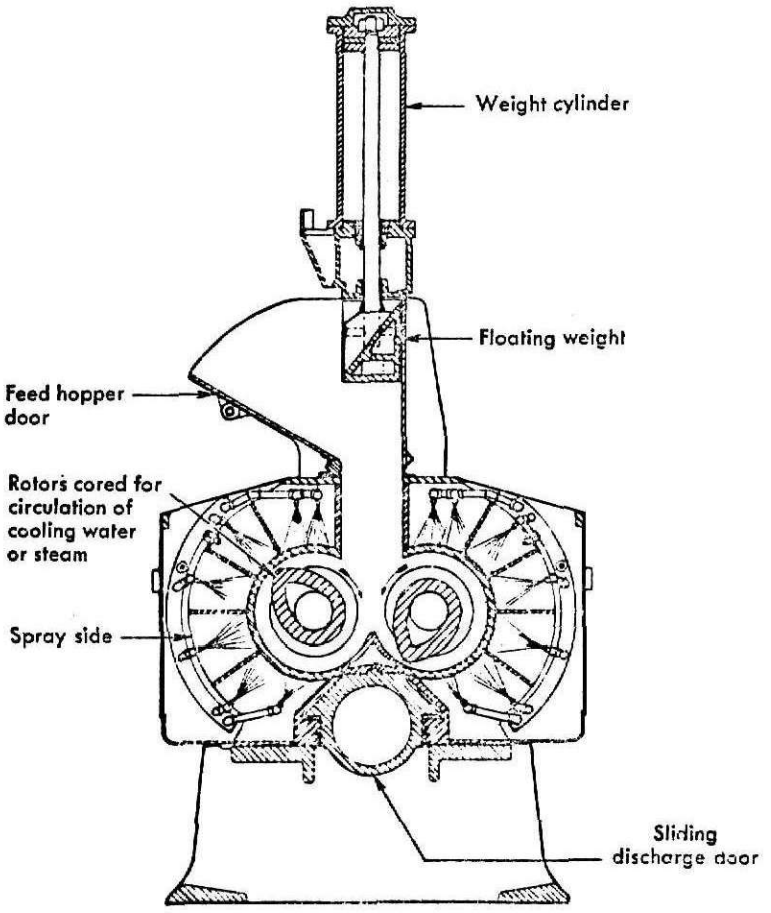


Fig. 14a. Banbury Mixer (By courtesy of Farrel Company, Division of USM Corp.)



Cross-section drawing of size 11 machine with spray-cooled sides.

Fig. 14b. Cross-section Drawing of Banbury Mixer

machine through a special dewatering valve.

ii) The remaining water is vaporized by heat produced by mechanical action of the stock and escapes through a special exhaust system

quick-curing of stocks

self-cleaning -- a single machine able to handle safely a variety of stocks of different colors or formulas in succession due to this characteristic

heavy construction of the body of the mixer with maximum rigidity and strength

all working parts enclosed to assure safe, clean, healthy working conditions

temperature control: cooling water or steam circulated through the cored rotors and a multiplicity of machined grooves on the outside of the mixing-chamber liner

Major Parts of Mixer:

weight cylinder

feed hopper door

two rotors

discharge door

Mixing Action:

Two spiral-shaped rotors in a completely enclosed mixing chamber revolve at slightly different speeds in opposite direction producing shearing action and force mixing inside the chamber. The internal parts of the mixing chamber and rotors are hard-surfaced to increase

mixing action. An air-operated ram in the feeding neck confines the batch within the chamber formed of the two interconnecting cylindrical spaces.

12. Airmix Mixer (Fig. 15)

Name of Mixer: Airmix Mixer

Manufacturer: Sprout, Waldron & Company, Inc.

Predominating Mechanism: convection and diffusion

Applications:

mixing of dry-materials

Features or Advantages:

extremely short mixing

high-capacity mixer providing for extremely accurate mixing results

mixer interior free from obstructions, easy cleaning by employing a few short bursts of air to scour the mixer shell walls chance of segregation of materials during discharge minimized low maintenance, low operating cost and low power consumption

Major Parts of Mixer:

mixing head (manifold and angular nozzles, cone valve)

Mixing Action:

The mixer may be filled either by hand, by mechanical or pneumatic means or by a combination of these methods. The air enters the mixer through the nozzles in the mixing head at a velocity near the speed of sound. The nozzles are positioned at an angle to cause the material to spiral

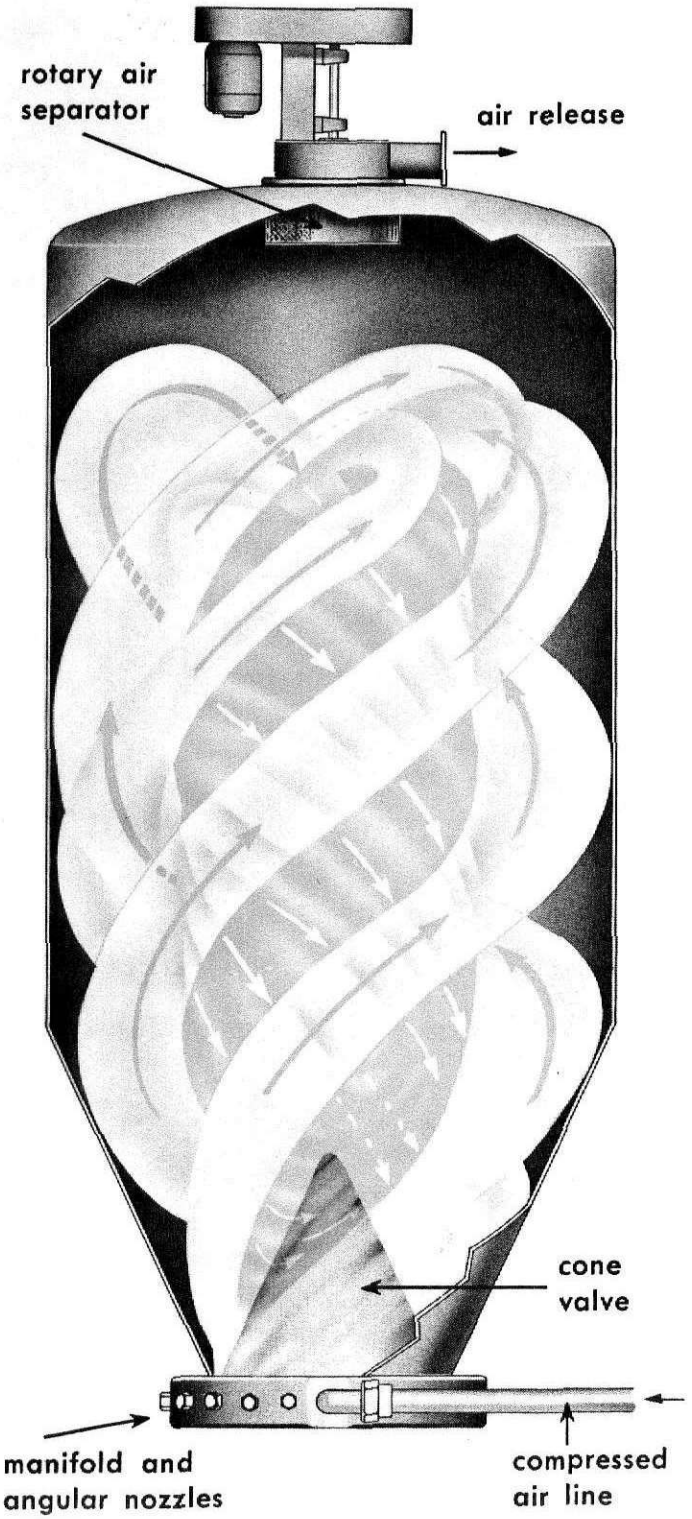


Fig. 15. Airmix Mixer (By courtesy of Sprout, Waldron & Company, Inc.)

upwards along the side of the tank. Materials in the center of the mixer flow down toward the mixing head to complete the circulation of material. The mixing cycle normally being in the range of 16 to 60 seconds usually consisting of a series of intermittent air blasts. At the completion of the mixing cycle, the cone valve is raised, and the material discharges freely.

13. Lodige Mixer (Fig. 16)

Name of Mixer: Littleford Lodige Mixer / Granulator

Manufacturer: Littleford Bros., Inc.

Predominating Mechanism: diffusion and shear

Applications:

food industry

pharmaceutical industry

chemical industry

ceramic wall and floor tile

Features or Advantages:

easy cleaning

addition of liquid or plastic materials, if necessary, into dry solids without the use of post-processing or finishing equipment maintaining or improving quality while reducing production time and cost

continuous mixing obtained with special design

Major Parts of Mixer:

high speed choppers

plow-shaped mixing tools

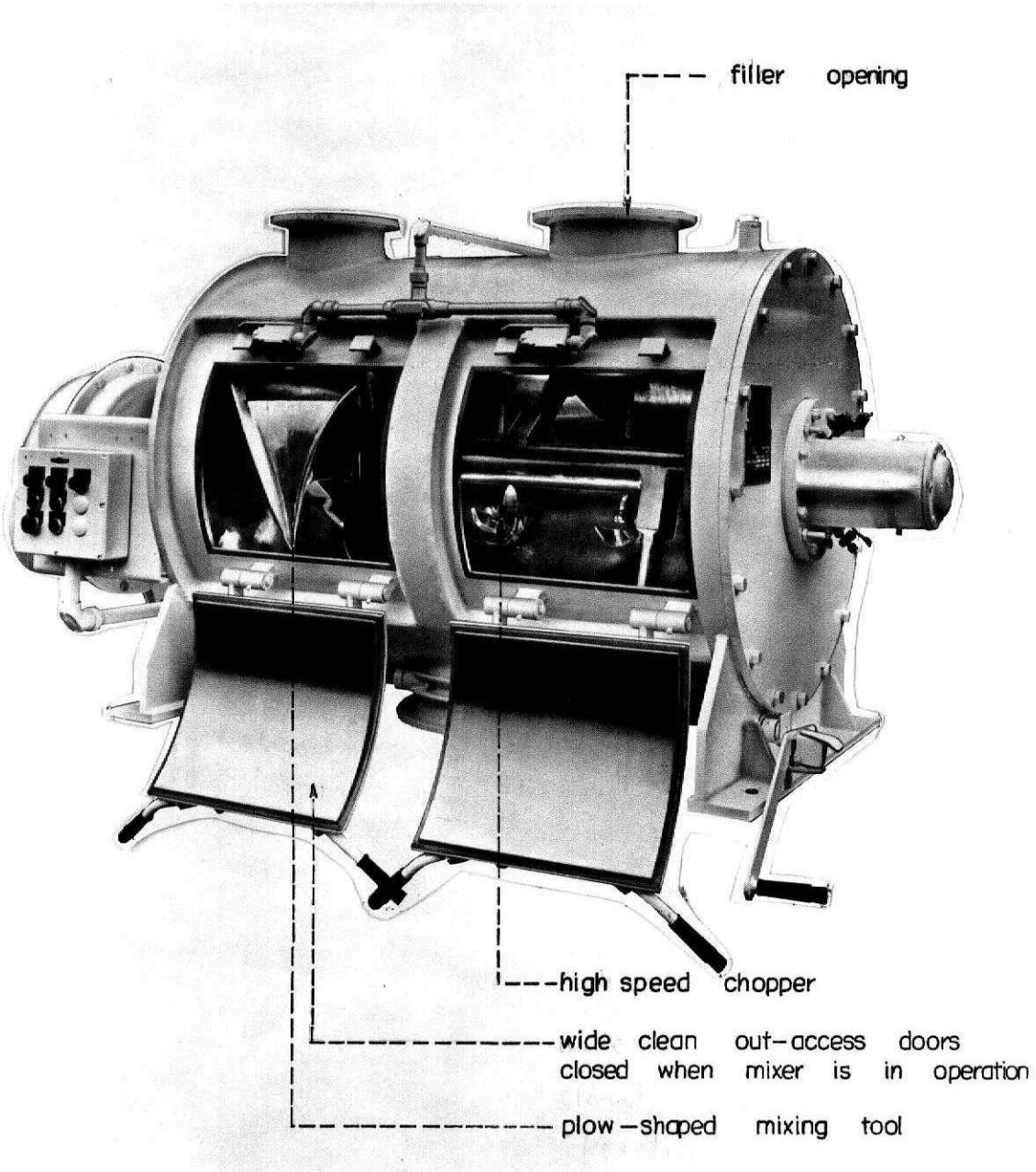


Fig. 16. Lodige Mixer (By courtesy of Littleford Bros., Inc.)

special construction for easy cleaning

Mixing Action:

The patented plow-shaped mixing tools radially mounted on a horizontal shaft revolves at a high speed within the mixing vessel. This special mixing element reduces reliance on gravity and develops a huring and whirling action resulting in an intense but gentle intermingling of the mix materials in free space and obtains the mixing action. The high speed choppers (3600 rpm) are precisely located in the mixing vessels where the plows constantly feed fresh product into and through the high shear choppers. The chopper blades then quickly control the agglomerates.

14. Gravity Mixer (Fig. 17)

Name of Mixer: In-tank Blender

Manufacturer: Systems Engineering & Manufacturing Comp.

Predominating Mechanism: convection

Applications:

blending free-flowing dry materials

Features or Advantages:

simplicity of construction and operation

ability to handle a range of materials with widely divergent flow properties

easy cleaning

maintenance costs practically non-existent

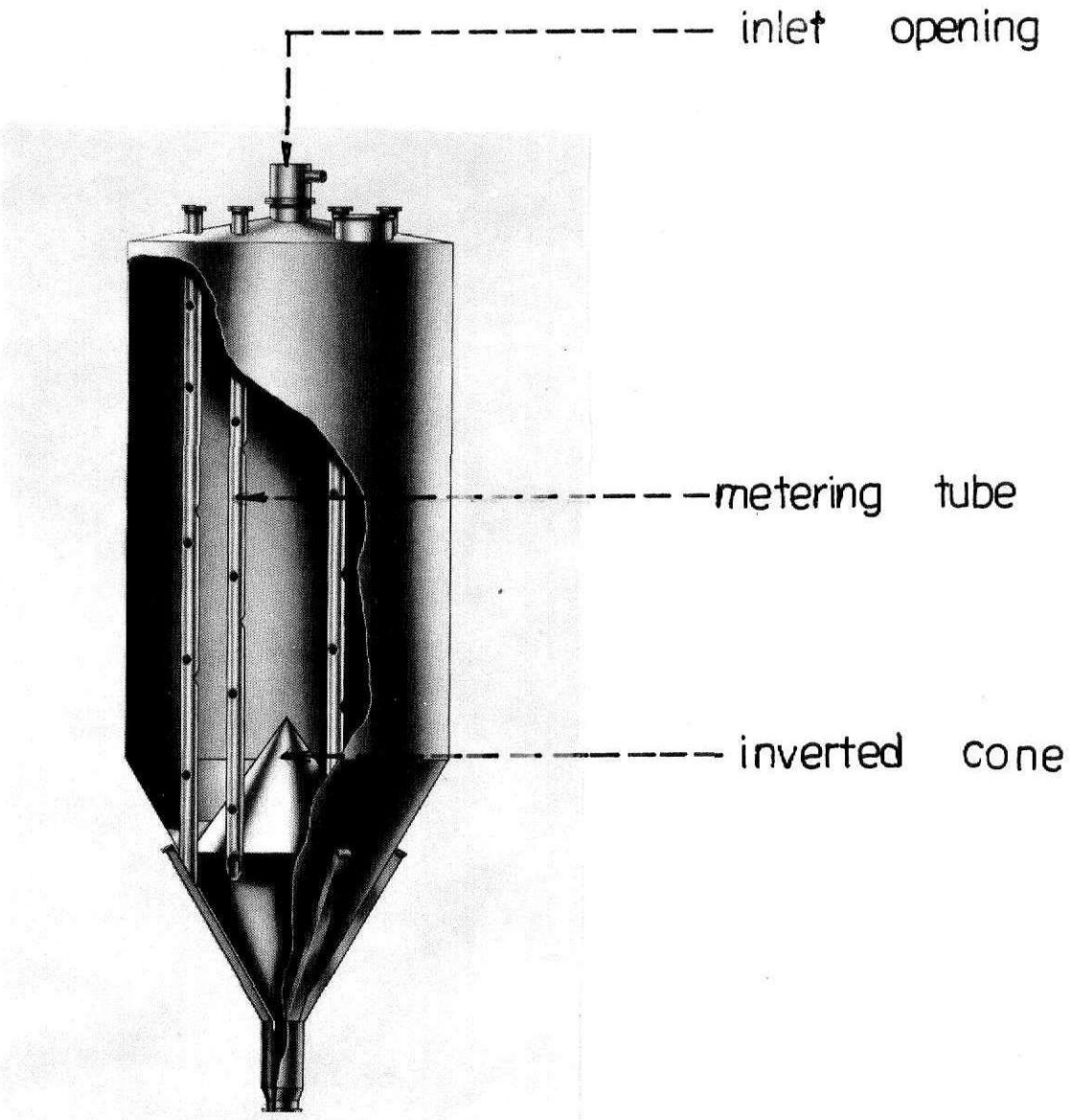


Fig. 17. Gravity Mixer (By courtesy of Systems Engineering & Manufacturing Comp.)

Major Parts of Mixer:

inverted cone inside the blender

metering tubes each with numerous holes

Mixing Action:

Materials filled in the tank are circulated to commingle the various strata in the tank. Recycling the materials one and a half times is sufficient for even the most critical blending operations before draining the blender. The vertical metering tubes are spaced inside the blender at the optimum location to minimize the horizontal distance of material flow into the holes in the tubes. Materials are allowed to flow around the periphery of the inverted cone eliminating dead spots at the edge of the material bed and preventing pipe flow through the center of the bed, and then into the hopper bottom.

15. Vibratory Mixer (Fig. 18)

Name of Mixer: Whirlpool Mixer

Manufacturer: Carman Industries, Inc.

Predominating Mechanism: convection and shear

Applications:

blending dry and semidry bulk granular solids

Features or Advantages:

no internal moving parts to create friction degradation or attrition

no tumbling action to cause impaction and incomplete discharge

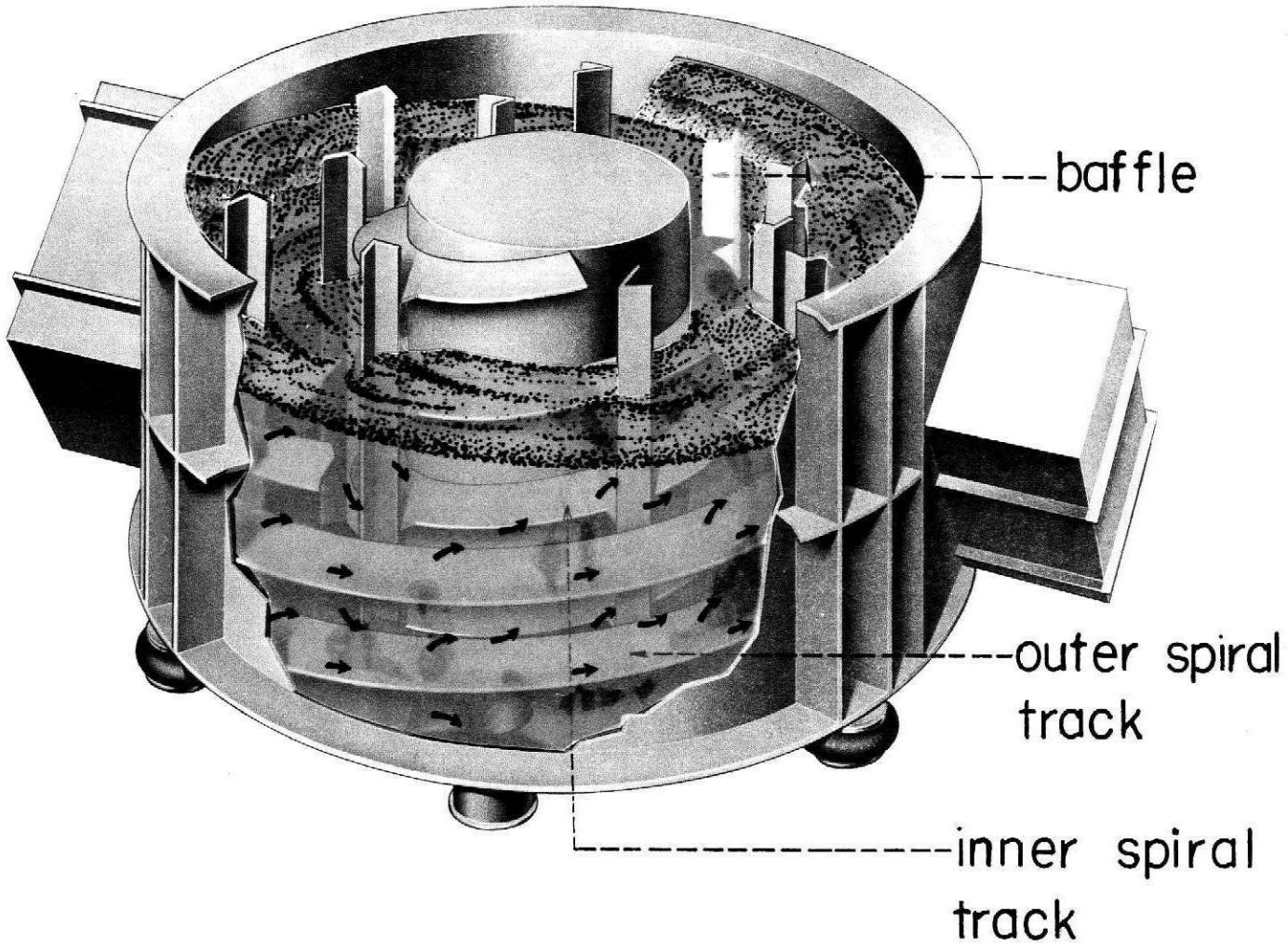


Fig. 18. Vibratory Mixer (By courtesy of Carman Industries, Inc.)

self-cleaning

maximum useable capacity

low horsepower requirements

Major Parts of Mixer:

cylindrical hopper with a flat bottom and straight sides

two spiral tracks, one mounted on the inside of the hopper wall and the other mounted near the center of the hopper

several baffles located between the two tracks

Mixing Action:

Unique directional vibrating action at proper frequency and stroke applied to the entire mixer assembly gently and continuously whirl the materials in the hopper. Materials are conveyed upward by the internal spiral tracks and deflected constantly to one track or the other by the baffles. The continuous whirling action causes the materials to be blended into one homogeneous mixture. After the mixing cycle is complete, the materials are discharged through an outlet in the bottom.

B. Continuous Mixers

1. Farrel Continuous Mixer (Fig. 19)

Name of Mixer: Farrel Continuous Mixer (FCM)

Manufacturer: Farrel Company, Division of USM Corp.

Predominating Mechanism: shear and convection

Applications:

polymer industry, rubber or plastic

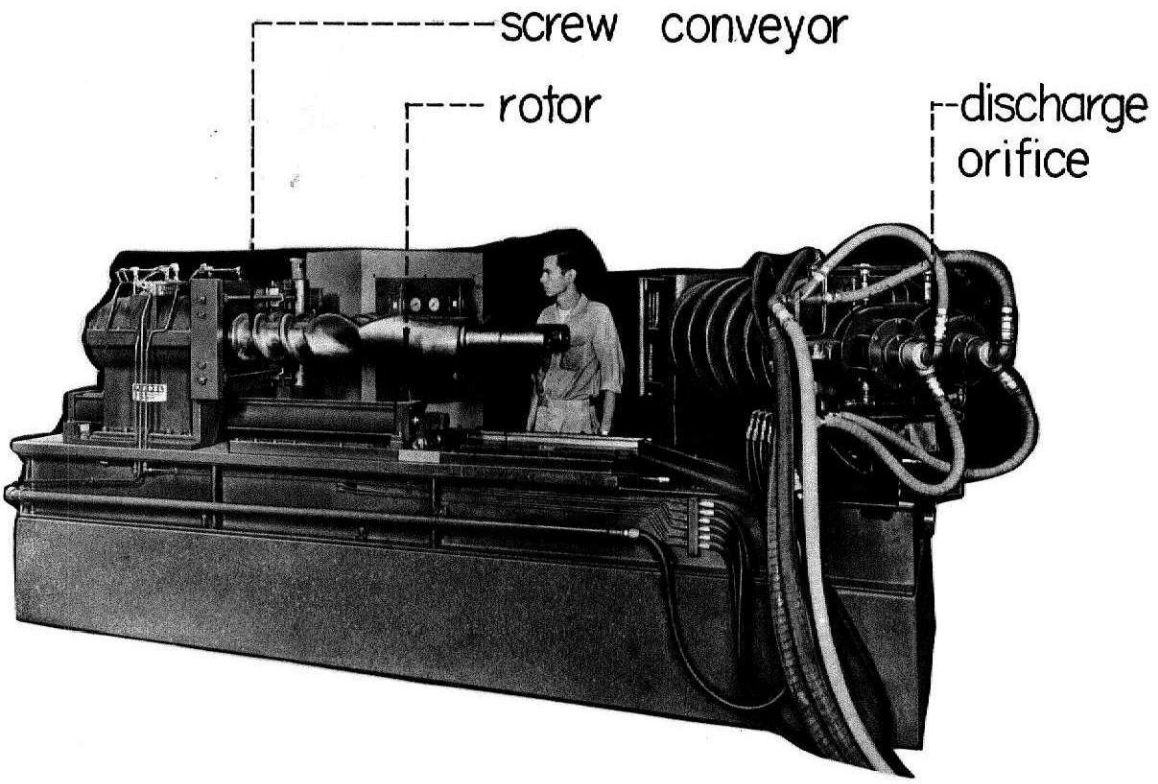


Fig. 19. Farrel Coutiuuous Mixer (By courtesy of Farrel Company, Division of USM Corp.)

Features or Advantages:

wide range of production rates

discharge temperature independent of production rate

continuous feed and discharge

insensitivity to wear -- relatively insensitive to increasing clearances and hence having a long, effective wear life

easy cleaning -- elimination of contamination

Major Parts of Mixer:

automatic feed

screw conveyor

two rotors

discharge orifice

Mixing Action:

The first section of the rotor acts as a screw conveyer, propelling the automatic-feed raw materials to the mixing section. Subsequently, intensive shear of materials occurs between rotor and chamber wall. Meantime, a rolling action of materials themselves and an interchange of materials between the two bores of the mixing zone exist. The action within this mixing section is similar to that within a Banbury Mixer. Because the feed screw constantly works, and the mixing action is rotary, there is little thrust or extruder action involved.

2. Continuous Tumbling Mixer (Fig. 20)

Name of Mixer: P-K Zig-zag continuous Solids-solids Blender

Manufacturer: The Patterson Kelly Co., Inc.

Predominating Mechanism: shear and convection

Applications:

simple multiple-component blends -- plastic powders, foods, pharmaceuticals, other chemicals, etc.

friable material combination -- flavorings, color, vitamins, etc. to cereal blends

solid-solid coatings

slurry blends

liquid coating of solids

Features or Advantages:

essentially a tumbler

particles move by gravity -- no paddles, screws or baffles

no violence and no scraping

easy cleaning

Major Parts of Mixer:

feeder

zig-zag tumbler

Mixing Action:

The blender mixes materials with a gentle tumbling action. Particles move by gravity and with multiple recycling. Solids are rolled gently as they move upstream and downstream in the sloping, rotating cylindrical legs. Random splitting, merging, tumbling and rolling bring particles into contact with one another.

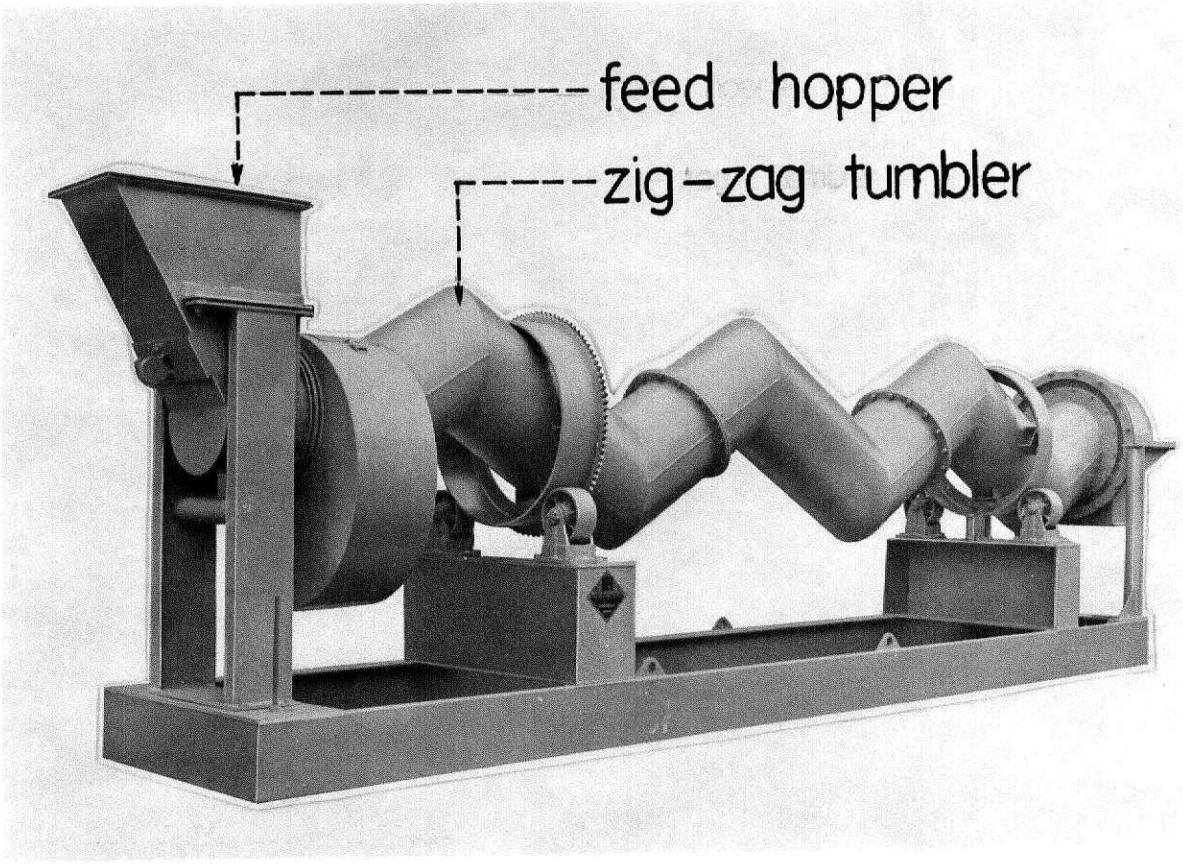


Fig. 20. Coutiuuous Tumbling Mixer (By courtesy of The Patterson Kelley Co., Inc.)

C. Selection of Solids-mixing Machines

There are a considerable number of mixers available for solids-solids mixing. In fact, there are so many that it is not easy to select one to best suit the particular mixing requirements of any one industry. Hence, in selecting the most suitable mixer, one should consider the factors influencing the cost and the mixing according to the characteristics of the equipment and the characteristics and loading of the materials. Two groups of criteria usually used in selecting a solids mixing machine are described below (12, 14, 34, 40, 43):

1. Characteristics of Mixers

Type of mixer -- batch or continuous

Capacity, dimension and geometrical shape

Design features -- shape of the agitating element and clearance between it and the wall of mixer body, location of baffles, spray nozzle or intensifier bar for the addition of the coating material, space saving design, etc.

Auxiliary equipment required

Speed of rotation of mixers or agitating elements

Ease of charge and discharge

Horsepower consumption

Temperature control -- cooling with or without auxiliary equipment

Ease of maintenance and cleaning

Sanitary construction and dust proof

Safety

Flexibility -- vacuum or pressure operation, variable-speed controlling, etc.

Long, effective wear life

2. Characteristics and Loading of Solids

Physical properties of each component -- particle size or size distribution, particle shape and surface, particle density, angle of repose, flowability, moisture content, etc.

Total volume of ingredients and quantity of each component added

Method (layer to layer, end to end, etc.) and sequence of addition of materials

In addition to these considerations, mixing time is important for different mixers and different substances. Pre-tests can be done to obtain comparative results. It should also be ascertained that the final mixture does not segregate through discharge or during transport. The costs of the installation of the mixer and manpower needed for operating and cleaning of the equipment should be considered simultaneously. In general, the decision of the type of the mixer used for some special requirements depends mostly on experience and practical judgements.

III. PERFORMANCE OF SOLIDS MIXERS

A. Basic Concept of the State of Mixedness

1. Review of the Elements of Statistics for Solids Mixing

Solids mixing is a random action and is considered as a statistical or stochastic process. The best equilibrium state reached by a solid mixture is the random arrangement of each component. Lacey (31) defined the final random mixture of two ingredients which differ only colors in them and do not cause any segregation effect by the following statement: "The probability of finding a particular kind of particle at any point is a constant, equal to the proportion of that kind of particle in the whole mixture." The statement implies a binomial distribution for this ideal mixing.

The binomial probability distribution is given by (28)

$$P(Y) = \binom{n}{Y} P^Y q^{(n-Y)} = {}_nC_Y P^Y q^{(n-Y)}$$

$$Y = 0, 1, 2, \ldots\ldots n.$$

where n = sample size

Y = number of successes in the sample of n

P = probability of a success in a single trial

$q = 1 - P$ = probability of a failure in a single trial

$P(Y)$ = probability of exactly Y successes

The mean, μ, of the binomial distribution, defined as the first moment about the origin, is

$$\mu = E(Y) = \sum_{\text{all } Y} YP(Y)$$

where $E(Y)$ = the expect value or average value of the variable Y

It can be shown (30) that

$$\mu = \sum_{\text{all } Y} \frac{n!}{Y!(n-Y)!} P^Y q^{(n-Y)} Y$$

$$= nP (P + q)^{n-1} = nP$$

The variance, σ^2, of the binomial distribution, defined as the second moment about the mean, can be shown (30) to be

$$\sigma^2 = E(Y-\mu)^2$$

$$= \sum_{Y=1}^{n} (Y-\mu)^2 P(Y)$$

$$= nP(1-P)$$

By changing into fraction of successes, one obtains

$$\mu = E(\frac{Y}{n}) = 1/n\ E(Y) = nP/n = P$$

$$\sigma^2 = E(Y/n - P)^2 = 1/n^2\ E(Y-nP)^2$$

$$= nPq/n^2 = Pq/n = P(1-P)/n$$

Applying the above equation to solids mixing, it can be found that the variance for the perfect random mixture, e.g., the final mixture by mixing two components A and B with the

identical properties but different colors, can be written as: (31)

$$\sigma_R^2 = P(1-P)/N$$

where

σ_R^2 = variance for the completely random mixture

N = the total number of particles per spot sample

P = the proportion of A (or B) particles in the entire mixture

The variance σ_0^2 before mixing with two ingredients completely segregated and without considering the interface effect is given by (36)

$$\sigma_0^2 = P(1-P)$$

As previously stated, solids-mixing is a statistical process and therefore a method to describe the state of mixing is one that can indicate the degree of dispersion of like particles throughout the whole mixture. Usually variance, or standard deviation, is used in the study of the mixing action. When mixing starts, the variance, calculated by sampling analysis, must fall between σ_R^2 and σ_0^2. The variance σ_R^2 for a random mixture is not easy to obtain because of the segregating effect due to the difference of sizes, shapes or densities of the two components.

Another theoretical distribution is the normal distribution whose frequency function is given by (28)

$$f(x) = [1/(2\pi)^{\frac{1}{2}}\ \sigma][e^{-(\frac{1}{2}\sigma^2)(x-\mu)^2}]$$

where

μ = theoretical mean of the normal distribution

σ^2 = theoretical variance of a random variable x

This distribution is a symmetrical, bell-shaped, continuous distribution with two parameters (μ and σ^2).

The random variable x can be transformed into new random variable,

$$Z = (x - \mu)/\sigma$$

It has the standardized normal distribution with u = 0 and $\sigma^2 = 1$. With this transformation in hand,

$$P(a < x < b) = P[Z_1 = ((a-\mu)/\sigma) < Z < ((b-\mu)/\sigma) = Z_2]$$

where P is the probability that Z will be contained between Z_1 and Z_2.

When a theoretical variance (σ^2) is unknown, Student's t-distribution is needed (28).

$$t = \frac{\sqrt{n}\ (\bar{x} - \mu)}{s}$$

where

n = number of spot samples

μ = true mean, i.e., theoretical mean of a normal population

S = standard deviation by estimation

$\bar{x}$ = mean of the individual measurement of spot samples

The t-distribution depends upon a parameter called the degree of freedom and is equal to n-1. This distribution is symmetric about the mean which is equal to zero. As the degrees of freedom approach infinity (i.e., $n - \infty$), the t-distribution tends to approximate the standard normal distribution. From the t-table (28), the percentage points of the t-distribution can be obtained. Then,

$$P(-t_{(\frac{\alpha}{2},\ n-1)} < \frac{\sqrt{n}\ (\bar{x} - \mu)}{S} < t_{(\frac{\alpha}{2},\ n-1)}) = 1 - \alpha$$

where

t = percentage points with 100 $(1-\alpha)\%$ of the area contained between them, i.e., the sum of the areas in the two tails equal to α.

By rearranging this expression, one obtains

$$P[A = (\bar{x} - t_{(\frac{\alpha}{2},\ n-1)} \frac{S}{\sqrt{n}}) < \mu < (\bar{x} + t_{(\frac{\alpha}{2},\ n-1)} \cdot \frac{S}{\sqrt{n}}) = B]$$

$$= 1 - \alpha$$

This implies that the true mean (estimated by $\bar{x}$) of a normal population with the unknown variance is covered by the interval bounded by the confidence limits A and B with 100 $(1-\alpha)$% confidence.

Similarly for true variance σ^2 (estimated by S^2),

$$P\left(\frac{nS^2}{\chi^2_{(1-\frac{\alpha}{2}),\,(n-1)}} < \sigma^2 < \frac{nS^2}{\chi^2_{\frac{\alpha}{2},\,(n-1)}}\right) = 1 - \alpha$$

where

χ^2 = chi-square, can be obtained from tables (19).

Actually, the upper and lower confidence limits for the true standard deviation can be easily obtained from figures (46) if the degree of freedom is known.

Finally the normal distribution can be considered as an approximation of the binomial distribution as the sample size n becomes larger and larger (28).

2. Criteria of the Degree of Mixing

For the mixing of a binary mixture, the mean $\bar{x}$ of the spot samples measured quantitatively is defined by

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

where

x_i = characteristic of the i'th spot sample such as particle fraction of one component, etc.

n = number of spot samples withdrawn

The sample variance used as an estimate of the true variance is defined as the average value for the squares of the deviations from the mean (25), i.e.,

$$S^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2$$

Rearrangement of this equation gives

$$S^2 = \frac{1}{n-1} \left[\Sigma x_i^2 - \frac{(\Sigma x_i)^2}{n} \right]$$

The standard deviation is given by

$$S = \sqrt{S^2}$$

In order to understand the performance of solids mixing, a mixing index M is usually used to indicate the degree of mixing. Generally the mixing index is a combination of the standard deviation of samples with other parameters to give a dimensionless ratio. More than 30 different criteria of the degree of mixing have been reviewed (17) and only some of the practical mixing indices are shown below:

Lacey (31)

$$M = \frac{\sigma_R}{S}$$

Kramers (32)

$$M = \frac{\sigma_0 - S}{\sigma_0 - \sigma_R}$$

Lacey's (32) modification of Kramers' formula

$$M = \frac{\sigma_0^2 - S^2}{\sigma_0^2 - \sigma_R^2} \qquad \text{or} \qquad 1 - M = \frac{S^2 - \sigma_R^2}{\sigma_0^2 - \sigma_R^2}$$

smith (41)

$$M = \frac{\sigma_0}{S}$$

Yano, Kanise and Tanaka (50)

$$M = \frac{S}{\sigma_0}$$

Poole (37)

$$M = \frac{S}{\sigma_R}$$

Ashton and Valentin (2)

$$M^2 = \frac{\log \sigma_0^2 - \log S^2}{\log \sigma_0^2 - \log \sigma_R^2}$$

where

M = mixing index

S = measured standard deviation of sample composition

σ_0 = theoretical standard deviation for unmixed materials

σ_R = theoretical standard deviation for completely random mixture

Ashton and Valentin (2) indicated that the actual sample variance with regard to mixedness is not exactly the variance calculated from a set of experimental results obtained by sampling and analysis of spot samples. The true sample variance S_M attributed to mixedness was expressed by

$$S_M = S^2 - S_a^2 - S_s^2$$

where S^2 = estimated sample variance

S_a^2 = sample variance due to analytical error

S_s^2 = sample variance due to sampling error

Ashton and Valentin (2) calculated the values of S_a^2 and attempted to assess the contribution of analytical error in a sample to the overall estimated variance S^2. In fact, for solids mixing the estimated overall sample variance S^2 still has practical advantages as an approximation of the actual sample variance S_M^2 attributed to mixedness only.

B. Factors affecting the Rate of Mixing and the Degree of Mixing

A number of factors affecting the rate of mixing and the degree of mixing are given below (44).

1. Material variables - size and size distribution, particle shape, density, angle of repose, roughness and moisture content of mixture.
2. Mixer variables - type of mixer, dimensions, fraction of the mixer volume occupied by the components, speed of rotation, baffles, geometrical effect and scale-up.
3. Others - method of loading, relative proportions of the tow materials and power requirement.

Some of these factors have been observed by various investigators and their methods are briefly described below:

Coulson and Maitra (15) developed the following rate equation for the mixing of solids in a drum mixer, i.e.,

$$\ln \frac{100}{X} = kt$$

where

X = percentage unmixed

t = mixing time in seconds

k = rate constant

The values of X can be determined by experiment and is defined as

$$X = (1 - n/30) \times 100$$

where

n = number of spot samples out of 30 spot samples containing approximately the same composition as in the whole system after a certain mixing time

By plotting the values of $\ln \frac{100}{X}$ against the corresponding values of mixing time t, a straight line with a slope k is obtained. Coulson and Maitra (15) investigated the influence of the various factors - particle size, density of each component, total volume of the material, speed of rotation of the drum, inclination of the drum and the relative proportions of the two components, on the absolute value of the rate constant k.

Carley-Macauly and Donald (11) express the rate equation by

$$\log V_p = - \frac{t}{\tau} + C$$

where

$V_p = S^2 - \sigma_R^2$ = estimated value of the systematic variance

S^2 = measured variance by experiment

σ_R^2 = theoretical variance for completely random mixture

t = number of revolutions of the mixer

C = integration constant

τ = inverse mixing rate = number of revoluions of mixer required to reduce the V_p value by one-tenth

The effect of variables - particle size, loading of the materials, speed of rotation and relative proportions of the components, on the values of τ have been investigated by Carley - Macauly and Donald (11) for sands or ballotini orginally placed layer by layer and distinguished only by color. The mixers used in the experiment included horizontal cylinder, inclined cylinder

and double cone with baffles.

The observation of factors affecting the solids mixing discussed so far has been limited to the mixing rate disregarding the final state of the mixture. Donald and Roseman (16) defined θ as the final degree of mixing, i.e., the finally steady value of V from the plot of log V_p against number of mixer revolutions. τ and θ have been used simultanuously to show the effects of changing the operating conditions of a horizontal cylinder, which include size, size difference, density difference, mixer fullness, speed of rotation, mixer length, relative proportion of the components and end-well surfaces.

Ashton and Valentin (2) carried out a number of experiments to examine the effects of speed, relative proportions of the two components and particle size on the mixedness in different mixers - Double cone, Airmix mixer, Nauta mixer or Z-blade mixer (Double-arm mixer) for mixtures of fine sand - fine calcite. In addition, the effect of density upon mixedness in the Airmix or Double cone mixer was observed for different pairs of materials such as Pyrites (sp. gr. = 4.7), witherite (sp. gr. = 4.2), sand (sp. gr. = 2.65). Calcite (sp. gr. = 2.7), Ammonium Sulphate (sp. gr. = 1.8), and Borax (sp. gr. = 1.7) so that pairs of ingredients were classified as an "easy" mixtures or "non-easy" mixtures.

Yano, Kanise, Hatano and Kurahasi (52) discussed the effects of rotational speed and charged colume of the powder on

the rate of mixing $(N\theta)_s$ and the degree of mixing (σ_s) where σ_s is the minimum estimated standard deviation during the mixing operation and $(N\theta)_s$ is the number of rotations of the mixers required to obtain σ_s. $(N\theta)_s$ and σ_s were shown simultaneously and separately against revolutional speed or charged volume of the components for different mixers (double, cone, twin-shell mixer, horizontal cylinder and cubic mixer) by the mixing of Na_2CO_3 - polyvinyl chloride, having the same size distribution. Continuing the experimental studies, Yano, Kanise, Tanaka and Kurahasi (53) examined the influences of the physical properties which were expressed by the characteristic constant, C_R, of materials upon the mixing degree and mixing speed of several types of mixers as mentioned above. Several types of powders - Na_2CO_3, polyvinyl chloride, glass, sand, Fe powder and Alundun with the same particle size distribution and several pairs of these powders were used for the investigations. The influence of particle size of powder on solids-mixing in different mixers then were continued to be observed by Yano, Kanise, Sano, Okamoto and Tsutsumi (54) for a Na_2CO_3 - sand system.

An exponential form of the rate of mixing ($S = S_0' e^{-\phi\theta}$, θ = time) has been suggested by Yano, Kanise and Sano (55). The effects of various factors - rotational speed of the mixers, volume occupied by the components, type of mixers, particle size and different pairs of materials - on the rate of mixing as indicated by the value of ϕ were investigated and an

empirical equation relating coefficient of mixing rate, Φ , as functions of various factors, was derived. Yano, Sano, Shirakawa and Tominaga (51) also used the coefficient of mixing velocity, Φ , to analyze the experimental results of the effects of various factors on the speed of the solids mixing for a two-component system, Na_2C0_3 - sand in a ribbon-type mixer.

All the results obtained by Coulson and Maitra (15), Carley-Macauly and Donald (11), Donald and Roseman (16), Ashton and Valentin (2), Yano, Kanise, Hatano and Kurahasi (52), Yano, Kanise, Tanaka and Kurahasi (53), Yano, Kanise, Sano, Okamoto and Tsutsumi (54), Yono, Kanise and Sano (55), and Yano, Sano, Shirakawa and Tominaga (51) can be summarized and some conclusions can be drawn from these results as described below.

1. There is an optimum volume to be occupied by the ingredients and optimum speed of rotation for operation of solids mixers. These optimum values are constant and independent of pairs of components being mixed with the same particle size if the same type and size of mixers, for example, twin-shell mixer, horizontal cylinder, cubic mixer and double cone mixer, are operated. The optimum rotational speed of each mixer is increased when the particle diameter increases while the optimum charged volume of powder has almost no influence.
2. When the relative proportions of the two ingredients become larger, the rate and degree of solids mixing

will improve.

3. The greater the size difference and density difference of the particles, the faster the mixing but the worse the final degree of mixing.
4. After mixing, demixing occurs when the difference of size or density of ingredients exists. The greater the difference, the more and faster the segregation. Campbell and Bauer (8) carried out a number of experiments to investigate variables influencing demixing and concluded that the major effect on segregation is the relative size difference while the difference of density or particle shape has a measurable but minor effects compared to that of size difference.

In addition to selecting the same size of particles to minimize the degree of segregation, fine powder materials can be utilized to eliminate the free-flowing properties of the batch and to obtain a random mixture with a higher probability. Actually demixing problems can be reduced by using continuous mixer instead of batch mixer because the residence time of the particles in the mixer is not long enough to cause segregation.

Cahn, Healy and Fuerstenau (7) experimentally investigated the influence of the geometry of the twin shell blender on the mixing of solids. Ciborowski and Wolny (13) studied the effect of the moisture content on solids mixing, and found that the rate of axial mixing increases with increasing moisture content of the particles if a diffusive mechanism is preserved.

C. Performance Data of Mixing Equipment

Because of the simplicity and convenience of studying the performance of different mixers observed by a number of investigators, the simpliest and most basic mixing index, S(standard deviation), is used in the discussion that follows. As previously described, an unbiased sample deviation is given by

$$s^2 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1}$$

where

x_i = particle fraction or weight fraction of one component in a binary mixture for the i'th sample

$\bar{x}$ = mean of the compositions of n spot samples

n = number of spot samples withdrawn for a sample

If the light probe described by Ashton, Schofield, and Valentin (1) is used to measure local compositions in binary mixtures of particles of different colors instead of a sampling thief, the standard deviation of relectivity probe meter readings becomes (23)

$$S = \sqrt{\frac{\sum_{i=1}^{n} (i - \bar{i})^2}{n - 1}}$$

where

i = probe meter reading, microampers (μa)

$\bar{I}$ = average probe meter reading of n spot readings, μa

n = number of probe meter readings

Gray (23) used this technique to determine and compare the performance of seven mixers.

The theoretical standard deviation σ_R for a completely random mixture with two powders having particles all of the same size is given by

$$\sigma_R = \sqrt{\frac{P(1 - P)}{N}}$$

where

P = proportion of one component

N = number of particles for each spot sample

When two components having ranges of particle sizes are mixed, the theoretical standard deviation σ_R of sample concentration of a completely random mixture becomes

$$\sigma_R = \sqrt{\frac{Pq}{\left[\frac{M}{q(\Sigma fw)_p + P(\Sigma fw)_q}\right]}}$$

where

p = weight fraction of monor component

q = weight fraction of major component

M = weight of a spot sample divided into several classes according to range of sizes

w = individual particle weight for each class, i.e., the arithmetic mean of the particle weights bounding that class

f = weight fraction in each class

Σfw = mean particle weight based on weight frequency

Poole, Taylor and Wall (37) derived this equation by modifying Strange's equation (42), which has also been used by Ashton, and Valentin (2). In fact, segregation prevents the final mix from a completely random state in the experiment.

If the mixing of multicomponents is required, chi-square, χ^2, can then be used as a measure of dispersion instead of variance which is only suitable for the mixing of two-component systems. Chi-square values can be calculated by the following equation (18).

$$\chi^2 = \Sigma \left[\frac{(O - E)^2}{E}\right]$$

where

O = observed number of particles of any component in a spot sample

E = corresponding expected number of particles based on average distribution of ingredients in mixture

Gayle and Gary (21, 22) studied the mixing of a multicomponent system in drum and elbow mixers and determined the degree of segregation, which is a combination of chi-square values for any mixture with those for random and segregated mixtures.

The detailed description (such as feeding type, components being mixed and their properties; features of mixer with operating speed; and sampling information) about the experiments of solids mixing by different investigators is given in tables 1 to 8 according to the following mixer type - drum; double cone; twin-shell mixer; or lodige and planetary mixers. The figure shown in Fig. 21 to Fig. 30 indicating the performance of the mixer type follows each table. The volume ratio of two components is 1 : 1 if no specification is made. For the fast and easy study about the experimental results for each type of mixer, the same unit is used in the tables 1 to 8. For instance, the unit of particle size - mesh number which defines the number of wires per linear inch of sieve cloth will change into the width (microns) of opening in wire cloth (6). Sieves used to determine particle size usually have square openings. However, other shapes of openings such as circular, rectangular and even slits are sometimes used.

It is seen from table 1 and Fig. 21 that glass beads used by Hogg (26, 27) are very difficult to mix in the drum mixer (or horizontal cylinder) with end to end loading. Carley-Macauly's data (9, 10) are not adequate to show the final state of mixture and longer time of mixing operation is required. De-mixing occured in Weidenbaum's work (44) because of density and particle shape differences and size effect. Yono's experiment (52) showed that a final and steady mixture had not been reached.

Table 1. Experimental of Horizontal Cylinder (Drum Mixer)

Feed type		End-to-end			
Investigator		Carley-Macauly, (9, 10)	Hogg, (26, 27)	Weidenbaum, (44)	Yano, Kanise, Hatano & Kurahasi, (52)
Components & their properties	Components	Sand with different colors	Glass beads with different colors (white & yellow)	Ottawa sand & salt	Na_2CO_3 & Polyvinyl Chloride
	Size range	853-599 μ (microns)	75-105 μ	-40/+50 mesh (420-297 μ)	-100/+200 Tyler Mesh (147-74 μ)
	Mean particle size	726 μ (microns)	90 μ		
	Bulk density g/c.c.		2.39 (white) 2.40 (yellow)	salt = 1.18 sand = 1.56	
	True density g/c.c.	2.6	4.15		
Characteristics of mixer	Particle shape		spherical	salt = cubic crystal Sand: smooth & irregular with spherical tendencies	

Table 1. Cont'd

Feed type		End-to-end			
Characteristics of mixer	Length (in.)	8	16	8.31	4.724 (12 cm.)
	Diameter (in.)	4	4	5.81	1.772 (4.5 cm.)
	volume (c.c.)	1648	3296	3600	741
	Operating speed (r.p.m.)	20	27	44-49	35.4
Fraction of filling by volume		$\frac{1}{3}$	$\frac{3}{5}$	$\frac{1}{3}$	13.5%
Sampling	Apparatus	Sampling thief (44)	Sampling device (by suction)	Sampling thief	Sampling thief
	Sampling Analysis	Counting	Counting	Counting	Chemical analysis (titration) for Na_2CO_3 in each spot sample (vol. fraction)
	No. of spot samples	14	15	27	7
	No. of samples	3	12	17	13
σ_R	P	0.5	0.5	0.5333	
	N	160	500	139	
	σ_R	0.0394	0.02235	0.042	

Table 2. Experimental of Horizontal Cylinder & Inclined Cylinder

Name of mixer		Horizontal Cylinder			Inclined Cylinder
Feed type		Layer by layer	Side by side	Side by side	Layer by layer
Investigator		Carley-Macauly, (9, 10)	Carley-Macauly, (9, 10)	Hogg, (26)	Carley-Macauly, (9, 10)
Characteristics of Components & their properties	Components	Sand with different colors		Quartz with different colors (half dyed green)	Sand with different colors
	Size range	500-422 μ			853-599 μ
	Mean particle size	461 μ		28 x 35 mesh	726 μ
	True density (g/c.c.)	2.6			2.6
Characteristics of Mixer	Length (in.)	8			$5\frac{1}{8}$
	Diameter (in.)	4			$3\frac{1}{2}$
	Volume (c.c.)	1648			808
	Operating Speed (r.p.m.)	20		4.48 (4% of the critical speed)	20
Fraction of filling by volume		$\frac{1}{3}$ (1000 g.)		$\frac{1}{2}$	$\frac{1}{2}$ (600 g.)

Table 2. Cont'd

Name of Mixer		Horizontal Cylinder			Inclined Cylinder
Sampling	Apparatus	Sampling thief			Sampling thief
	Sampling Analysis	Counting		Estimated from photographs	Counting
	No. of spot samples	55	45		50
	No. of samples	8	8	9	10
σ_R	P	0.5	0.5	0.5	0.5
	N	45	45		32
	σ_R	0.0748	0.0748		0.088

Table 3. Experimental of Double Cone

Feed type			Layer by Layer		Side by Side	
Investigator		Kaufman, (29)	Carley-Macauly (9, 10)			Yano, Kanise, Hatano & Kurahasi (52)
Components & their properties	Components	Procaine penicillin G (measured) & dihydrostreptomycin sulfate	Sand with different colors			Na_2CO_3 & Polyvinyl Chloride (P.V.C.)
	Size range		853-599 μ	500-422 μ	853-599 μ	-100/+200 Tyler mesh (147-74 μ)
	Mean particle size		726 μ	461 μ	726 μ	
	True density (g/c.c.)		2.6			
Characteristics of mixer	Dimension (see Fig. 23) A (in.)	1.15	3			
	B (in.)	1.6	0			0
	C (in.)	4.6	$6\frac{1}{4}$			4.724 (12 cm.)
	D	90°	90°			90°
	Volume	1 pint				741 c.c.
	Operating Speed (r.p.m.)		20			27.3
	Specific design		Designed with baffle			R = 2.756" (7cm.)

Table 3. Cont'd

Feed Type			Layer by Layer			Side by Side
Fraction of filling by volume		65% (50 wt.% of penicillin)	Just more than fills lower cone (1000 g.)			13.5%
Sampling	Apparatus	Sampling thief with sampling guide (4)	Sampling thief			Sampling thief
	Sampling analysis			Counting		Chemical analysis (titration) for Na_2CO_3
	No. of Spot samples	10	50	55	2 (one from each side)	7
	No. of samples	9	7	8	6	6
σ_R	P		0.5	0.5	0.5	0.5
	N		35	40	1000	
	σ_R	0.05 (specified) - wt. fraction	0.0845	0.0791	0.0158	

Table 4. Experimental of Twin-shell Mixer

Investigator		Kaufman, (29)	Weidenbaum, Corson & Miller (47)	Yano, Kanise, Tanaka & Kurahasi (53)	Cahn, Itealy & Fuerstenau (7)	Oleniczak (35)
Feed Type			Side by side	Side by side	Side by side Layer by layer	Layer by layer
Components & their properties	Components	Procaine penicillin G & dihydrostreptomycin sulfate	Salt & sand	Na_2CO_3 & P.V.C. (Polyvinyl chloride)	Calcite($CaCO_3$) & quartz (SiO_2)	Commercial white sea sand with different colors
	Size range		-40/+50mesh (420-297 μ)	-100/+200 Tyler mesh (147-74 μ)		(710 - 590 μ) 25 - 30 mesh
	Particle size				28- 35 mesh	
	Bulk density (g/c.c.)		Sand=1.42 Salt=1.28	Na_2CO_3=1.11-0.89 P.V.C.=0.55-0.4	$CaCO_3$= 1.35 SiO_2 = 1.21	
	True density (g/c.c.)		Sand=2.2 Salt=2.16	Na_2CO_3= 2.55 P.V.C.= 1.39		
	Particle shape		Sand=irregularly shaped grain Salt = cubic crystal			

Table 4. Cont'd

Character-istics of mixer	Volume (c.c.)	473	473	741	1078	1945	
	Operating Speed (r.p.m.)		24	60	24	33	
Fraction of filling by volume		65% (50 wt% of penicillin)	55%	9.5%	40%	41.4%	51.4%
Sampling	Apparatus	Sampling thief with sampling guide		Sampling thief			
	Sampling analysis	Chemical analysis (wt. fraction)	Counting	Chemical analysis-titration for Na_2CO_3 (vol. fraction)	Chemical analysis-titration	Counting	
	No. of spot Samples	10	10	7	8	21	24
	No. of Samples	9	20	13	8(side by side) 10(layerbylayer)	9	10
	P				0.5	0.5	0.5
	N				850	73	77
	σ_R	0.05 (specified)	0.068		0.0172	0.0584	0.0571

Table 5. Experimental of Planetary and Lodige Mixer

Investigator		Hersey, (24)	Poole, Taylor & Wall, (37)		
Components & their properties	Components	Potassium dichromate & exsiccated Sodium sulphate (1:9)	Copper & nickel metal powders (10:1)	Urania & nickel powders (10:1)	Urania & thoria (ThO_2) (10:1)
	Size range (μ)	K_2CrO_4 = 170-42.5	Ni = 45-15 Cu = 85-10	Ni = 45-15 UO_2(I) = 40-0.5 UO_2(II) = 50-0.5	Ni = 45-15 ThO_2 = 15-2.5
	Mean size (μ)	Na_2SO_4 = 48	Ni = 35 Cu = 55	Ni = 35 UO_2(I) = 20 UO_2(II) = 35	Ni = 35 ThO_2 = 10
	True density (g/c.c.)	K_2CrO_4 = 2.68 Na_2SO_4 = 2.7	8.9 (both)	Ni = 8.9 UO_2 = 10.9	Ni = 8.9 ThO_2 = 8.5
	Particle Shape		spheroidal	Ni - spheroidal UO_2 - rough, equiaxed	Ni - spheroidal UO_2 - square
	Properties		free-flowing	Great agglomerating tendency	Cohesive & slight agglomerating tendency

Table 5. Cont'd

Investigator		Hersey, (24)	Poole, Taylor & Wall, (37)	
Characteristics of mixer	Length (in.)		$6\frac{3}{4}$	
	Diameter (in.)		$7\frac{1}{2}$	
	Operating speed (r.p.m.)	K-beater = 60	Double plough-shaped shovels = 240 Drum = 40	
	Other		Filling-spot cover carrying perforated baffle plates aligned normally to the axis	
filling by weight (g.)		500	3000	
Sampling	Apparatus	Sampling thief	Sampling thief with sampling grid	
	Sampling analysis	Chemical analysis using H_2SO_4	Chemical analysis by spectrophotometer	
	No. of spot samples	10 - 20	10	
	No. of samples	4	5	4
	Other		Drum set vertically from a horizontal position when sampling	

Table 6. Experimental of Several Mixers

Investigator		Yano, Kanise, Hatano & Kurahasi, (52)		Yano, Kanise, Tanaka & Kurahasi (53)	Yano, Sano, Shirakawa & Tominaga (51)
Name of Mixer		Horizontal Cylinder	Double Cone	Twin-shell	Ribbon mixer
Feed type		End-to-end	Side by side		End-to-end
Components	Components	Na_2CO_3 & Polyvinyl Chloride (P.V.C.)			Na_2CO_3 & sand
	Particle size	-100/+200 Tyler mesh (147-74μ)			-65/+80 Tyler mesh (208-175μ)
	True density (g./c.c.)	Na_2CO_3 = 2.55 P.V.C. = 1.39			
Characteristics of mixer	Dimension (cm.)	Length = 12 Diameter = 4.5	R = 7 B = 0 C = 12 D = 90°		Mixing vessel length = 38 width = 12 max. depth = 15
	Total volume (c.c.)		741		6260
	Operating speed (r.p.m.)	35.4	27.3	60	Mixing ribbon = 80
	Other				Outside & inside ribbons rotating in opposite direction Vol. to top of outer ribbon = 4770 c.c.

Table 6. Cont'd

Fraction of filling by volume		13.5%	13.5%	9.5%	17.3%
Sampling	Apparatus	Sampling thief			
	Sampling analysis	Chemical analysis (titration) for Na_2CO_3(vol. fraction)			
	No. of spot samples	7			9
	No. of samples	13	6	13	9

Table 7. Experimental by Ashton & Valentin (2)

	Name of mixer	Double cone	Airmix mixer	Nauta mixer	Double-arm mixer
	Feed type	Layer by layer			
Components	Components	Find sand & fine calcite ($CaCO_3$)			
	Size range	180 - 110 μ			
	Mean particle size (μ)	Sand = 160		Calcite = 155	
	True density (g/c.c.)	Sand = 2.65		Calcite = 2.7	
Mixer	Working capacity (ft^3)	1			
	Operating speed	50 r.p.m.	70 lb/in^2 gauge	2.86 r.p.m.	One blade at 12 r.p.m. The other at 24 r.p.m. rotating in opposite directing
Sampling	Apparatus	Thief-type sampling probe			
	Sampling analysis	Chemical analysis for each spot sample			
	No. of spot samples	44		85	70
	No. of samples	7	5	6	5
	σ_R	0.084 (wt. fraction) - from modified stange equation (P1, P2)			

Table 8. Experimental by Gray, J. B. (21)

Name of mixer		Horizontal cylinder	Double cone	Twin-shell	Planetary mixer	Ribbon mixer	Muller mixer	Concrete mixer (baffled cylinder)
Feed type		Layer by layer (component in larger proportion dumped first)						
Components	Components	Silica sand & a classified ilmenite A (91 : 9)						
	Size range (mesh)	Silica sand = 65 - 200 (230 - 74 μ) Ilmenite particles = 150-325(99-44 μ)						
	True density (g/c.c.)	Sand = 2.6			Ilmenite = 4.3			
	Porperty	Free-flowing						
Mixer	Volume (ft^3)	0.67	0.45	0.5	0.42	3.2	2.75	15
	Operating speed (r.p.m.)	48	32.6	32.6	60	90	33.3	16.2
Filling	Sand (lb.)	36	16.5	16.5	16.1	98.5	99	243
	Ilmenite (lb.)	3.6	1.65	1.65	1.61	9.8	9.9	26.9
Sampling	Apparatus	Photoelectric probe together with photocell meter						
	No. of spot readings	32	10	10	7	36	32	30
	No. of samples	8	8	8	7	6	7	7

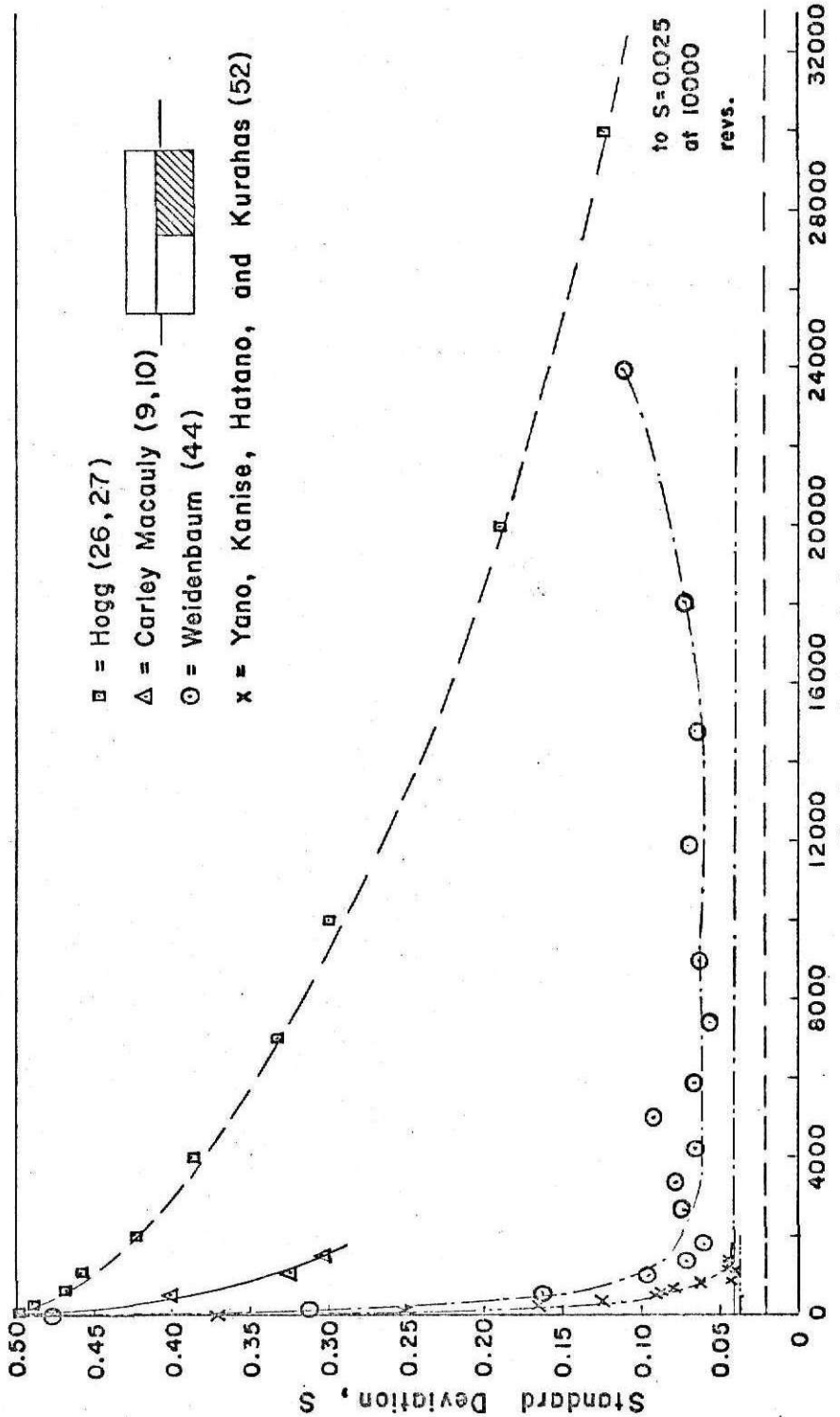


Fig. 21 Standard deviation versus revolutions for horizontal cylinder with end-by-end loading.

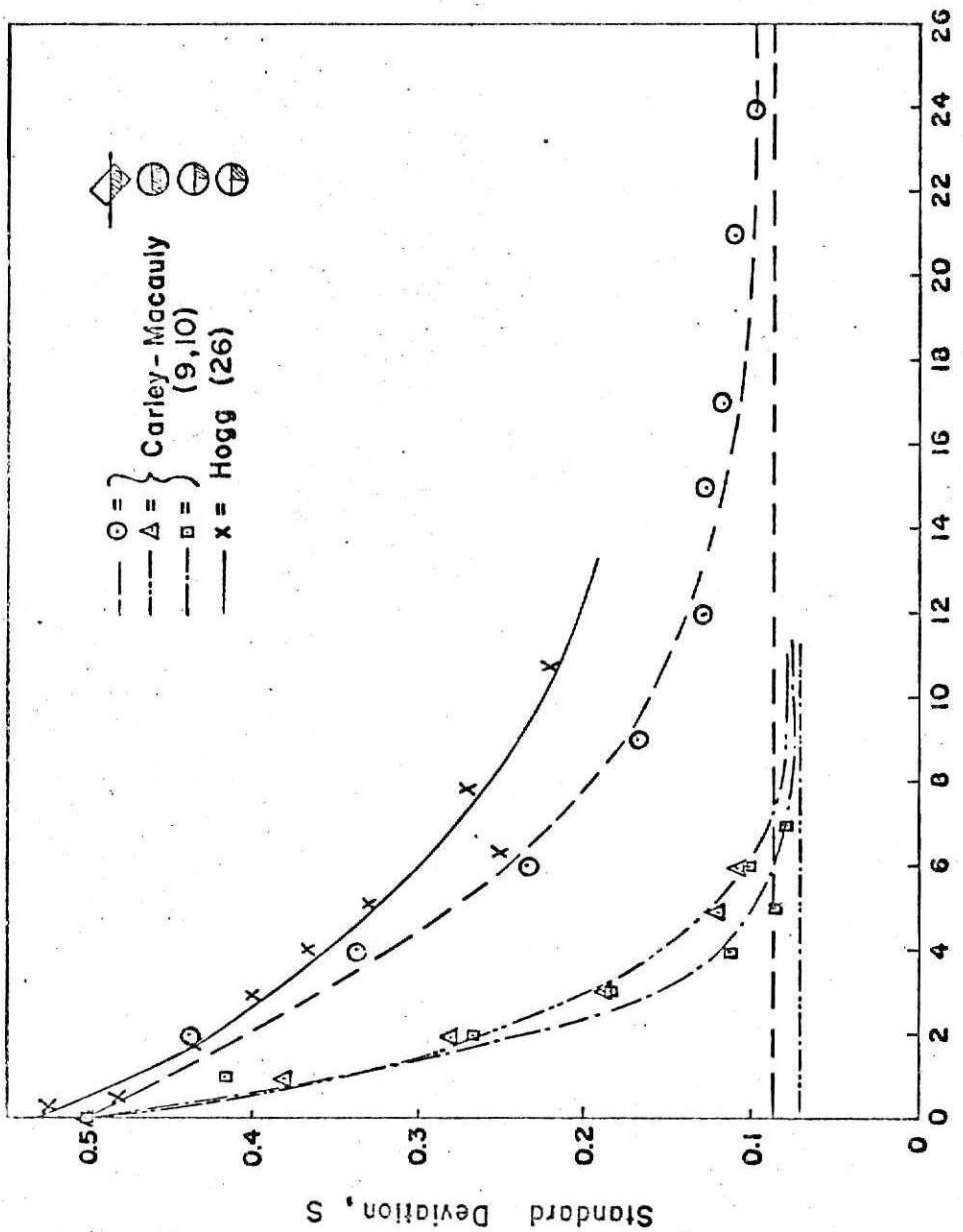


Fig. 22 Standard deviation versus revolutions for inclined and horizontal cylinder with layer by layer loading.

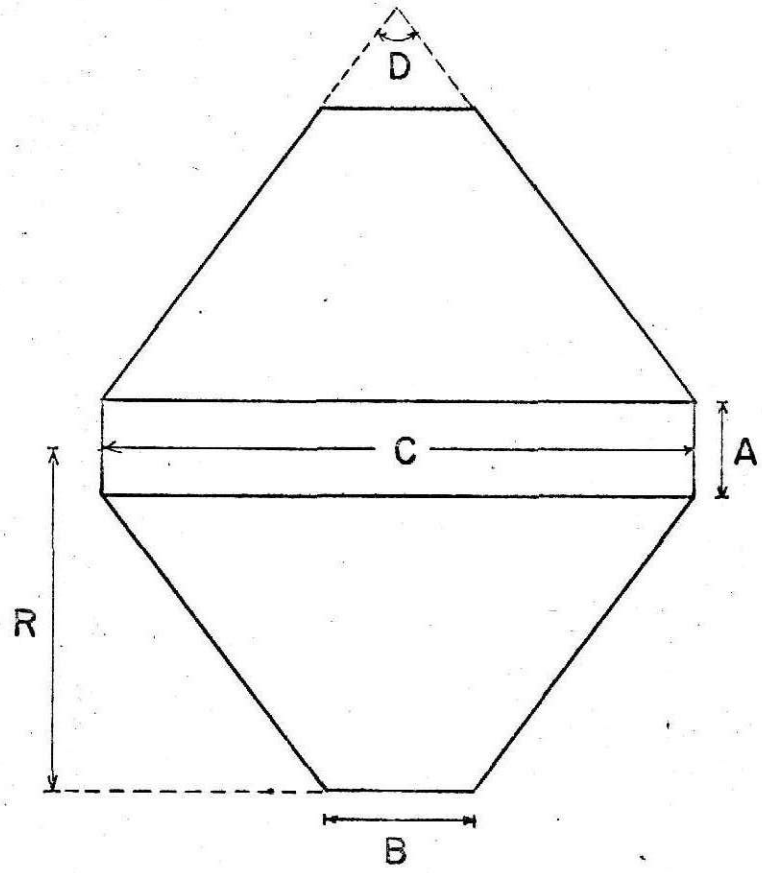


Fig. 23 Configurations of a double cone .

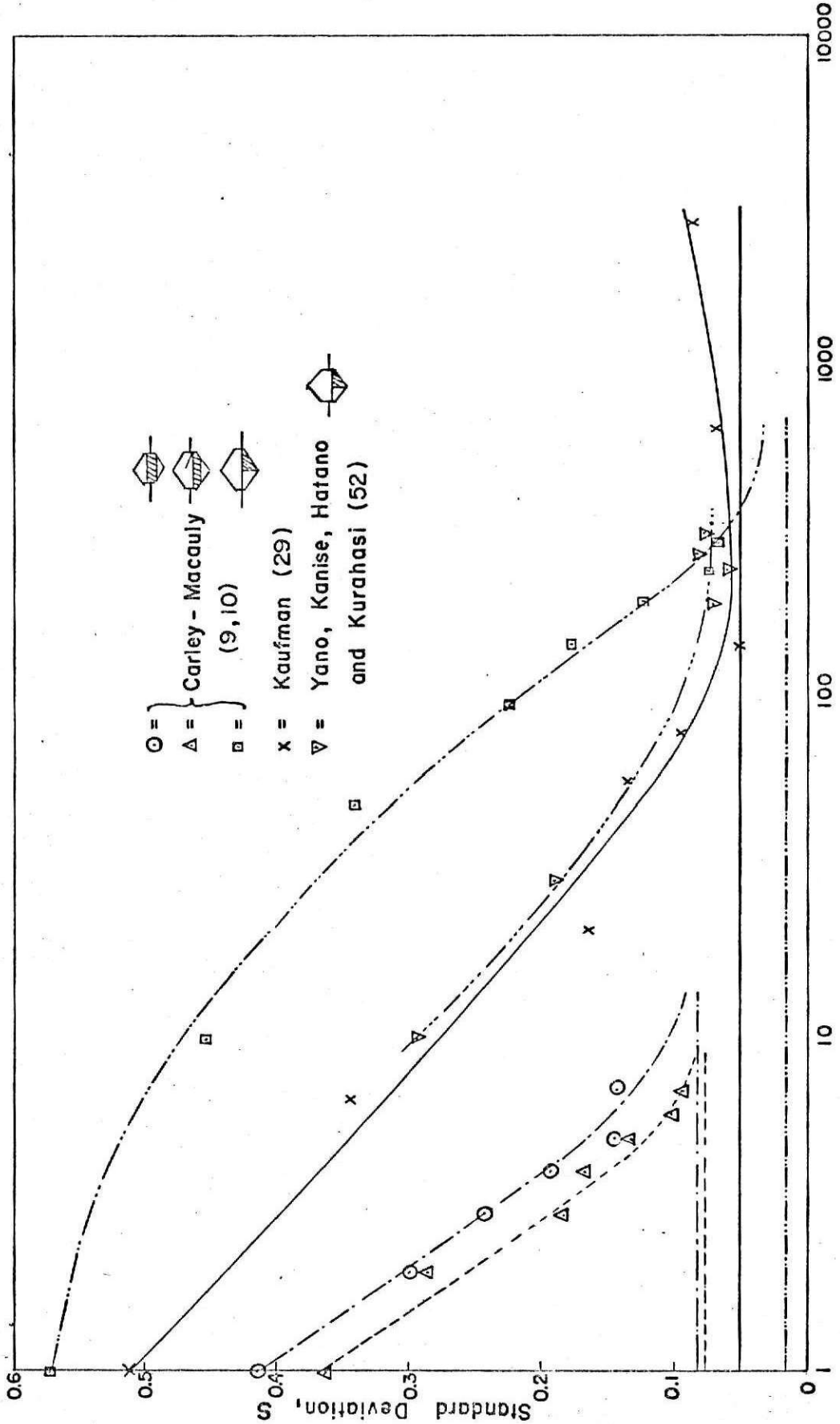


Fig. 24 Mixing of double - cone mixer.

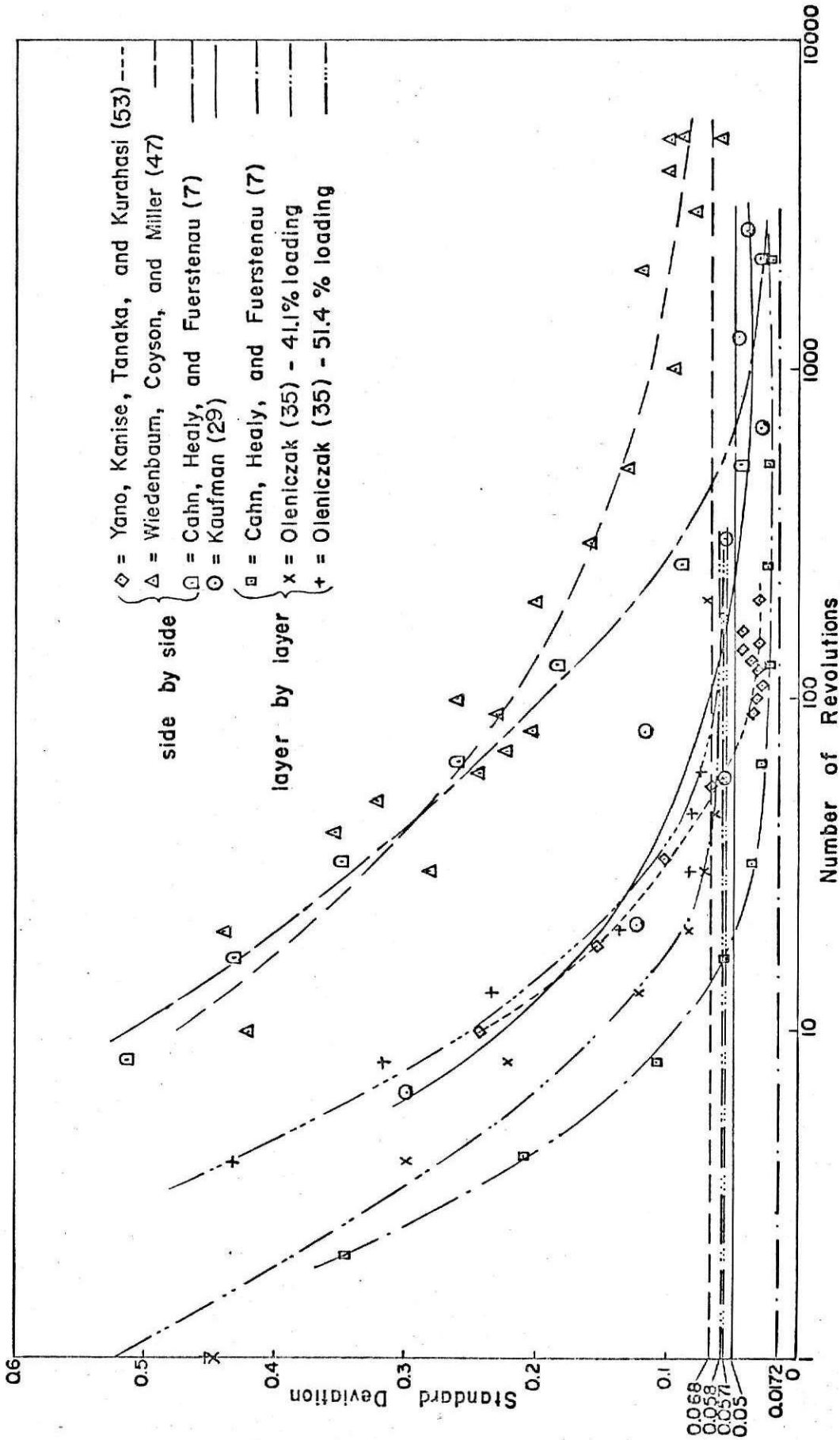


Fig. 25 Mixing of twin shell mixers.

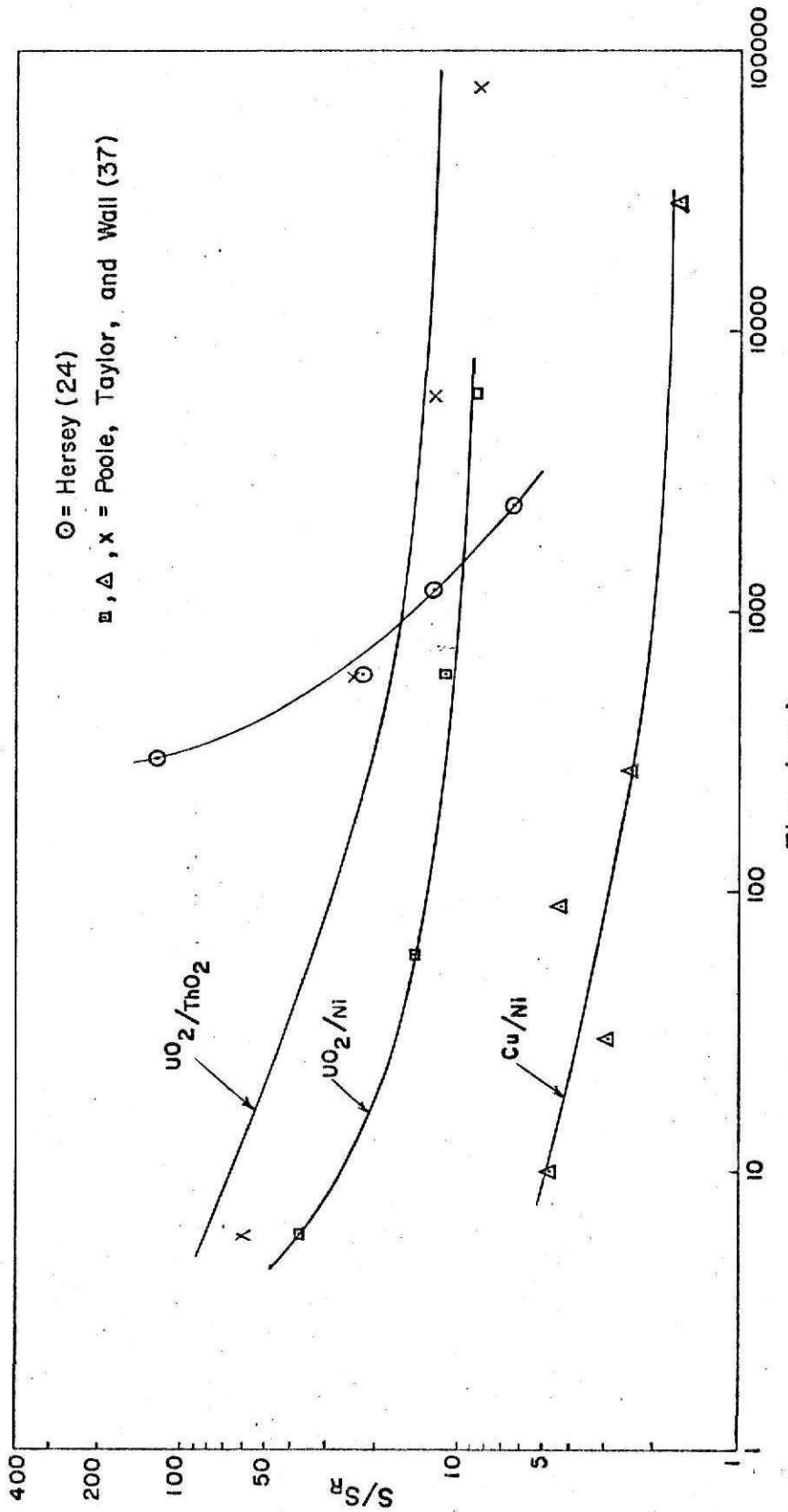


Fig. 26 Mixing of Lodige mixer and planetary mixer.

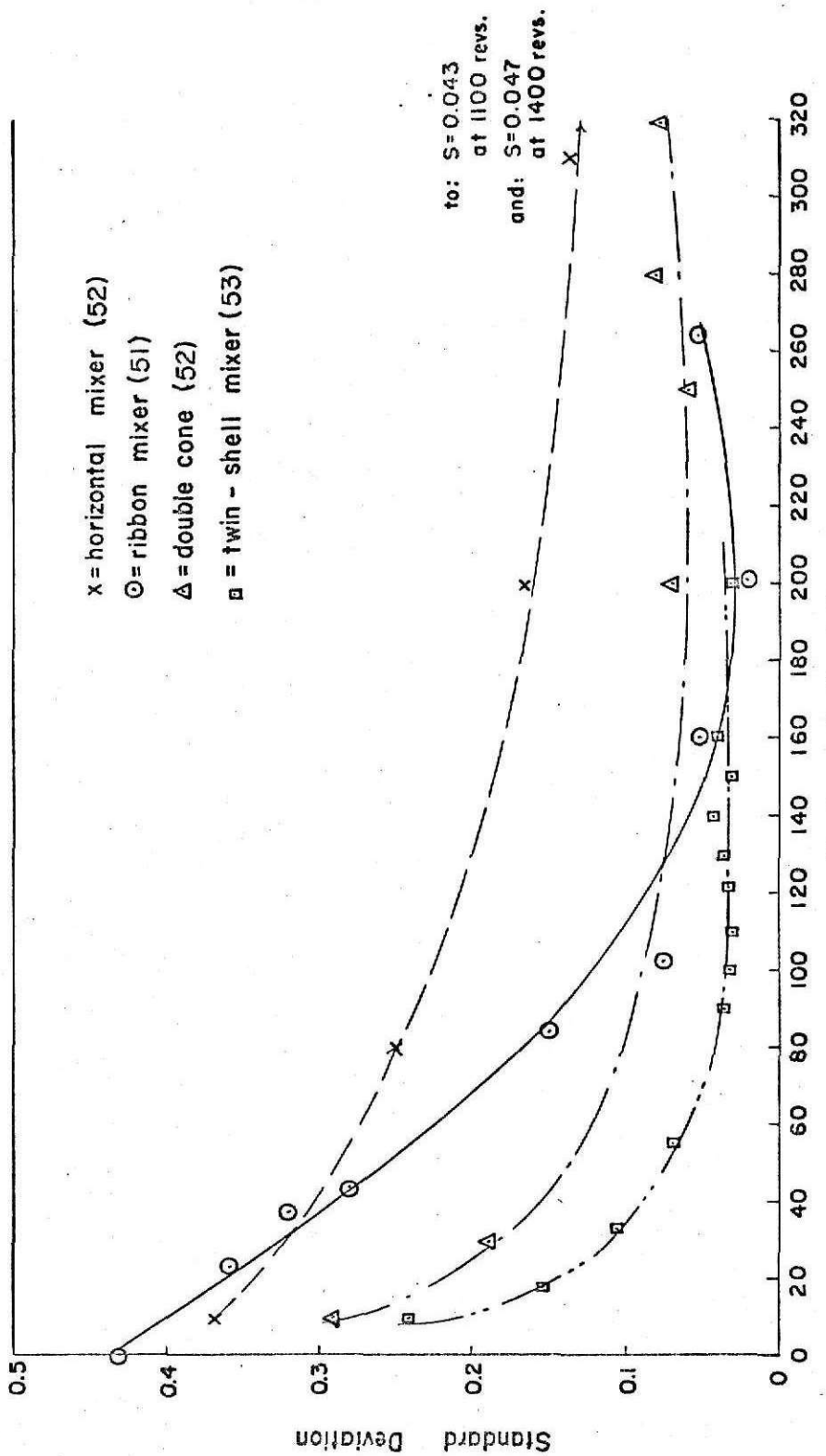


Fig. 27 Comparison of performances of several mixers.

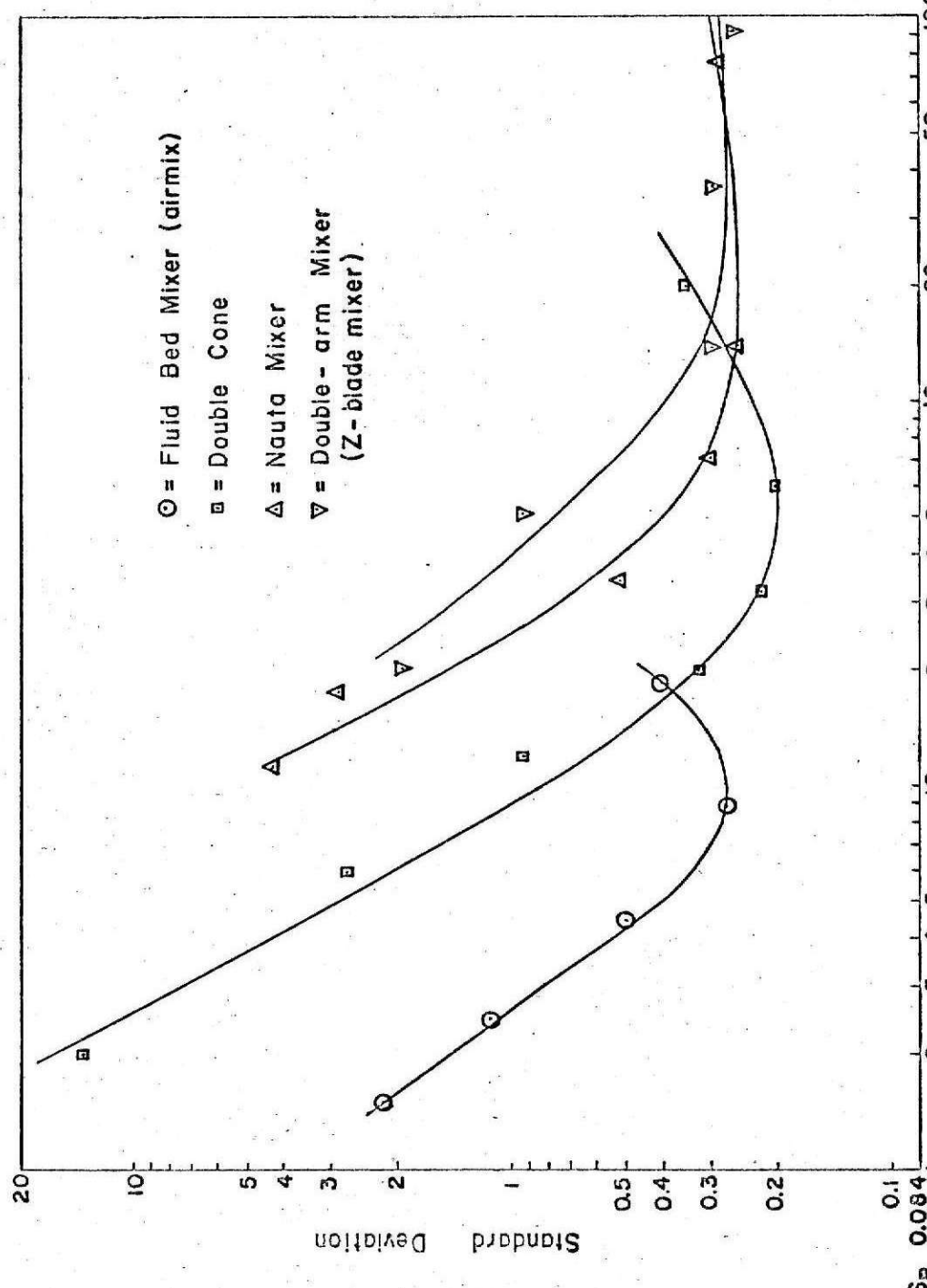


Fig. 28 Comparison of mixers for mixtures of 1:1 sand-calcite (2).

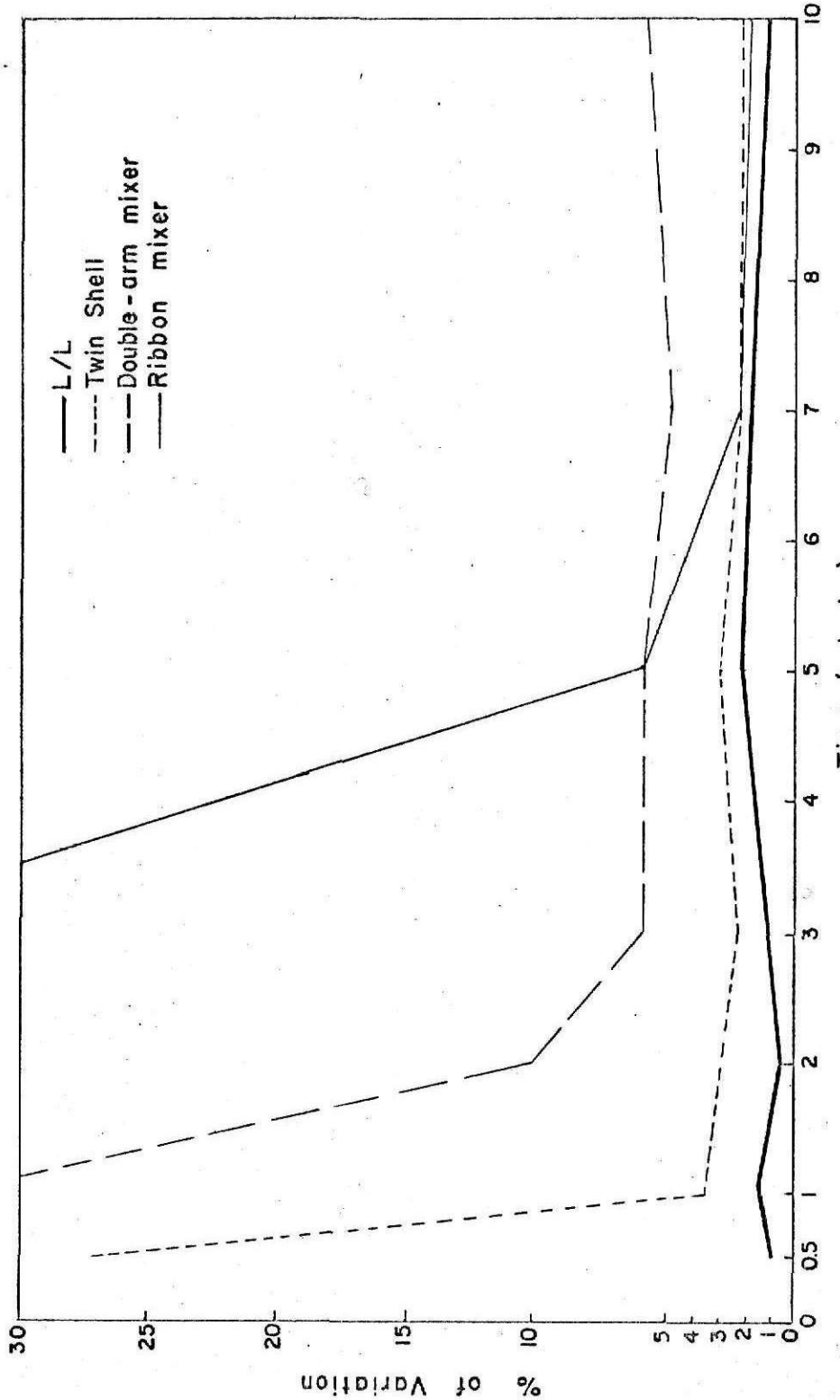


Fig. 29 Performance of several mixers from Littleford bulletin (33).

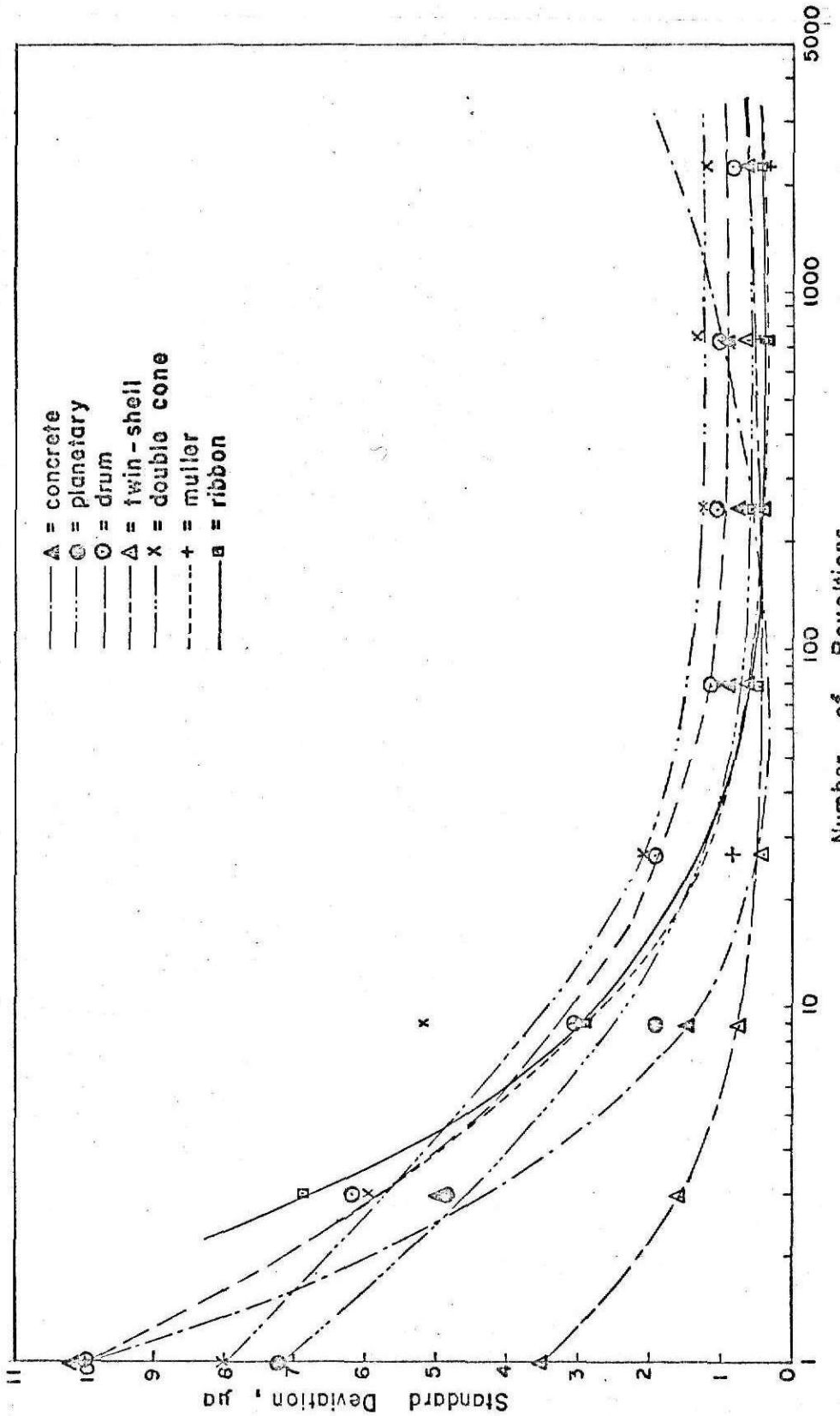


Fig. 30 Mixing comparison with different mixers (23).

Table 2 and Fig. 22 show the performance of horizontal cylinder and inclined cylinder with layer by layer loading. It is obvious that the mixing with layer by layer filling is faster than end to end filling. There is no large difference between the mixing of horizontal and inclined cylinder and no difference between the layer loading and side by side loading.

Solids-mixing with a double cone mixer (Table 3 and Fig. 24) designed with a baffle did not improve the performance to any extent. However, layer by layer loading increased the rate of mixing action considerably. The rate of mixing with side by side filling was low compared with that of layer loading type.

The performance of a twin-shell mixer as shown in Table 4 and Fig. 25 indicated that layer by layer loading is advantageous, and no segregation appeared due to density or particle shape difference.

The effect of different properties of the components on the solids mixing by the same Lodige mixer is shown in Table 5 and Fig. 26. Free-flowing materials mixed faster and gave rise to a better degree of mixing than the urania-nickel or urania-thoria system. Agglomerating (urania-nickel system) or cohesive (urania-thoria system) tendency of these ingredients prevented the mixture from reaching a random state. The performance data of a planetary mixer by Hersey (4) are not sufficient for a detailed analysis. Both authors selected components with a size distribution and determined the values of random standard deviations by utilizing the modified

Stange's equation (37).

D. Comparison of Several Mixers

Japanese investigators (51, 52, 53) carried out systematic experiments to study the performance and factors affecting the solids mixing of different mixers. Their performance data were tabulated in Table 6 and Fig. 27. It is apparent that the drum mixer had very slow mixing action and led to a low degree of mixing. The twin shell had the fastest mixing rate and yielded the best final mixture among the four mixers. In fact, segregation occured after a certain mixing time when a ribbon mixer was used.

Ashton and Valentin (2) studied the performance of double cone, Airmix, Nauta and double-arm mixers. Their data are summarized in Table 7 and Fig. 28. Apparently segregation occurred in the airmix and double cone mixers after best mixing, i.e., the minimum standard deviation was reached. Rates of mixing were in the following order - Airmix (fastest); double cone; nauta mixer; and double-arm mixer (slowest).

Another comparison is given in Lodige Mixer's bulletin (33). The components used in the experiments were Terra Alba ($CaSO_4$, $2H_2O$) and Salicylamide (39 : 1) with 70/100 mesh (210 - 149μ) size. Each sample contained ten spot samples. The performance results are shown in Fig. 29.

Gray (23) investigated and compared the mixing of solids of different particle sizes and densities for seven solids-mixers (Table 8 and Fig. 30) using a sampling probe which

measured the intensity of light reflected from a layer of particles immediately outside the lucite window. Only the concrete mixer (baffled cylinder) showed strong demixing effect due to size and density difference. The ribbon and muller mixers gave almost the same performance except at the first period while the double cone, drum and planetary mixers performed similarly. Gray (23) showed that segregation in a twin-shell mixer due to size and density difference can be eliminted by using sticky components.

The performance data on the various mixers cited above (51, 52, 53, 2, 33, 23) have been compared by three methods. First, values of the minimum standard deviation (S_{min}) of the mixers were compared. The lower the minimum standard deviation, the higher the uniformity of composition of the mixture. Second, compare the rate of mixing for solids-mixers by checking the number of revolutions (R_{min}) or time (θ_{min}) required to reach the minimum standard deviation described above. The less the time or number of revolutions, the faster the mixing action. Third, compare the final state of mixtures by checking the steady or last values of standard deviation (S_f). A lower final standard deviation corresponds to a better degree of mixing. All results are listed in Table 9.

In summary, the comparison of mixing equipment is complicated because their performances are characterized not only by the mixing rate but also by the degree of mixing. The mixer which gives a fast mixing may not yield an intimate

Table 9. Comparison of the Performances of Different Solids Mixers

Yano, Sano, Shirakawa, and Tominaga (51), Yano, Kanise, Hatano and Kurahasi (52), and Yano, Kanise, Tanaka, and Kurahasi (53):

Name of Mixer	S_{min}	R_{min}	S_f
ribbon mixer	0.03	200	0.05*
twin-shell	0.035	110	0.035
drum	0.043	1100	0.045
double cone	0.061	200	0.07

Ashton and Valentin (2):

Name of Mixer	S_{min}	θ_{min}	S_f
double cone	0.2	5.1	0.405
Nauta mixer	0.258	15.0	0.3
Airmix mixer	0.273	0.95	0.35
double-arm	0.273	32.0	0.282

Littleford-Lodige mixer's bulletin (33):

Name of Mixer	S_{min}	θ_{min}	S_f
Lodige mixer	0.6	2	1.3
ribbon mixer	1.8	11	1.8
twin-shell	2.4	3	2.2
double-arm	5.0	7	6.0

Table 9. Con't

Gray (23):

Name of Mixer	S_{min}	θ_{min}	S_f
concrete mixer	0.35	60	1.7*
twin-shell	0.4	80	0.62
ribbon mixer	0.4	400	0.4
muller	0.4	400	0.4
planetary	0.6	300	0.6
drum	0.95	300	0.95
double cone	1.25	300	1.25

* Value which is not definite because of strong demixing.

final mixture and vice versa. Even if the mixer can achieve good mixture in a short mixing time, it does not prove that the final mixture is intimate and well mixed unless segregation does not appear after an extended operation in spite of size, density or shape differences of the materials being mixed. Both mixing rate and mixing degree depend upon the type of mixer and its characteristics; components being mixed and their properties; and the fraction and mode of the loading. Also, some mixers are designed orginally for special purposes such as the muller for the foundry and sand industry etc. It is hard to compare the mixers studied by different investigators because different components with various properties, mixers with different features and operating conditions, and even different types of feeding as well as sampling methods have been used.

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SYSTEMATIC REVIEW OF SOLIDS MIXERS AND THEIR PERFORMANCES

by

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AN ABSTRACT OF A MASTER'S REPORT

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Characteristics of twenty solids-mixers which include eighteen batch mixer - planetary mixer, helicone mixer, double-arm mixer, pan-type compulsory mixer, Marion mixer, drum mixer, double cone, twin-shell mixer, Muller, mill, ribbon mixer, vertical spiral mixer, Nauta mixer, Banbury mixer, Airmix mixer, Lodige mixer, gravity mixer and vibratory mixer and two continuous mixer - Farrel continuous mixer and continuous tumbling mixer were reviewed systematically in detail. The performance of solids-mixers - horizontal cylinder (drum), double cone, twin-shell mixer, Lodige mixer and planetary mixer was discussed respectively from Figures which were drawn from all the possible collected experimental data obtained by different investigators and by using the same expression, i.e., standard deviation against the number of revolutions of the mixer according to the type of mixing equipment. The performance data of different solids-mixers were compared based on three criteria - state of best mixture (minimum standard deviation), rate of mixing (time or number of revolutions required to reach the best mixture), and appearance of final mixture (steady or last value of standard deviation). The factors affecting both degree and rate of mixing were summarized.