Chemical
Specialized drying processing equipment

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Drying is widely applied in the process industries, and yet not explored. Unlike other unit operations, drying has not yet been reduced to a universal computerised design procedure. Drying is still an art. The variety of available dryers was developed, to match, in one way or another, the specific drying characteristics of the products to be dried. A unique group of dryers, not widely known among the academia and industries, are the specialised contact single-shaft or twin-shaft kneaders-dryers.
This lecture concisely reviews the development and evolution of specialised contact kneaders-dryers, presents the field of their application, defines the selection criteria, describes a basic design procedure, and closes with a list of parameters, that helps one to decide between the implementation of a batch or a continuous operating dryer.

INTRODUCTION

Specialised contact kneaders-dryers are applied to dry materials that exhibit a multiple phase change while the contained volatile components are evaporated. During drying, a multiple phase change is manifested by the gradual but continuous change of the rheological consistency of the process material from liquid, to highly viscous, pasty, and eventually but not necessarily to a free-flowing solid. Further more, a multiple phase change is often coupled with side effects like foaming, stickiness or crust formation, difficult product flow in the process chamber of the dryer, fluctuation of product temperature and power uptake.

Regarding the drying operation, phase changes primarily influence the heat and mass transfer phenomena and consequently the specific drying capacity, or the drying time, but also the uniform product distribution in the process chamber of the dryer, and the product homogeneity. Such difficult drying processes are feasible only if dryers are available that with their design features would match the complex needs of drying sticky, pasty, or crust forming products. Table 1 shows the corresponding match between the complex needs of such drying processes and the design features of the specialised kneaders-dryers.

Table 1. Drying Process Requirements and Features of Specialised Kneaders-Dryers

Process Requirements	Functions	Features
1. To process multiphase changes in a single unit 2. Efficient mass transfer 3. Permit flash evaporation of superheated feed stocks, ensure low vapour velocities, prevent entrainment 4. Processing of product with viscosities up to $5 \cdot 10^4$ Pa·s	Mechanical	1. Intermeshing of static and rotating elements, adjustable internal geometry 2. High interface renewal rate 3. Large cross-sectional area 4. Heavy duty design, specific torque up to 40 Nm/l
1. Close control of product temperature; high energy flux	Thermal	1. Large self-cleaning heat exchange surfaces

1. Long residence time for slow, diffusion controlled drying 2. Vacuum or pressure operation, handling of toxic, flammable, or hazardous materials 3. Handling of corrosive or abrasive products 4. Integration with up-stream and down-stream process steps	Operational	1. Large useful volume 2. Closed, contained construction 3. Welded design in any weldable material of construction, provision of wear protection 4. Units for batch or continuous operation

DEVELOPMENT AND EVOLUTION

Till the late sixties there existed no dryer, who could fulfill these features. Due to the lack of specialized drying processing equipment, leading manufacturers of dyestuffs and pigments, specialty chemicals and intermediates for pharmaceuticals applied shelf type batch dryers, spray dryers, batch paddle dryers, or continuous submerged disc dryers, the latter with recycling of dry material into the wet feed stock. The recognition of the gap within the drying processing equipment lead to the very first development of the unique All-Phases Continuous twin-shaft contact kneader-dryer (Figure 1). His first appearance on the European market was in 1970. In 1975 followed the DISCOTHERM B Continuous single-shaft contact kneader-dryer (Figure 2). To date there exist no comparable single-shaft indirect kneader-dryer to DISCOTHERM B. As twin-shaft contact kneader-dryers are available the Co-Rotating Processor, the Opposite-Rotating Processor, and the E.f.C.I. dryer.

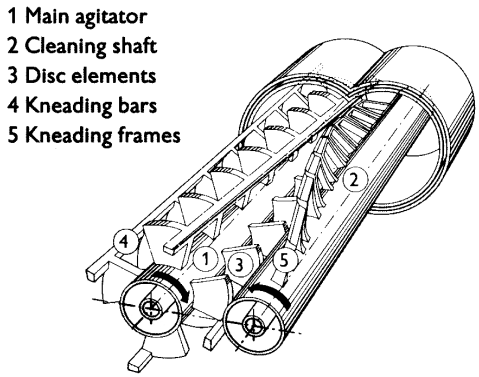

Figure 1. All-Phases Kneader-Dryer

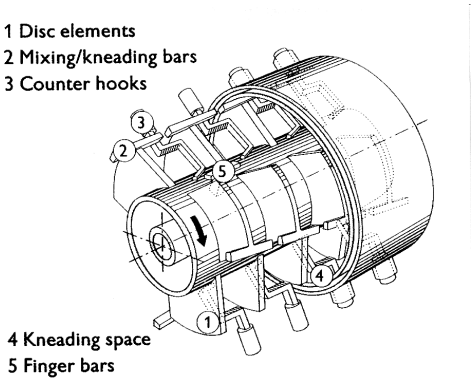

Figure 2. DISCOTHERM B Kneader-Dryer

The common characteristics of the specialised drying processing equipment are the agitation and the self-cleaning effect. Agitation improves the rate of heat transfer, and consequently the rate of drying. The provision of small clearances between static and rotating parts, the installation of intermeshing static parts, or the application of two intermeshing shafts, ensure the self-cleaning effect of the heat exchange surfaces, the frequent interface renewal, and the homogenisation of the process mass with respect to volatiles content and temperature. Though such types of dryers would not forcibly be

seen as mixers, their mixing and homogenisation efficiency is remarkable. Differences are also noted between the various specialised indirect kneaders-dryers. They are mainly found in the internal geometry of the shafts. In models where two shafts are installed the differences are limited to the sense of rotation, i.e., co-rotating, or opposite rotating, and the speed ratio between the two shafts, i.e., 1 to 1, 1 to 2, 1 to 4, 4 to 5, or 1 to 3.

FIELD OF APPLICATIONS

The first application of the kneaders-dryers was in the fine chemicals industries followed by the dyestuffs industries. In the mid seventies followed the drying of polymer granules and industrial residues. In the early eighties were realised the first drying applications for pharmaceutical intermediates. It was interesting to observe that the majority of the processes took place under vacuum, whether in continuous or batch mode operation. Is also important to mention that continuous vacuum drying processes were realized thanks to the provision of special lock feed and discharge systems. These systems allowed the continuous feeding of the wet feed stock into vacuum and the discharge of the dry final product from vacuum to atmospheric pressure with simultaneous cooling.

It is also necessary to explain the name kneaders-dryers. It was realized that in contact drying of materials, going through a pasty and sticky transition phase, the heat and mass transfer would soon cease without efficient kneading. The kneading action is generated when the rotating shaft intermeshes with the static parts, which are positioned in the inner surface of the process chamber of the dryer, or, in case of a twin-shaft dryer, when the two shafts intermesh along the central axis of the process chamber of the dryer. The kneading action is particularly accentuated when polymers are dried. Under the kneading action it is developed the necessary active surface renewal, which in turn improves the drying rate.

POSITIONING OF THE KNEADERS-DRYERS

The specialized indirect kneaders-dryers were developed to fill up the processing equipment gap between kneaders and screw-type machines on one hand, and on the other hand conventional paddle or disc dryers. Kneaders and screw-type machines have relatively small working volumes and heat exchange surfaces. Paddle, or disc dryers have larger working volumes and heat exchange surfaces but lack a kneading effect and self cleaning of heat exchange surfaces. The specialized kneaders-dryers combine the effective mixing kneading action of kneaders and screw-type equipment (specific kneading energy up to 0.25 kWh/kg), with the large working volumes and heat exchange surfaces of the paddle or disc dryers. Figure 3 shows the positioning of the specialized kneaders-dryers.

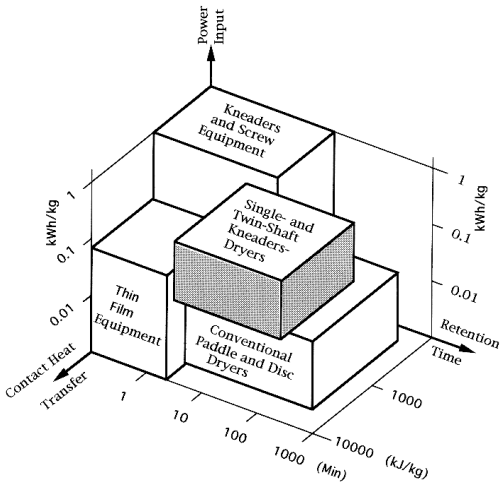

Figure 3. Positioning of Kneaders-Dryers

SELECTION CRITERIA

The selection of a specialized contact kneader-dryer is justified when a conventional dryer would not fulfill the process and product constrains. The careful consideration to implement a contact kneader-dryer limits considerably the number of applications of these specialized processing equipment.

Prior to commenting on the selection criteria is important to consider the definition of the drying process. Drying is understood as the unit operation whereby, through heating, a volatile component, or a mixture of volatiles, is evaporated from a non-volatile material, producing a final product relatively or completely free of volatile(-s). The volatile(-s) component(-s) can be organic or water and the final product may be of powdery, granular, pasty, or viscous consistency. Based on this broader definition of the drying process, the selection criteria are given in Table 2.

Table 2. Selection Criteria for Specialized Contact Kneaders-Dryers

Criterion
1. Good mixing / kneading action in all phases; surface renewal in viscous and pasty phases; crushing of agglomerates
2. Retention time ≥ 10 min. allowing implementation of slow diffusion limited final drying periods
3. Under pressure or vacuum operation; closed design
4. Intensive heat exchange for sticky and crust forming products
5. High bulk density of the final product
6. Plug flow conditions; product quality

DESIGN PROCEDURE

The design procedure of a specialized drying processing equipment is the proprietary Know-How of the manufacturer. Though attempts have been made to simulate the heat transfer during drying, the developed penetration theory was successfully applied only to particulate materials (Tsotsas, 1984) and recently for pastes (Dittler, 1997). However, the reliable basis for the design is provided from pilot tests with one's representative product applying the specific type of dryer. Some guiding principles are given here contributing to the design calculation of the heat exchange surface, the volume of the dryer, and the installed power of the drive unit. A reasonable preliminary design calculation requires the provision of key data concerning the product to be dried (Table 3), the operating conditions (Table 4), and available energies on site. If available, it is also helpful to have drying data from existing full-scale operating dryers.

Table 3. Key Data of the Product to be dried

Data	Feed	Wetting Component(-s)	Product
1. Composition of feed and product streams	required		required
2. Wetting component(-s) content	required		required
3. Free, bound, and crystalline water content, sorption isotherm	required		required
4. Specific gravity, bulk density	desired	desired	desired
5. Specific heat	required	required	required
6. Melting and softening point, sensitivity to heat	required		required
7. Explosive limits	required	required	required

8. Boiling point		required	
9. Heat of vaporization		required	
10. Consistency, flow properties, tendency to adhere	required		required
11. Plastification by shearing effects	if applicable		if applicable

Table 4. Operating Conditions

Parameter	Comment
1. Mode of operation; number of shifts per day	1. Continuous or batch
2. Hourly or daily capacity	2. Feed rate (continuous) or batch size (batch)
3. Operating pressure	3. Under pressure, vacuum, or atmospheric
4. Protection against explosive hazards	4. Electric installations
5. Multipurpose character; product changes	5. Of interest for batch dryers

Once these data are known, the design basis is defined and the total heat exchange surface can be calculated using equation 1, where $\dot{Q}$ is the sum of heat flows as given by equation 2.

$$\dot{Q} = \tilde{U} * A * \tilde{\Delta T} \quad (1)$$

$$\dot{Q} = \dot{Q}_{heat\text{-}up} + \dot{Q}_{evap} + \dot{Q}_{acc} - \dot{Q}_{mech} \quad (2)$$

The mean overall heat transfer coefficient, $\tilde{U}$, needs to be measured experimentally. Nevertheless, some guiding values of this parameter are given (Table 5), depending on the consistency of the product to be dried.

Table 5. Guiding Values of the Mean Overall Heat Transfer Coefficient - $\tilde{U}$

Product consistency	$\tilde{U}$ - value, in $W/m^2 \bullet K$
Free flowing, granular, powdery	30 to 100
Pasty, highly viscous	80 to 180
Pumpable low viscosity fluid	100 to 400

These values may only be applied for preliminary design calculations. When crust formation occurs $\tilde{U}$-value as low as 20 $W/m^2 * K$ have been measured. To systematically investigate the phase changes of a product being dried, and in order to measure the range of the $\tilde{U}$-values, it is recommended to perform batch drying pilot tests.

The actual design, however, would explicitly consider the various heat flows as defined under equations 3 to 6.

$$\dot{Q}_{heat\text{-}up} = \left[\dot{m}_s * c_{ps} + \sum_1^j \dot{m}_{l_j} * c_{pl_j}\right] * \Delta T_1 \quad ; \quad \Delta T_1 = T_{bpl_j} - T_f \tag{3}$$

$$\dot{Q}_{evap} = \sum_1^k y * \dot{m}_{l_k} * \Delta h_{vl_k} \quad ; \quad y \le 1 \text{ and } k \le j \tag{4}$$

$$\dot{Q}_{acc} = \left[\dot{m}_s * c_{ps} + \sum_1^k (1-y) * \dot{m}_{l_k} * c_{pl_k}\right] * \Delta T_2 \; ; \; \Delta T_2 = T_p - T_{bpl_k} \text{ and } k \le j-1 \tag{5}$$

$$\dot{Q}_{mech} = \frac{1}{cf} * M_d * n \quad ; \quad cf = \text{conversion factor} \tag{6}$$

Additionally the mode of operation of the dryer, whether continuous or batch, should also be taken into account. For the continuous mode of operation the dryer could be seen as consisting of three consecutive sections, i.e., the heating-up, the main evaporation, and the final evaporation section. These sections can be explicitly investigated during pilot testing, the mean $\tilde{U}$ and $\tilde{\Delta T}$ values can be deduced, and the total heat exchange surface can be calculated as follows:

$$A = \sum \left(\frac{\dot{Q}_{heat-up} - \dot{Q}_{mech}}{\tilde{U}_{heat-up} * \tilde{\Delta T}_{heat-up}} + \frac{\dot{Q}_{evap} - \dot{Q}_{mech}}{\tilde{U}_{evap} * \tilde{\Delta T}_{evap}} + \frac{\dot{Q}_{acc} - \dot{Q}_{mech}}{\tilde{U}_{acc} * \tilde{\Delta T}_{acc}} \right) \tag{7}$$

For the batch mode of operation the limiting parameter is the net batch time, i.e., the time required for the drying operation excluding the time to charge and discharge the dryer. Therefore, the heat exchange surface of the batch dryer has to be accordingly selected in order to match with the net batch cycle.

$$t_{net\ batch} = \sum \frac{1}{A} * \left(\frac{Q_{heat-up} - Q_{mech}}{\tilde{U}_{heat-up} * \tilde{\Delta T}_{heat-up}} + \frac{Q_{evap} - Q_{mech}}{\tilde{U}_{evap} * \tilde{\Delta T}_{evap}} + \frac{Q_{acc} - Q_{mech}}{\tilde{U}_{acc} * \tilde{\Delta T}_{acc}} \right) \tag{8}$$

The mean overall heat transfer coefficient, as defined by equation 9, is particularly sensitive to the thickness of the crust (δ_{crust}) formed on the heat exchange surfaces. It is on one hand the self cleaning effect of the internals of the specialized kneaders-dryers, and on the other hand the provision of small clearances between rotating and stationary parts, that limits the negative effect of the crust formation. A positive effect on the mean overall heat transfer coefficient has the speed of rotation. Investigations with wet particulate materials showed a linear relationship between mean overall heat transfer coefficient and speed of rotation. The positive effect of the speed of rotation becomes important at low moisture contents.

$$\frac{1}{\tilde{U}} = \frac{1}{\alpha_i} + \frac{\delta_{crust}}{\lambda_{crust}} + \frac{\delta_{wall}}{\lambda_{wall}} + \frac{1}{\alpha_a} \quad (9)$$

The volume of the dryer is a secondary parameter, though directly correlated with the heat exchange surface. For each heat exchange surface is defined a volume. There exists no degree of freedom. The volume of a dryer is important for continuous drying processes. It defines the residence time of the process product, which can be a limiting parameter for either temperature sensitive materials, or diffusion controlled drying processes, or often for both. The residence time is defined by equation 10.

$$\tau = \frac{V * \varphi * \left(\rho_f + \rho_p\right)}{\left(\dot{m}_f + \dot{m}_p\right)} \quad ; \quad 0.4 \le \varphi \le 0.8 \quad (10)$$

In equation 6, the torque (M_d) can be hardly estimated. This parameter is rather measured by pilot tests on the specific type of dryer. However, the viscosity of the product to be dried should be known as a function of shear rate at different temperatures. The following principle function applies:

$$M_d \propto f\left(\text{hold up}, \eta, \dot{\gamma}, n, \text{geometry / type of dryer}\right) \quad (11)$$

Should the product adhere on the heated surfaces, the torque, and consequently the dissipation energy due to friction, though considerable, can only be determined with pilot tests. If free flowing particulate products are dried in large drying units the torque can be calculated according to the following formula:

$$M_d = F_{frictions} * \frac{D}{2} \quad (12)$$

In conclusion the reliable way to measure the torque, and to consider the torque variations over the entire drying step, is the execution of pilot tests with one's representative product. The installed drive power is calculated by:

$$P = \frac{M_d * n}{cf * \eta_{eff}} \quad ; \quad cf = \text{conversion factor} \quad \text{and} \quad \eta_{eff} = \text{motor efficiency} \quad (13)$$

The influence of the torque on the overall energy balance and on the product temperature is shown in Figures 4 and 5. Figure 4 shows the combined process of cellulose slurry drying and its simultaneous dissolution in NMMO (N-Methylmorpholin-N-Oxide). Cellulose slurry, a pulpy mass of cellulose in NMMO water solution, is continuously fed into a single-shaft contact kneader-dryer where is dried to a final water content of 12% by weight. During drying the NMMO concentration increases leading to the dissolution of cellulose. The product is temperature sensitive but also the NMMO is an explosion hazard. Hence the process must be temperature controlled. Extensive pilot tests showed that the torque is contributing some 20% to 55% to the necessary energy input. Taking this into consideration the dryer needs to be carefully heated in order to prevent temperature overshooting.

Figure 5 shows the vacuum drying of a plant extract. The feed stream is a 45% water solution of low viscosity. The plant extract must be dried to the final moisture content of 3% by weight. The product temperature may not exceed 70°C. Drying is accomplished under vacuum and heating temperature of 80°C. During drying the consistency of the process mass changes from liquid to viscous paste before becoming a powdery free flowing dry product. The phase changes can be easily seen following the evolution of the torque curve. The influence of the torque on the product temperature is also clearly shown. In order to avoid excessive overshooting of the product temperature both the heating temperature and the shaft speed was reduced. This complex drying behaviour can hardly be predicted so that the design of a full-scale dryer must be based on pilot tests.

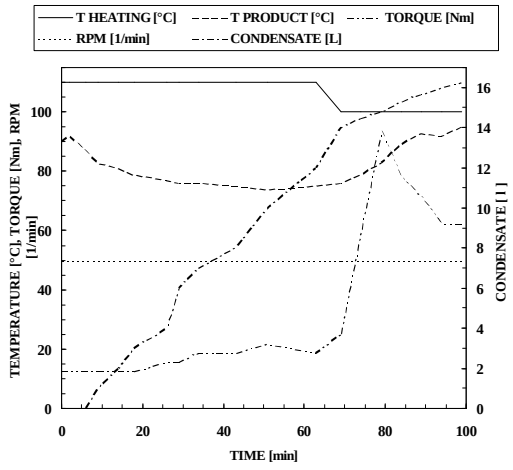

Figure 4. Cellulose Drying/Dissolution

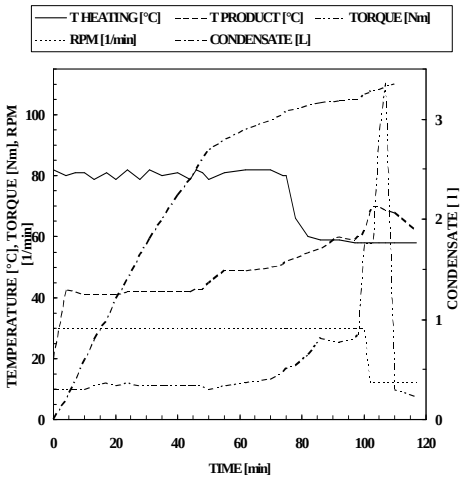

Figure 5. Vacuum Drying of Plant Extract

CONTINUOUS OR BATCH MODE OF OPERATION

Table 6 lists the parameters, which lead to the selection of a continuous or batch operating contact kneader-dryer. However, these criteria can also be applied to non specialized drying processing equipment.

Table 6. Selection Criteria for Batch or Continuous operating Contact Kneaders-Dryers

Parameter / Criterion	Batch Operation	Continuous Operation
1. Final product is : a/ Viscous or pasty b/ Free flowing	a/ Not recommended, difficult to discharge b/ Recommended	a/ Recommended b/ Recommended
2. Operating pressure a/ under pressure b/ under vacuum	For either operating pressure simple feed and discharge systems, low investment	For either operating pressure are necessary specialized feed and discharge systems, high costs
3. Highly viscous phase	Not recommended because heavy duty drives necessary with high energy consumption	Recommended because lower duty drives necessary with less energy consumption
4. Processing capacity	For low to moderate capacities	For moderate to high capacities

5. Shift operation (1-2 per day)	Possible, flexible, recommended	Not recommended
6. Multipurpose	Recommended, can handle various products	Not recommended because not easily adjustable to various products

LITERATURE CITED

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Dittler, A., Bamberger, T., Gehrmann, D., Schlünder, E.U., Measurement and simulation of the vacuum contact drying of pastes in a LIST-type paddle dryer, 1997, Chem. Eng. Proc., (36), pp 301-308.

NOTATION

A	heat exchange surface	m^2
c_p	specific heat	$kJ/(kg \bullet K)$
D	diameter	m
Δh_v	heat of vaporisation	kJ/kg
F	force	N
M_d	Torque	Nm
$\dot{m}$	mass rate	kg/h
n	speed of rotation	min^{-1}
P	power	kW
$\dot{Q}$	heat flow	W
t	time	h
T	temperature	K
ΔT	temperature difference	K
U	overall heat transfer coefficient	$W/(m^2 \bullet K)$
V	equipment volume	m^3
y	mass fraction	-

Greek letters

α	heat transfer coefficient	$W/(m^2 \bullet K)$
$\dot{\gamma}$	shear rate	s^{-1}
δ	thickness	m
η	viscosity	$Pa \bullet s$
η_{eff}	efficiency	-
λ	thermal conductivity	$W/(m \bullet K)$
ρ	bulk density	kg/m^3
τ	residence time	h
φ	fill level	-

Subscripts and superscripts

bp	boiling point
cf	conversion factor
f	feed
hm	heating medium
l	liquid
p	product
s	solid
~	mean value

Indices

j and k	number ofvolatile components in the feed and vapour stream respectively
i	refers to oil side
a	refers to product side
evap	evaporation
acc	accumulation
mech	mechanical

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