Thermal Dewatering of Waste Sludge in an Agitated Drum Dryer

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Abstract: This study presents experiences of drying waste sludge in an agitated drum dryer. Measurements were performed on an agitated drum dryer apparatus equipped with up-to-date instrumentation. As waste sludge is prone to adhesion and balling, it is important to identify the conditions appropriate for drying. Different cases were examined; during measurements, the rotational speed of the agitator, the quantity and moisture content of the sludge fed in as well as the temperature of the wall and the drying gas were changed. The measurement data were used to represent the temperatures characteristic of drying and the mass changes of the product. Volumetric mass transfer coefficients were determined from the measurements and a modified Sherwood number was derived from them. The dimensionless Sh'-Re' equation enables to dimension agitated drum dryers.

Keywords: agitated drum dryer; Sherwood number; volumetric mass transfer coefficient; waste sludge drying

1 Introduction

Activated sludge treatment of waste water is one of the most wide-spread biological waste water treatment procedures. The apparatus used is a floating bed bioreactor fed on an on-going basis. The biomass substantially remains in the reactor: although some sludge constantly leaves the basin, most of it is fed back in order to ensure an appropriate sludge concentration [1]. The sludge increment is called excess sludge, transport and deposition of which is costly; however, after proper dewatering it can be burnt and thereby it can serve as a basic material for heat and power generation. In order for burning at an adequate degree of efficiency, the maximum moisture content of the product can be 45%, to be achieved by drying. In recent decades, a number of authors have discussed the drying of waste sludge [2, 3]. *Chen et al.* collected and presented devices suitable for dewatering and drying waste sludge in their work [4]. *Stuart et al.* summarized

the benefits and drawbacks of various dryers in their work [5]. Several publications presented the application of recycled cooking oil into a solid sludge as a drying technology [6, 7, 8]. In these cases, used oil was heated up and waste sludge was directly added. By using this procedure, the product can be dried quickly and very efficiently. Drying is a highly energy-intensive process, but waste heat utilizable for this purpose can be found in infinity of cases. In absence of waste heat, an alternative solution is presented in the publications by *Slim et al.*, *Seginer et al.* and *Leon* [9, 10, 11], where drying by solar energy was highlighted. In this procedure, the constant drying parameters cannot be ensured continuously and the quantity of fluid evaporated highly depends on environmental and climatic conditions.

Due to its unfavourable physical properties, waste sludge is difficult to dry in traditional dryers. These materials stick to the wall of the dryer because of their high moisture content and they tend to cake at lower levels of moisture content. The agitated drum dryer with wall heating applied by us reduces unfavourable phenomena occurring in the case of sludge drying; drying tests were performed by in our measurements sludge from a waste water treatment plant [12]. The drying of waste sludge was tested in a similar device by *Ferrasse et al.* [13]. The initial moisture content of the waste sludge examined by us was approx. 80%, while the final moisture content was required to be 45%. We also performed measurements where the initial moisture content was reduced by backmixing dry matter, in a similar fashion to *Léonard et al.* [14]. Drying gas speed was selected for our measurements so that the dried product should not be carried away – or only negligibly – by the gas flow. In order to specify the geometry of the dryer (diameter, length), mass transfer properties are required, which can be determined by experiments. By reason of the characteristic of a mixed conglomerate, the surface of heat and mass transfer is not known, therefore a volumetric evaporation coefficient widely accepted in the literature was specified. In the course of their calculations, *Léonard et al.* referred the contact area between the gas and the product to the initial external area [15].

The aim of the article is to create a modified Sherwood number was derived from volumetric evaporation coefficients and plotted against a modified Reynolds number providing a correlation suitable for dimensioning dryers.

2 Experimantal Apparatus, Materials and Methods

2.1 Experimental Apparatus

Experimental tests were performed on the agitated drum dryer shown in *Figure 1*. Within the dryer, heat transmission is not only effected by convection through the drying gas but also by conduction from the mantle of the drum. Drying of the

paste-like waste sludge is considerably accelerated by the application of electric wall heating.

The measurement station was designed for drying paste-like and granular products by simultaneous conductive and convective heat transfer. The measurement station, equipped with up-to-date instrumentation, is also suitable for studying the vary of simultaneous heat and mass transfer. Drum dryer (D-102-01) is the central component of the mechanical system. The dryer of intermittent operation consists of a 765 mm long, 250 mm wide and 275 mm high U-profile drum covered by a plain plate. The drying gas is fed in axially and is removed through the pipe end on the plain cover of the equipment. The lower, semi-cylindrical surface of the drum is equipped with controllable electric wall heating. The paste-like product in the dryer is moved by a special agitator scratcher driven by an electric motor (M-102-03). The rotational speed of the agitator can be adjusted by a continuous frequency converter within a broad range (0÷95 1/min) (SIC-102-07). The drum dryer, as well as the electric motor and driving gear to drive the agitator are mounted on the same framework structure. The apparatus stands on a scale (S-102-02), of Sartorius IS 300 IGG-H type, with a maximum capacity of 300 kg and accuracy of 2 g.

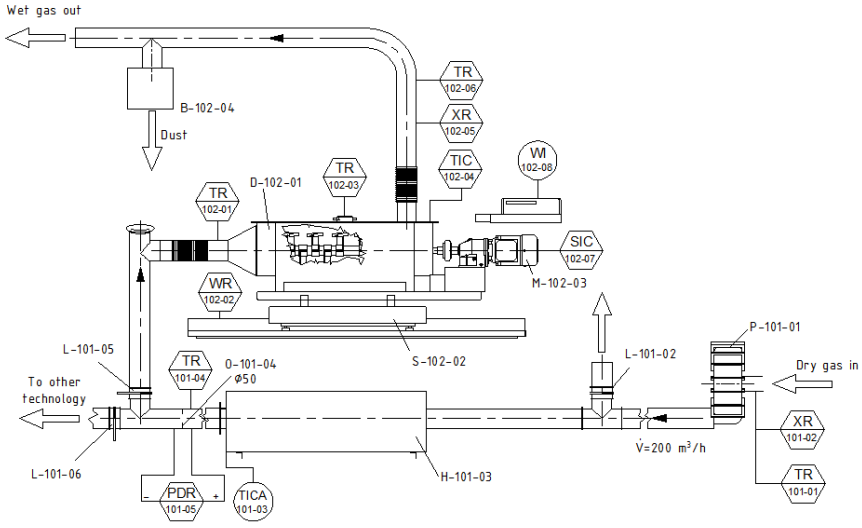

Figure 1

Instrumentation of agitated drum dryer measurement station

D-102-01: Drum dryer; M-102-03: Motor with driving gear; H-101-03: Electric air heater; P-101-01: Air blower; S-102-02: Scale; L-101-02: Volumetric flow rate controller; B-102-04: Dust separator

The drying gas is heated by an electric air heater (H-101-03) equipped with a temperature controller (TICA-101-03). The volumetric flow of the drying air, moved by an Effepizetta SCL-SH65 fan (P-101-01), can be modified by a gap controller (L-101-02).

In order to determine the volumetric flow of the drying gas, the pressure drop of the drying gas at a standard measuring orifice and its temperature were measured. Measurements included the temperature of the gas entering (TR-102-01) and exiting (TR-102-06) the drum, as well as the wet bulb temperature of the exiting gas (XR-102-05), wherefrom the exit moisture content of the gas can be determined. The surface temperature of the product to be dried was measured in the middle of the dryer longitudinally by an infrared thermometer (TR-102-03). Decrease in the wet product mass in the dryer (WR-102-02) was continuously measured and recorded by a data logger. The moisture content of the incoming gas (XR-101-02) and the environmental temperature (TR-101-01) were also measured. The dryer drum can be heated electrically from the mantle side, its temperature can be kept at a given value by an automatic controller. Wall temperature was measured at 2/3 of the length of the drum (TIC-102-04).

In order to record the parameters of drying, sensors were connected to an Almemo 2590-9 type Ahlborn data logger instrument which recorded the values measured at 10-second intervals. The data recorded by the data logger were used for plotting changes in the wet product mass and the changes of temperatures (gas at entry, gas at exit, wall, and product) in the function of drying time.

2.2 Materials and Methods

Measurements aimed to test the drying properties of sludge and to identify parameters favourable to drying. The impact of the initial moisture content of the sludge on drying, wall heating temperature and rotational speed of the agitator were examined. *Table 1* summarizes measurements with different drying parameters, where the drum loading factor (l) can be defined as follows:

$$l = \frac{V_P}{V_D} \tag{1}$$

Table 1
Values measured

No.	$T_{G,in}$	Y_{in}	$\dot{m}_G$	T_W	n	$m_{P,in}$	l	$x_{P,in}$	$x_{P,out}$
	[°C]	[g_{wa}/kg_{dG}]	[kg/h]	[°C]	[1/min]	[kg]	[-]	[kg_{H2O}/kg_P]	[kg_{H2O}/kg_P]
1	100.7	5.0	239.3	80.0	38	5.19	0.16	0.831	0.507
2	100.7	4.1	185.4	67.1	50	7.84	0.21	0.810	0.509
3	110.9	9.7	150.9	70.6	28.5	5.52	0.15	0.799	0.478
4	110.2	13.4	183.5	72.7	28.5	5.47	0.15	0.796	0.465
5	110.5	9.1	168.4	80.4	38	5.07	0.14	0.612	0.216
6	110.3	10.6	167.9	87.8	38	5.56	0.17	0.821	0.284
7	110.3	9.4	166.8	65.4	38	8.33	0.22	0.782	0.212
8	110.3	8.6	166.4	65.4	38	8.28	0.21	0.778	0.284
9	110.1	9.0	166.0	66.3	38	6.19	0.15	0.350	0.185
10	110.1	9.1	166.8	65.8	38	8.10	0.19	0.650	0.288
11	108.7	8.9	166.5	65.1	38	7.82	0.18	0.534	0.221
12	109.1	10.0	167.7	66.1	38	7.09	0.20	0.786	0.476

At measurements No. 1-4, 7, 8, and 12, the product was fed in bulk (*Figure 2*), without any pre-treatment – without grinding and backmixing –, distributed evenly along the length of the apparatus. Measurements differed in the speed of the drying gas and the quantity of the dried product (load level).

Figure 2
Initial waste sludge (No. 1)

At measurement No. 5, the wet product was fed pre-treated – screened/mashed through a plastic sieve of 10x10 mm hole size (*Figure 3*) and backmixed with sludge dried earlier. The granular product was also attempted to be produced by grinding, but it was found that the wet product kneaded and made plastic during grinding compacted again before being fed into the apparatus, thereby breaking into small pieces was unnecessary. As the product tended to stick at this time as well, at measurement 6 it was already fed into the drying chamber with the original moisture content, with dry sludge powder sprinkled over the surface of the wet product screened, thereby reducing the clumping of granules. It was found at these experiments that the dry sludge powder sprinkled over the surface did not affect the process of drying and the end result perceptibly. As a result of mixing, the powder immediately got wet and its properties corresponded to those of the conglomerate. The grinding did not have a perceivable impact on the process of drying as the product gradually got compacted again as a result of mixing.

Figure 3
Sludge mashed through a sieve (No. 5)

As regards temperature curves at experiments No. 1-8, product and wall temperature curves showed irregularities after 40-50 minutes, which came to an end after a while. It can be stated on the basis of visual findings that in this interval the nature of the product changed from plastic into powdery.

At measurement 9, sludge powder dried earlier was dried further on. The measurement was performed in the phase of decreasing drying rate.

Based on the findings of earlier measurements, the initially ointment-like product, sticking both to the wall and the agitator, granulated at approx. 65% moisture content and it stopped sticking. At measurement 10, although the initial moisture content of the product was 65%, it still behaved as a smearing material. In order to avoid this, it was deemed necessary to apply further backmixing to reach lower moisture content values, in the course of which the moisture content of the mix was set lower than 65% (53.4%) at measurement 11. The product was fed into the pre-heated apparatus. First the dry product and then the wet product was filled in. As a result of agitation, the two materials got mixed quickly, and after a short while a granular load was produced. Adhesion of the product to the wall could not be detected. Initially it stuck to the agitator but this soon discontinued. At this measurement we succeeded in producing a non-adhesive load behaving like a granular conglomerate.

Figure 4
Waste sludge in the course of drying (No. 6)

The initially sticky, large-grained waste sludge was transformed into a small-grained powdery material easy to handle (*Figure 4*).

3 Results and Discussion

In the course of measurements, the following parameters were recorded continuously: entry and exit temperatures of the drying gas, the inlet volumetric flow of the drying gas, dryer wall temperature during wall heating, and the surface temperature of the product. Temperatures and product mass changes were

depicted in the function of time on the diagrams included in *Figure 5* in case of four measurements optionally selected. The serial numbers of measurements are shown in the diagram title.

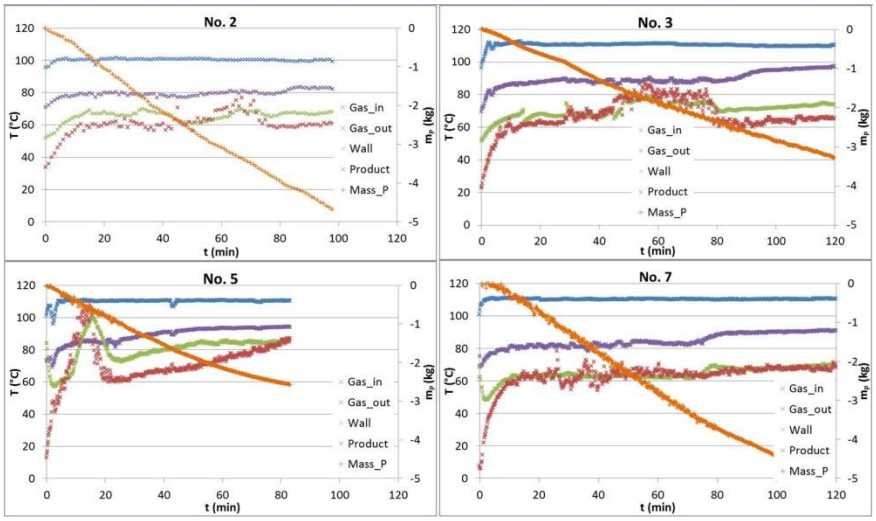

Figure 5
Temperature developments and changes in the mass of the waste sludge in the function of time (diagram titles refer to the serial number of measurements)

The entry temperature of the drying gas and the wall temperature were kept at a constant value, still, temperature fluctuations can be observed in the course of some measurements. The reason for this is that the output of the electric heating unit could not balance the high rate of heat extraction by the wet sludge. As product temperature was measured by an infrared thermometer placed on top of the dryer, it happened that the infrared thermometer would measure the temperature of the wall below it rather than product temperature because of agitation (the product stuck on the agitator or it was carried away from the below the measurement point of the thermometer). In such moments, temperature leaps larger than expected were observed (e.g. between minutes 45-80 in measurement 3). Changes in product moisture content can be calculated from its mass reduction.

Figure 5 clearly shows phases of constant drying rate. At some of the measurements (Nr. 5-9), the drying process reached levels below the critical moisture content of the product. In these cases (e.g. after 50 minutes during measurement Nr. 5), mass change and, as a consequence, the drying rate also reduced.

Drying rate can be calculated by the following correlation:

$$N = -\frac{dm_P}{dt}\frac{1}{A_{G-P}} = -\frac{dX}{dt}\frac{m_{dP}}{A_{G-P}}. \qquad (2)$$

As it is highly uncertain and difficult to determine the contact area of the gas and the product in case of bulky and granular materials, the diagrams show – instead of the drying rate – the $\frac{dm_P}{dt}$ ratio proportionate therewith. *Figure 6* shows mass reduction rate in function of product moisture content in case of the four measurements selected. The diagrams show the phases of constant and falling drying rates, respectively.

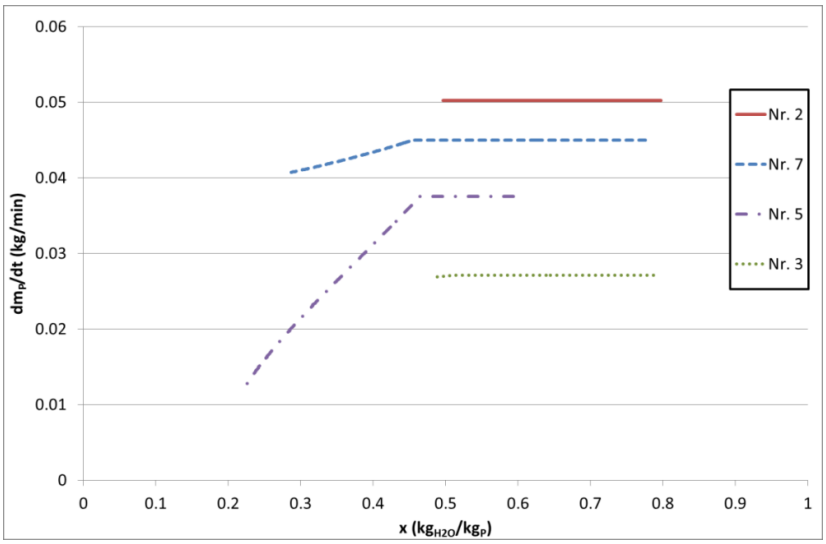

Figure 6

dm_P/dt in function of product moisture content in case of the four measurements selected

VOLUMETRIC EVAPORATION COEFFICIENT

The dryer can be dimensioned for operation by using the differential equation to describe changes in the temperature and moisture content of the drying gas [16]. In order to apply this differential equation system, it is essential to know the heat and mass transfer coefficients. By reason of the specificities of a mixed conglomerate, the actual surface to contact the drying gas is not known, therefore the volumetric heat transfer and evaporation coefficients ($\alpha a, \sigma a$) widely used in the literature are applied. The experiments performed are suitable for determining the volumetric mass transfer (evaporation) coefficient.

The following can be stated for the period of constant drying rate:

$$N = -\frac{dm_P}{A_{G-P} \cdot dt} = \sigma_{G-P}(Y_F - Y_G) \tag{3}$$

where the specific volumetric interfacial surface area between the gas and the product is:

$$a_{G-P} = \frac{A_{G-P}}{V_D} \tag{4}$$

Correlation between the evaporation coefficient and the mass transfer coefficient based on *Szentgyörgyi et al.* [17]:

$$\sigma_{G-P} = \rho_G k_c \tag{5}$$

Volumetric evaporation coefficient in the phase of constant drying rate, using equations (3) and (4):

$$\sigma a_{G-P} = -\frac{dm_P}{(Y_F - Y_G) \cdot V_D \cdot dt} \tag{6}$$

Mass transfer factor based on the Chilton-Colburn analogy, according to Treybal [18]:

$$j_M(Re) = St_M \cdot Sc_{G-P}^{2/3} \tag{7}$$

where

$$St_M = \frac{Sh_{G-P}}{Re \cdot Sc_{G-P}} \tag{8}$$

The Sherwood number can be stated in general for cases of mass transfer in plane, spherical and granular conglomerates by using equations (7) and (8) and applying the dimensionless numbers derived from the transfer coefficients:

$$Sh_{G-P} = j_M(Re) \cdot Re \cdot Sc_{G-P}^{1/3} = B \cdot Re^C \cdot Sc_{G-P}^{1/3} \tag{9}$$

where:

$$Sh_{G-P} = \frac{k_c \cdot d}{D_{v-G}} \tag{10}$$

$$Re = \frac{v_G \cdot d}{\upsilon_G} \tag{11}$$

$$Sc_{G-P} = \frac{\upsilon_G}{D_{v-G}} \tag{12}$$

This method can also be applied in case of the modified Sherwood and Reynolds numbers characterizing the gas/solid substance. The dimensionless equation can be stated in the following form:

$$Sh'_{G-P} = B \cdot Re'^C \cdot Sc_{G-P}^{1/3} \tag{13}$$

The volumetric evaporation coefficient can be determined from measurement data and by using equation (6), wherefrom the modified Sherwood number (*Sh'*) can be produced as follows by applying equations (4), (5), and (10):

$$Sh'_{G-P} = \frac{k_c \cdot \rho_G \cdot a_{G-P} \cdot d^2}{D_{v-G} \cdot \rho_G} = \frac{\sigma a_{G-P} \cdot d^2}{D_{v-G} \cdot \rho_G} \tag{14}$$

The modified Reynolds number by taking into consideration the characteristic velocities developed within the apparatus [16]:

$$Re' = \frac{\sqrt{(v_{cir}^2 + v_{ax}^2)} \cdot d}{\upsilon_G} \tag{15}$$

Constants B and C in equation (13) containing dimensionless numbers can be different depending on the way of mass transfer. In order to determine unknown constants:

$$Sh'_{G-P}/Sc_{G-P}^{1/3} = B \cdot Re'^{C} \tag{16}$$

In respect of measurements including phases of constant drying rate, the connection defined by equation (16) was determined and plotted in function of the modified Reynolds number.

On the diagram in *Figure 7*, the values yielded in the course of waste sludge drying are indicated by '♦'. The points covered a narrow range due to the fact that the drying parameter (and size of the product) was changed within a small range.

In order to extend the measurement range, earlier measurements [16] performed on other materials (millet, sunflower seed, wood block) were also used, assessed and processed in the manner described above. The values yielded are indicated by '+' in *Figure 7*.

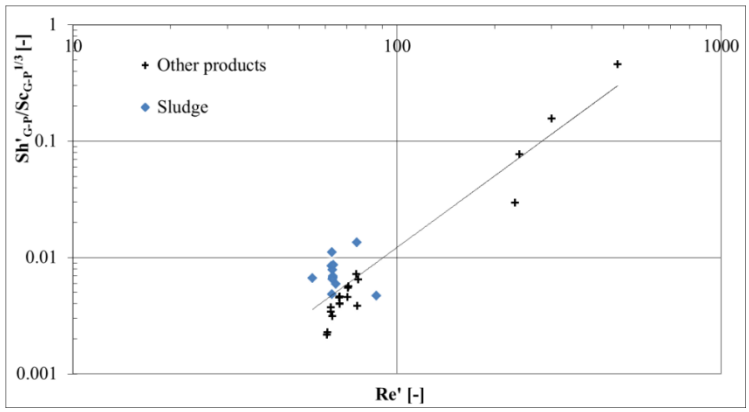

Figure 7
Correlation of $\mathrm{Sh}'_{\mathrm{G-P}}/\mathrm{Sc}_{\mathrm{G-P}}^{1/3}$ in function of the modified Reynolds number

The domain was considerably extended by supplementing earlier measurement point values ($55 < Re' < 480$). By fitting a straight line on the points depicted on the diagram of logarithmic scale (*Figure 7*), the equation of the straight line can be stated by the following correlation:

$$\frac{Sh'_{G-P}}{Sc_{G-P}^{1/3}} = 1.01 \cdot 10^{-6} \cdot Re'^{2,04} \tag{17}$$

Validity range of the equation to define the volumetric evaporation coefficient for conductive/convective drying in an agitated drum dryer:

- $T_P/T_W \approx 0.9$ and
- $0.68 \leq T_W/T_G \leq 0.83$ and
- $55 < Re' < 480$ and
- $0.1 < l < 0.25$.

Conclusion

The excess sludge to be dried, with an initial moisture content of 78-80% was a highly adhesive substance smearing along the wall of the dryer. It produced 'sausage'-type formations along the vertical wall part of the apparatus, it stuck on the agitator of the dryer, and it revolved in lumps within the drying chamber. After the moisture content of the sludge reached 65%, smearing and sticking gradually came to an end and the product granulated. Even the dried small-grained product contained some pieces of the size of a peanut, with higher moisture content than that of the main bulk. In order to reduce the initial moisture content, the product already dried (x_P=0.2÷0.4) was backmixed. Thereby the product conglomerate mixed to have an initial moisture content of approx. 65% is granular and therefore it is easy to dry. Wall heating had a favourable impact on sludge drying. No burning on the wall was observed in the temperature range applied.

At the end of these experiments, product load levels were about half or one third of the initial value. In order to prevent clogging and to realize convective drying effectively, an intermittent drum dryer should be loaded at a maximum load level of *l=0.22*.

A volumetric evaporation coefficient function was determined by using our sludge experiments and based on our earlier measurements. The results yielded can be very useful for the dimensioning of agitated drum dryers, thus providing industrial benefits to waste water treatment plants (transport cost reductions, deposition) and the renewables sector.

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Nomenclature

A	*Surface of heat and mass transfer*	m^2
a	*Volumetric interfacial surface area*	m^2/m^3
B	*Constant*	-
C	*Constant*	-
c	*Specific heat*	*J/kg/°C*
D	*Diffusion coefficient*	m^2/s
d	*Diameter of the product*	*m*
j	*Chilton-Colburn-factor*	-
k_c	*Mass transfer coefficient*	*m/s*
l	*Drum loading factor*	-
Le	*Lewis number*	-
m	*Mass of the product*	*kg*
Δm_P	*Decrease in the wet product mass*	*kg*

$\dot{m}$	*Mass flow*	*kg/s*
N	*Drying rate*	$kg/m^2/s$
n	*Rotational speed*	*1/s*
Re	*Reynolds number*	-
Re'	*Modified Reynolds number*	-
Sc	*Schmidt number*	-
Sh	*Sherwood number*	-
Sh'	*Modified Sherwood number*	-
St	*Stanton number*	-
T	*Temperature*	*°C*
t	*Time*	*s*
v	*Velocity*	*m/s*
V	*Volume*	m^3
x	*Moisture content of product on wet basis*	kg_{H2O}/kg_P
Y	*Absolute humidity of gas on dry basis*	kg_v/kg_{dG}
α	*Heat transfer coefficient*	$W/m^2/°C$
υ	*Kinematic viscosity*	m^2/s
ρ	*Density*	kg/m^3
σ	*Evaporation coefficient*	$kg/m^2/s$
σa	*Volumetric evaporation coefficient*	$kg/m^3/s$

Subscripts

ax	*Axial*
cir	*Circumferential*
D	*Dryer*
F	*Interface of the product*
G	*Humid drying gas*
G-P	*Between the drying gas and the product*
in	*Inlet*
H2O	*Water*
M	*Mass transfer*
out	*Outlet*
P	*Wet product*
v-G	*Between the vapour and the drying gas*
W	*Wall of the dryer*

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