Energy Performance of Convective Dryers*

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ABSTRACT

Following the background information to energy efficiency measures this paper presents the methodology and the calculation results on energy performance of several industrial dryers quantified in terms of the specific energy consumption and compared to the results obtained from the Baker and McKenzie’s adiabatic dryer model for convective dryers. Examples of performance assessment are given for indirectly heated spouted bed dryer with inert particles and spray dryer with integrated fluidized bed. Because the energy performance determination is based on temperature and humidity of the ambient and exhaust air, the calculation method is also given for gas-fired direct dryers represented by a natural-gas heated pneumatic dryer where combustion air and generated water vapor have to be accounted for.

Keywords: Convective dryers; Drying; Energy efficiency; Fast spouted bed; Hybrid dryer; Specific energy consumption; Pneumatic dryer.

INTRODUCTION

The energy cost in terms of heat represents a significant fraction of the total drying cost especially in the case of the most popular convective dryers. Even though almost 100% of the thermal energy contained in the fuel is passed into drying air in direct dryers in contrast to roughly 70% in indirect dryers, the additional heat losses to the ambient and discharged with the exhaust gas reduce the overall thermal efficiency to 60% or less. Novel, more efficient dryers and hybrid systems such as heat-pump dryers, for example, can reduce energy expenditures but at increased investment and operating costs besides the technology risk from not industrially-proven drying systems.

Except for certain technologies such as contact drying, dielectric drying, sorption drying or freeze drying [1], the majority of wet materials are dried by convection either by: (1) dispersing solutions, suspensions or thin pasty materials into hot air stream as in spray drying, pulse combustion drying and drying with shock waves, (2) blowing hot air through a wet granular material, as in rotary, fluidized bed, or spouted bed dryers, or (3) contacting the wet solid or particulate material with hot air stream as in belt, pneumatic and paper dryers. Hot air drying requires high energy input due to inefficient air-to-material heat transfer and significant amount of energy lost with exhaust air, even if its temperature approaches the wet bulb temperature. Thus, the energy efficiency of convective dryers is of great importance since they account for about 85% of all industrial dryers [2]. Various measures, such as partial recycling of exhaust gas or heat recovery [3] in addition to the use of multi-stage dryers [4], can increase the overall energy efficiency of the dryer. Yet, the energy cost in terms of heat represents a significant percentage of the total drying costs, especially when using inefficient methods such as indirect heating of a drying air. Concentration of the raw liquid material by evaporation (e.g., milk) and osmotic dehydration of fruits and berries prior to thermal drying, for example, are considered as options to reduce energy demand in food industry.

The performance of a dryer or drying system is characterized by various indices, including energy efficiency, thermal efficiency, volumetric evaporation rate, specific heat consumption, surface heat losses, unit steam consumption, and others which were defined to reflect the particularities of various drying technologies such as intermittent drying, microwave-assisted drying, or heat pump drying. Of all these indices the energy efficiency and specific heat consumption are most frequently exploited to assess the dryer performance from the energy viewpoint. The specific energy consumption appears to be advantageous over the energy efficiency as it has a well defined benchmarking value for adiabatic dryer whereas evaluation of the dryer performance through the energy efficiency requires the knowledge of the maximum energy efficiency which depends on the material properties and drying conditions.

A great help to the dryer users in process analysis and simulation as well as dryer selection, troubleshooting, and information search could be the commercially available and in-house developed software packages reviewed by Kemp [5]. Regarding energy issues, of particular interest in examining the energy performance of industrial dryers under operation appears to be the Excel-VBA tool developed to fill the gap in computer-based tools. It allows calculation of the energy use in industrial dryers, evaluation of the potential for energy savings, and analysis of the options for reducing energy consumption [6]. In this tool, the calculations of real and theoretical energy efficiency are based on the concept of the excess specific energy consumption proposed by Baker and McKenzie [7] for indirectly heated spray dryers, and extended to fluidized bed dryers. However, aforementioned paper [6] focuses only on the background information on energy performance determination, outlines the general architecture of the calculation tool, and presents an example of input data and calculation results. Therefore, this paper aims at providing the potential users of this tool with some examples of energy performance calculations for representative single- and two-stage convective dryers with direct and indirect heating as well as highlights some specific conditions to be accounted for such as flawless determination of exhaust air temperature or negative temperature of ambient air.

BASIC MEASURES OF ENERGY PERFORMANCE

Energy/Thermal Efficiency

The widely used energy efficiency (η) relates the energy used for moisture evaporation at the material feed temperature (E_{ev}) to the total energy supplied to the dryer (E_t)

$$\eta = \frac{E_{ev}}{E_t} \tag{1}$$

Details regarding E_{ev} and E_t calculations can be found in the recent book on food dehydration [8]. Considering only the energy used to heat drying air which enters a single-pass theoretical convective dryer, Equation 1 can be rewritten as

$$\eta^t = \frac{\Delta H}{W^*(I_i - I_a)} = \frac{\Delta H(Y_i - Y_a)}{I_i - I_a} = \frac{\Delta H(Y_o - Y_a)}{I_o - I_a} \tag{2}$$

The specific air consumption (W*) is given by mass of air required to evaporate 1 kg of water [9]

$$W^* = \frac{W_g}{W_{ev}} = \frac{1}{Y_o - Y_a} \tag{3}$$

A theoretical dryer is defined as a dryer with no heat spent for heating the material and transportation equipment, heat is not supplied to the internal heater, heat is not lost to the ambient atmosphere, and the inlet material temperature is 0°C. Thus, the energy efficiency of a real dryer can be determined from the following relation:

$$\eta = \frac{\Delta H}{W^*\left(I_o - I_a\right) + \Sigma Q_l} \tag{4}$$

or expressed in terms of the theoretical dryer

$$\eta = \frac{1}{\frac{1}{\eta^t} + \frac{\Sigma Q_l}{\Delta H}} \tag{5}$$

where $\sum Q_l$ represents the overall heat losses from the dryer.

For low-humidity and low-temperature convective drying, the energy efficiency can be approximated by thermal efficiency (η_T) that is based on the inlet air temperature (T_i), the outlet air temperature (T_o) and the ambient temperature (T_a)

$$\eta_T = \frac{T_i - T_o}{T_i - T_a} \tag{6}$$

The thermal (energy) efficiency does not indicate how good the dryer is unless it is compared with the maximum thermal efficiency ($\eta_{T,\ max}$) which is attained when the outlet air temperature equals either the wet bulb temperature (T_{WB}) or the negligibly lower [10, 11] adiabatic saturation temperature (T_{AS})

$$\eta_{T,max} = \frac{T_i - T_{WB}}{T_i - T_a} = \frac{T_i - T_{AS}}{T_i - T_a} \tag{7}$$

From Eq. 1 it follows that the maximum energy efficiency exists when the outlet air is saturated with water vapor (Y_o^{sat}) that can be attained for a given evaporation rate when the air flow is minimal, yet securing both heat and hydrodynamic requirements. Thus,

$$\eta_{max} = \frac{\Delta H\left(Y_o^{sat} - Y_a\right)}{I_o - I_a} \tag{8}$$

Complete saturation of exhaust air never occurs in practice because the exhaust gas temperature should be kept below the saturation temperature (typically by 10°C [7]) to avoid condensation in exhaust ducts and cyclone/filter systems.

When drying hygroscopic materials, the relative humidity of the air stream at any point in the dryer should be lower than the equilibrium relative humidity at this point. Thus, for such materials the maximum energy efficiency is restricted not by the exhaust air saturation but by the equilibrium humidity (Y_o^{eq}) determined from sorption isotherms [8]

$$\eta_{max} = \frac{\Delta H\left(Y_o^{eq} - Y_a\right)}{I_o - I_a} \tag{9}$$

Specific Energy Consumption

An alternative measure of dryer efficiency is the specific energy consumption (E_s), which is defined as the heat input to the dryer (Q_h) per unit mass of evaporated water (W_{ev}) [12]. Because for convective dryers the heat input is given as power supplied to the heater then

$$E_s = \frac{Q_h}{W_{ev}} = \frac{Q_h}{F_S\left(X_F - X_P\right)} \tag{10}$$

where F_S is the solids-based material feed rate, and X_F and X_P represent the moisture contents (dry basis) in the feed and the product, respectively. Figure 1 presents the schematics of a single-stage indirectly-heated convective dryer in which the specific nomenclature used by Baker and co-workers has been retained to facilitate future analysis of the source publications.

Insert Figure 1 here

In industrial practice, the feed flow rate (F) is given in kg/h of the material fed to the dryer and the feed moisture content is given in mass percent of solids (X_S). Thus, the rate of water evaporation can be calculated from the following relationship:

$$W_{ev} = F\frac{X_F - X_P}{1 + X_F} \tag{11}$$

where

$$X_F = \frac{100 - X_S}{X_S} \tag{12}$$

Baker and McKenzie [7] derived the following expression for the specific energy consumption of a theoretical dryer, which indicates that the specific energy consumption of an unspecified indirectly-heated convective dryer depends on the temperature and humidity of the outlet air and the heat loss

$$E_s = c_g \left(\frac{T_o/(1-\eta_l) - T_a}{Y_o - Y_a} \right) + \Delta H_{ref} \left(\frac{Y_o/(1-\eta_l) - Y_a}{Y_o - Y_a} \right) \tag{13}$$

where ΔH_{ref} is the latent heat of evaporation at 0°C, taken as the reference temperature, c_g is the heat capacity of air (gas), and η_l is the thermal loss factor of the dryer.

The thermal loss factor in Eq. 13 is defined as

$$\eta_l = \frac{Q_l}{W_g I_i} \tag{14}$$

where W_g is the dry basis air-flow rate.

For an adiabatic dryer $\eta_l = 0$ so Equation 13 reduces to

$$E_{s,a} = c_g \left(\frac{T_o - T_a}{Y_o - Y_a} \right) + \Delta H_{ref} \tag{15}$$

where $E_{s.a}$ is the specific energy consumption of an ideal adiabatic dryer under given operating conditions.

A difference between specific energy consumption of the real and theoretical dryers operated at the same exhaust air temperature and humidity gives the excess specific energy consumption, which is a measure of the wasted energy due to heat losses and other inefficiencies [7]

$$E_{s,x} = E_s - E_{s,a} \tag{16}$$

The concept of using the specific energy consumption to evaluate the performance of indirectly-heated spray dryers presented by Baker and McKenzie [7] and extended to fluidized bed dryers [12-14], was successfully validated for other single-stage and combined convective dryers during the development of the aforementioned calculation tool [6]. Because in that paper only the input data and results of calculations had been presented, details of energy performance evaluation for representative dryers are given in the subsequent paragraph.

ENERGY PERFORMANCE EVALUATION FOR SELECTED DRYERS

Fast Spouted Bed Dryer with Inert Particles.

The principle behind drying of liquid materials on inert solid particles (also called *carriers* as they carry on the material during drying) lies in atomizing the liquid feed such as a solution, suspension or soft paste which then coats in a thin layer the surface of inert particles. These particles are "*fluidized*" either by the sole hydrodynamic impact of the hot air stream, or in combination with mechanical impact induced by mixers, vibrators, screw conveyors and others. The liquid coat on the particle surface dries by convective heat transfer from hot air, and contact heat transfer due to sensible heat accumulated in the inert particles when they pass the hot air zone. It should be noted that although heat transfer by conduction complements convective heat transfer, this type of a dryer falls into a category of convective dryers as the thermal energy for water evaporation is supplied exclusively by the hot air stream.

Because of water evaporation during drying, the liquid coat on the particle surface turns eventually into a brittle shell which is then chipped off from the particle surface, powdered by particle-to-particle and particle-to-wall collisions and discharged from the drying chamber with the exhaust air. Of various configurations of dryers with inert carriers [1] the most frequently examined is the jet-spouted bed with inert particles. Here, the high-velocity stream of hot air (the *jet*) brings the solid particles into the *spout-like* motion, practically in the entire volume of the conical or conical-cylindrical drying chamber.

The laboratory ($V=0.035\ m^3$) jet-spouted bed dryer with inert carriers and its pilot-scale variant ($V=0.66\ m^3$) termed the fast spouted bed (FSB) dryer with inert carriers (Fig. 2) [15] have thoroughly been laboratory and industrially tested by CanmetENERGY (Varennes, QC, Canada) for a variety of products including vegetable starch, egg yolk, pine and alfalfa extracts, soups made from cooked and homogenized lentils, green peas and chicken pea, and the like. To reduce heat losses the pilot dryer, heater and ducts have been insulated with a 10-cm thick water-repellent mineral wool and covered with the 3.2-mm thick stainless steel sheath. The laboratory dryer, heater and ducts were covered with a sandwich insulation consisting of a 1-mm wire mesh, 5-cm mineral wool and 1.6-mm elastomeric resin. The liquid feed was dispersed by a two-fluid nozzle (model SU 42 – ¼; Spraying Systems Co., USA) located either at the bottom or at the top of the dryer. More information about both dryers and representative results from drying pea starch in a pilot unit are given in the recent paper by Benali [16].

Insert Figure 2 here

The experiments with a pilot dryer located at an industrial site, started always with thermal and hydrodynamic stabilization by running the dryer for 20 min with tap water. Then, the dryer fed with the tested material of biological nature was continuously operated from 6 to 8 hours a day. In view of it ample instrumentation, precise control and typically 4000 hours of tests with a given material, this dryer has been selected for verification of the method for energy performance evaluation. The simplified schematic of the dryer with input and output parameters pertinent to the Baker and McKenzie's adiabatic dryer model [7] is shown in Fig. 1.

In contrast to the majority of convective dryers the exhaust air humidity was continuously measured with the Vaisala HUMICAMP temperature/humidity probe (model HMT 335, Vaisala Oyi, Finland) with accuracy ± 0.10°C and ± 0.6% @ 0-40% RH with permissible accuracy of ± 1.0% RH. However, similarly to the problem reported by Al-Mansour et al. [17] on the discrepancy between the measured exhaust humidity and the one calculated from the mass balance over the dryer, the balance-based humidity was found more reliable as it presents the average value over the entire time of dryer operation whereas the sensor-based relative humidity fluctuates between 3.9 and 4.7%.

It should be noted that the Baker and McKenzie's adiabatic dryer model is based on the exhaust air parameters at the dryer outlet not after the cyclone as it could be concluded from the measuring points shown in the paper by Al-Mansour et al. [17]. Thus, the integrated humidity and temperature sensor in the pilot FSB dryer was placed after the cyclone and absolute humidity was determined from combined RH and T_{co} measurements. However, energy performance calculations were based on the outlet air temperature (T_o) that was measured close to the dryer outlet albeit the temperature difference was only 1.5°C.

Insert Table 1 and Table 2 here

The characteristics of the dryer and operating parameters over 6-hour run are given in Table 1 whereas results of calculations are compiled in Table 2.

Interestingly, the FSB dryer is fairly energy efficient as indicated by the excess specific energy consumption and also by thermal efficiency of 52%, even though the high-velocity air stream is needed to spout the inert particles.

Spray Dryer with Integrated Fluid Bed

The multi-stage dryers represent a combination of several single-stage dryers such as a spray dryer with external fluid bed that can be considered as separated dryers, or a hybrid configuration such as a spray dryer with integrated fluid bed where it is not possible to break up such a dryer for the calculation purpose.

Insert Figure 3 here

Figure 3 presents the schematics of a hybrid dryer consisting of the conventional spray dryer and a built-in fluidized bed dryer. In this particular configuration designed for drying heat-sensitive and hygroscopic biomaterials, the co-current spray dryer is fed from the top by two high-pressure nozzles which disperse the liquid feed into fine droplets. To prevent material deterioration both nozzles are cooled by two ambient air streams injected into the nozzles casing. The liquid sprays generated by the nozzles are then dried by the co-currently flowing primary hot air stream heated to the required temperature in a steam-air heat exchanger. The partially dry material falls into the cylindrical fluid bed dryer supplied from the bottom with the secondary hot air stream heated indirectly in a steam-air heat exchanger. In case of excessive ambient air humidity, the air stream injected to the fluid bed dryer is dehumidified in a heat exchanger by cooling with cold water. The fraction of dry fine particles (~ 0.1 mm) is entrained with exhaust air to the cyclone whereas the main part of the material is discharged from the fluidized bed through an air-lock. In the majority of hygroscopic materials exemplified by the specialty carbohydrates the product has to be obtained in the form of granules with size varying from 1 to 2 mm. The granulation takes place in the fluidized bed of this combined dryer by adjusting air velocity, temperature and baffles/partitions in the fluidized bed. In such a situation the powdery fraction of the material collected in the cyclone is returned back to the dryer through the pneumatic transport in a dehumidified and moderately heated air. Thus, the granular product material is discharged from the fluidized bed component of this combined dryer. To reduce heat losses all parts of the dryer have been insulated with a 1-cm mineral wool and covered with an aluminum foil.

Regarding the condition to be satisfied for the presented method of energy performance evaluation, the drying air (inlet air) comes from two hot air streams, namely from the primary air supplied to the spray dryer and from the secondary air supplied to the integrated fluid bed dryer. Thus, the exhaust air is the sum of both air streams and the air used to cool the nozzles. Regarding the heat input the cooling air streams can be neglected as they constitute only 6% of the drying air but accounted in the exhaust air humidity. Also, as reported by the dryer operator, the air stream for pneumatic transport of particles back to the hybrid dryer is negligible in this configuration. Therefore, this combined dryer can be simplified to a single-stage convective dryer represented by Fig. 1 where the heat input to the dryer is given as the sum of the heat input to the spray dryer and fluid bed dryer.

The characteristics of the dryer and results of calculations are given in Tables 3 and 4, respectively.

Insert Table 3 here
Insert Table 4 here

Because of process variability, the dryer designed for operation with two nozzles can be fed only through one nozzle at the same air flow rates. However, in this case the energy performance drops dramatically as not entire dryer volume and all air stream are fully utilized. It is demonstrated through much higher specific energy consumption (c.f., Table 4) and reduced thermal efficiency, which drops from 28.6% when the feed is dispersed by two nozzles to 26%

for the one-nozzle feed. Such an effect could be exploited to monitor the operation of the dryer with a multi-nozzle feed through the soft sensor control based on the appropriate software if the outlet air humidity is reliably measured.

Gas-Fired Pneumatic Dryer.

Regarding the mode of heat transfer, convective dryers belong to the group of direct dryers because heat for water evaporation is transferred by direct contact of the dried material with a stream of hot gas such as air, carbon dioxide or nitrogen, superheated steam, or flue gases from combustion of fossil fuels. Commonly, however, direct dryers are perceived as convective dryers where heat is usually supplied by a mixture of air and products of fuel combustion. To avoid ambiguity, such dryers are referred to as direct-fired dryers or gas-fired dryers, if natural gas is combusted in the burner.

Natural gas (NG) is a hydrocarbon mixture consisting primarily of methane (95.53-97.3%) and ethane (2.06 – 2.1%) with admixtures of nitrogen, carbon dioxide, hydrogen, sulfur compounds in various concentration depending on the gas source. Natural gas from Canadian sources is practically free from sulfur compounds so it is the most commonly used in gas-fired industrial dryers in agri-food industry. The limiting factor in the use of natural gas in drying is relatively high amount of water vapor generated during combustion, which reduces the moisture holding capacity of a gas phase and may limit drying of hygroscopic products.
The combustion of methane being the main component of natural gas takes place according the following exothermal reaction:

$$\mathrm{CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + Q} \tag{17}$$

Stoichiometric combustion requires 9.5 m^3 of air per 1 m^3 of methane. The water vapor generated due to combustion of 1 m^3 of natural gas is 2 m^3, which referred to 10.5 m^3 of combustion products gives the water vapor concentration of 19% vol. In terms of mass calculations, 1 kg of methane requires 16.5 kg of air for stoichiometric combustion which generates 2.136 kg of water. The real concentration of water vapor in flue gasses is usually lower (~ 18% vol.) because excess air is needed for complete combustion of natural gas. Since the flame temperature for stoichiometric combustion of NG reaches 2770°C the flue gases should be diluted with ambient air to reduce the drying gas temperature and provide sufficient air flow to satisfy hydrodynamic requirements. Therefore, the mixing chamber should follow the gas-fired combustor although in the majority of cases both components are combined into a combustion system depicted in Figure 4.

Insert Figure 4 here

Regarding the Baker and McKenzie's adiabatic dryer model and the methodology for specific energy calculations which leads to excess specific energy consumption given by Eq. 16, the crucial is the additional water vapor generated during combustion of natural gas (or other fossil fuel such as butane or propane) and the combustion air. Accepting the ideogram shown in Figure 1, the mass flow rate of ambient air should be a sum of flow rates of drying air and air needed for complete combustion (stoichiometric and excess air). The water vapor generated in the combustion process increases the outlet gas humidity but this additional humidity does not result from drying so basically it does not affect the outlet gas temperature and, therefore, it can be considered as an inert gas. However, the combustion air complements the drying air in the outlet gas so the outlet humidity should be computed as a mass of water evaporated in the dryer over the combined mass of drying air, excess air and combustion products (N_2 and CO_2).

The industrial dryer under evaluation is a single-pass pneumatic dryer of 0.83 m in diameter and a 15 m high vertical column through which a drying gas is drafted by the exhaust fan. The dryer is fitted with a duct-type gas burner placed in a combustion chamber that is fed with natural gas and combustion air taken from the ambient. The flue gasses from the burner are mixed with the main stream of an ambient air to lower the drying gas temperature to the required one. Because of hydrodynamic requirements for pneumatic transport of dispersed material, the drying air flow rate is fairly constant so the inlet gas temperature is controlled by the NG flow rate. The material to be dried is received from the centrifuge as the wet cake, stored in a surge bin with a sweeper arm and then transported by a variable speed screw conveyor to the hammer mill located at the feed section of the dryer. The dry material entrained with exhaust gas is separated in two serial cyclones. The oversize particles (> 0.22 mm) collected in the first cyclone are disintegrated in the pin mill. To reduce heat losses, the burner and the dryer are covered with a 5-cm thermally-resistant solid insulation. Table 5 presents the operating characteristics of the dryer whereas the results of calculations are given in Table 6.

Insert Table 5 here
Insert Table 6 here

CONCLUDING REMARKS

1. The Baker and McKenzie's (B-McK) adiabatic dryer model developed primarily for single-stage indirect spray dryer can successfully be used for energy performance of various convective dryers in both single-stage and combined (multi-stage) configurations where drying air passes each drying stage. Otherwise, the combined dryer exemplified by the spray dryer with external fluid bed dryer should be considered as a combination of separate dryers.
2. The B-McK model can be used for direct dryers if combustion water is accounted for.
3. The B-McK model allows detection of faulty operation of the dryer such as clogged nozzle in the multi-nozzle feeding system as the specific energy consumption increases dramatically.

NOMENCLATURE

c	Heat capacity, kJ/(kg K)
d. b.	Dry basis
E	Energy, J
E_s	Specific energy consumption, kJ/kg H_2O
$E_{s, a}$	Specific energy consumption of adiabatic dryer, kJ/kg H_2O
$E_{s, x}$	Excess specific energy consumption, kJ/kg H_2O
F	Feed rate, kg/h
F_S	Feed rate (dry basis), kg/s
FSB	Fast spouted bed

HHV	Higher heating value, MJ/m^3
ΔH	Latent heat of vaporization, kJ/kg
I	Enthalpy, kJ/kg
NG	Natural gas
ΣQ_l	Heat losses, kJ/kg H_2O
Q	Heat rate, kJ/s
RH	Air relative humidity, %
T	Temperature, K (°C)
V	Volume, m^3
w.b.	Wet basis
W*	Specific air consumption, kg air/kg H_2O
W	Flow rate, kg/s
X	Material moisture content (d. b.), kg H_2O/kg dry material
Y	Absolute air humidity, kg H_2O/kg dry air
η	Energy efficiency, -
η_l	Thermal loss factor, -
η_T	Thermal efficiency, -

Subscripts

a	Ambient
AS	Adiabatic saturation
c	Cyclone
ev	Evaporation

f	Flue gases
F	Feed
g	Gas (air)
h	Heater
i	Inlet
l	Losses
max	Maximum
NG	Natural gas
o	Outlet
P	Product
ref	Reference
S	Solids
t	Total
T	Thermal
w	Water
WB	Wet bulb

Superscripts

c	Combustion
eq	Equilibrium
t	Theoretical
sat	Saturation

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Figure captions

Figure 1. Representation of the convective dryer analyzed by the Baker and McKenzie model.

Figure 2. Fast spouted bed dryer with inert particles.

Figure 3. Spray dryer with integrated fluidized bed.

Figure 4. Ideogram of the combustion system.

Table 1.

Dryer characteristics and operating parameters for pilot-scale fast spouted bed dryer with inert carriers.

Material	Fermented whey proteins
Feed characteristics	
- Mass flow rate of liquid feed	120 kg/h
- Solids content / Moisture content	15-16% w/w / 5.45 kg/kg d.b.*
- Temperature	30.6-34.2°C
Product	
- Moisture content	0.0287-0.0307 kg/kg d.b. (2.97 kg/kg d.b.)*
Drying air	
- Mass flow rate	3221.1 kg/h
- Ambient humidity	66.0-68.1% (67% at 22.0°C)*
- Ambient temperature	21.7 – 22.8°C (22.0°C)*
- Inlet air temperature	190°C
- Outlet air temperature (dryer)	102.5°C
- Outlet air temperature (cyclone)	101.0°C
- Outlet air relative humidity (cyclone)	3.9-4.7% at 101.0°C
- Outlet air absolute humidity (mass balance)	0.04164 kg/kg
Inert particles	8 kg of 5-mm Teflon beads

* Value taken for calculations in the case of fluctuating parameter

Table 2.

Energy performance - results of calculations for FSB dryer.

W_{ev}, kg/h	(Y_o-Y_a), kg/kg	E_s, kJ/kg H_2O	$E_{s,\,a}$, kJ/kg H_2O
100.8	0.03042	5601.73	5161.63

Table 3.

Dryer characteristics and operating parameters for industrial spray dryer with integrated fluid bed.

Material	Het-sensitive and hygroscopic carbohydrates
Feed characteristics	
- Mass flow rate of liquid feed	161 kg/h [(a)] ; 342 kg/h [(b)]
- Solids content / Moisture content	68.4% w/w [(a)] (0.4620 kg/kg d.b.)
	68.5% w/w [(b)] (0.4598 kg/kg d.b.)
Product	
- Moisture content	0.0310 kg/kg d.b.[(a)] ; 0.0417 kg/kg d.b. [(b)]
Drying air	
- Mass flow rate	125000 kg/h (1); 4500 kg/h (2); 2x500 kg/h (3)
- Ambient humidity	0.0163 kg/kg [(a)] ; 0.00108 kg/kg [(b)]
- Ambient temperature	29.3°C [(a)] ; 21.9°C [(b)]
- Inlet air temperature	133°C [(a)] (1); 53°C [(b)] (2)
- Outlet air temperature (dryer)	29.3°C [(a)] ; 21.9°C [(b)]
- Outlet air humidity (mass balance)	0.01883 kg/kg [(a)] ; 0.01624 kg/kg [(b)]

[(a)] One nozzle; [(b)] Two nozzles

1, 2 and 3 indicate air streams as shown in Fig. 3.

Table 4.

Energy performance - results of calculations for spray dryer with integrated fluid bed.

F, kg/h	W_{ev}, kg/h	(Y_o-Y_a), kg/kg	E_s, kJ/kg H_2O	$E_{s,a}$, kJ/kg H_2O
161 [(a)]	45.57	0.00253	29486	26610
342 [(b)]	97.96	0.00544	16900	15275

[(a)] One nozzle; [(b)] Two nozzles

Table 5.

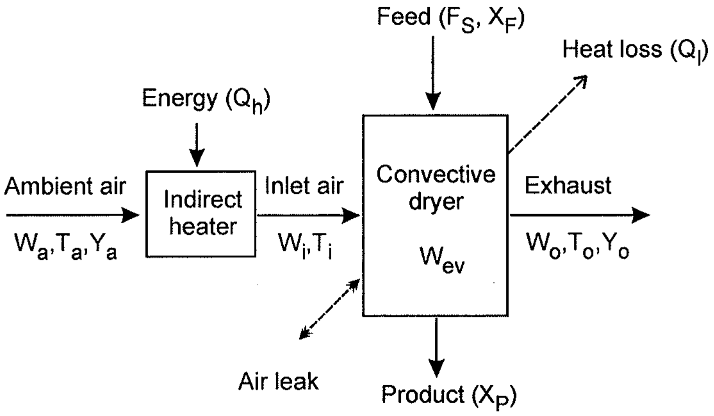
Dryer characteristics and operating parameters for gas-fired pneumatic dryer.

Material	Starch (industrial grade)
Feed characteristics	
- Moisture content	33% w.b. (0.493 kg/kg d.b.)
- Temperature	40°C
Product	
- Mass flow rate	4167 kg/h at 12% w.b.
- Moisture content	12% w.b. (0.136 kg/kg d.b.)
- Particle size	0.09-0.20 mm
- Bulk density	650 kg/m^3
Drying air	
- Mass flow rate (drying air)	28792.8 kg/h
- Mass flow rate (combustion air-total)	2330.5 kg/h
- Mass flow rate (combustion air-stoichiometric)	1942 kg/h
- Ambient humidity	48%
- Ambient temperature	16.7°C
- Inlet air temperature	213.9°C
- Outlet air temperature	67.2°C
- Outlet air humidity	0.0555 kg/kg
Heat source	
- Natural gas	117.7 kg/h (at HHV= 53.10 MJ/kg)
- Excess air	20%

Table 6.

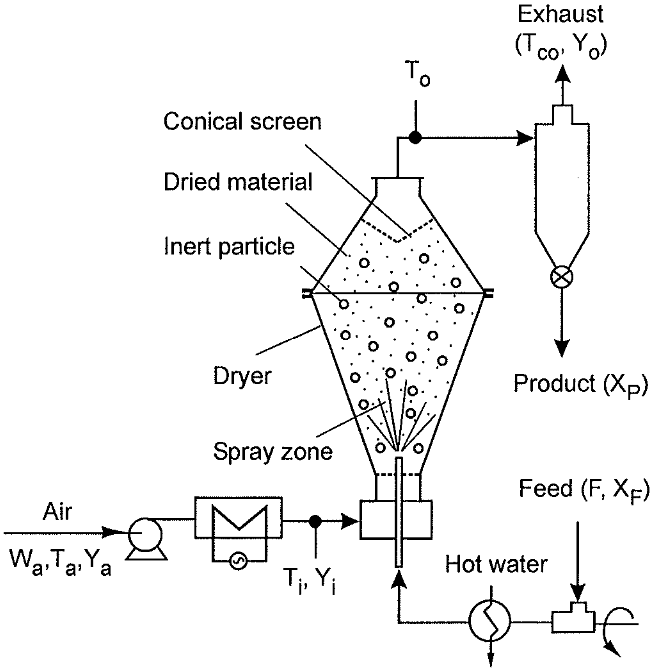
Energy performance - results of calculations for gas-fired pneumatic dryer.

W_{ev}, kg/h	W^c_w, kg/h	(Y_o-Y_a), kg/kg	E_s, kJ/kg H_2O	$E_{s,\,a}$, kJ/kg H_2O
1304.2	251.41	0.04555	4705.5	3608.7



Feed (F_S, X_F)
Heat loss (Q_l)
Energy (Q_h)
Ambient air
W_a,T_a,Y_a
Indirect heater
Inlet air
W_i,T_i
Convective dryer
W_{ev}
Exhaust
W_o,T_o,Y_o
Air leak
Product (X_P)

Fig. 1



Exhaust
(T_{co}, Y_o)
T_o
Conical screen
Dried material
Inert particle
Dryer
Spray zone
Product (X_P)
Feed (F, X_F)
Air
W_a,T_a,Y_a
T_i, Y_i
Hot water

Fig. 2

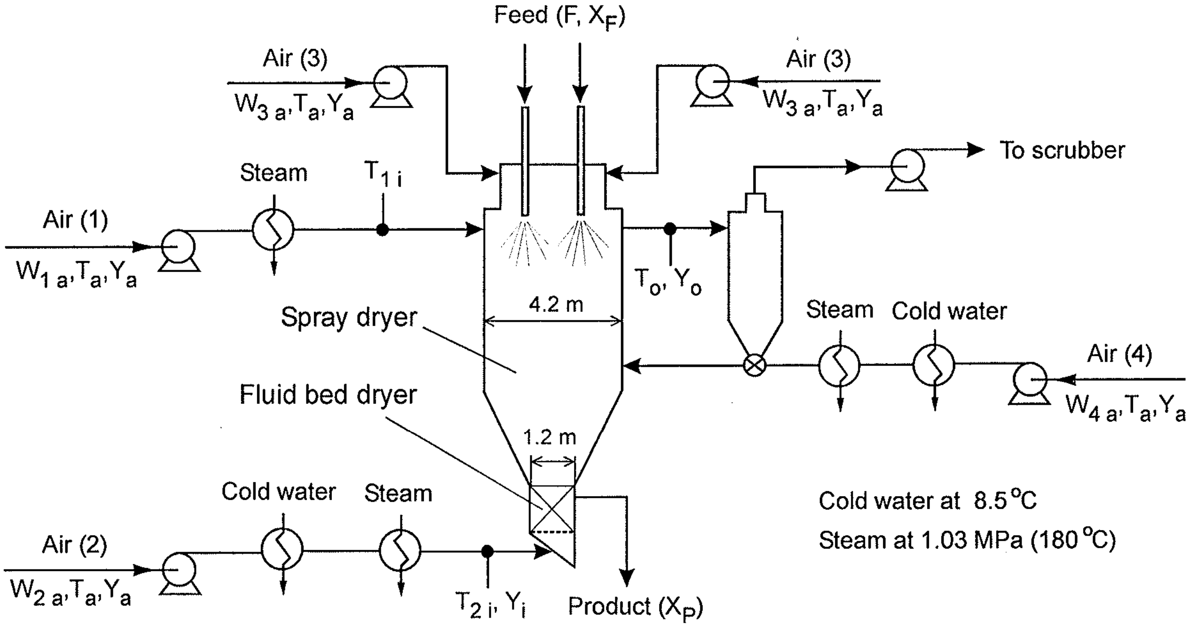

Feed (F, X_F)
Air (3)
W3 a,Ta,Ya
Air (3)
W3 a,Ta,Ya
To scrubber
Steam
T1 i
Air (1)
W1 a,Ta,Ya
To, Yo
4.2 m
Spray dryer
Steam
Cold water
Air (4)
W4 a,Ta,Ya
Fluid bed dryer
1.2 m
Cold water
Steam
Air (2)
W2 a,Ta,Ya
T2 i, Yi
Product (X_P)
Cold water at 8.5 °C
Steam at 1.03 MPa (180 °C)

Fig. 3

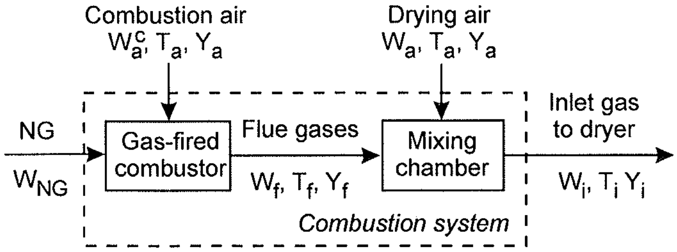

Combustion air
W_a^c, Ta, Ya
Drying air
Wa, Ta, Ya
NG
W_NG
Gas-fired combustor
Flue gases
Wf, Tf, Yf
Mixing chamber
Inlet gas to dryer
Wi, Ti Yi
Combustion system

Fig. 4