EXCEL-BASED TOOL TO ANALYSE ENERGY PERFORMANCE OF CONVECTIVE DRYERS

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Abstract: An algorithm to examine the energy performance of convective dryers was developed and transformed into an Excel-based calculation tool. Provided with the input data for a given industrial dryer, this tool allows the energy use to be quantified in terms of the specific energy consumption and energy efficiency. The energy use can then be compared with the corresponding values for an ideal adiabatic dryer to identify the potential for energy savings. The algorithm accounts for direct and indirect dryers as the single and multi-stage units operated in closed or open cycles. In addition, the maximum energy efficiency can be determined for non-hygroscopic materials through the sorption isotherms. The tool permits identification of the major sources of dryer inefficiency, and allows energy savings to be calculated for several low- and high-cost measures such as dryer insulation, partial recycling of exhaust air, feed pre-heating, and others. The tool is built as a modular system comprising the following main components: dryer identification, calculation of actual energy consumption, comparison with the theoretical energy consumption, identification of sources of energy inefficiency, and analysis of options to reduce energy consumption.

Keywords: convective dryers, drying, energy, efficiency, heat consumption, inefficiency, specific energy consumption, software

1. INTRODUCTION

With the rapid growth in capacity and operation speed of personal computers, an increase is noted in the development of various software programs devoted to thermal drying (Baker and Lababidi, 2000, 2001; Baker *et al*., 2004; Kemp *et al*., 1887; Marinos-Kouris *et al*., 1996; Maroulis *et a*l., 2007; Menshutina and Kudra, 2001). Kemp (2007) provided an excellent overview of the state-of-the art on drying softwares. He not only described available software packages but also discussed issues of general matter such as the strategy for the development of drying softwares, barriers in software design and implementation, limitations and challenges on the progress, and future developments.

Despite considerable efforts on RD&D, few commercial software packages specifically intended for drying, dryers, and drying systems have been commercialized. These are Simprosys for design and simulation of drying and evaporation systems (Gong and Mujumdar, 2008), dryPak for dryer design calculations for various gas-solvent systems (Pakowski, 1994), and DrySel for dryer selection marketed by Aspen Technology. Other drying softwares are suitable for process analysis and simulation. Examples are the DrySPECC2 and DrySim designed by NIZO Food Research (The Netherlands) for modeling and simulation of spray dryers, and process simulators such as Aspen Plus. Also, several algorithms were developed for dryer selection, troubleshooting, and information search (Maroulis et al., 2007; Kemp and Gardiner, 2001; Baker et al., 2004; Baker and Lababidi, 2000; Menshutina and Kudra, 2001).

Interestingly, the existing software and calculation tools do not consider energy aspects even though the drying is recognized as a particularly energy-intensive unit operation. To fill this gap, an attempt was made to develop a computer-based tool allowing the calculation of energy use in industrial dryers, evaluate the potential for energy savings, and analyze options for reducing energy consumption.

2. GENERAL DESCRIPTION OF THE CALCULATION TOOL

The software is built as a modular system depicted in Figure 1.

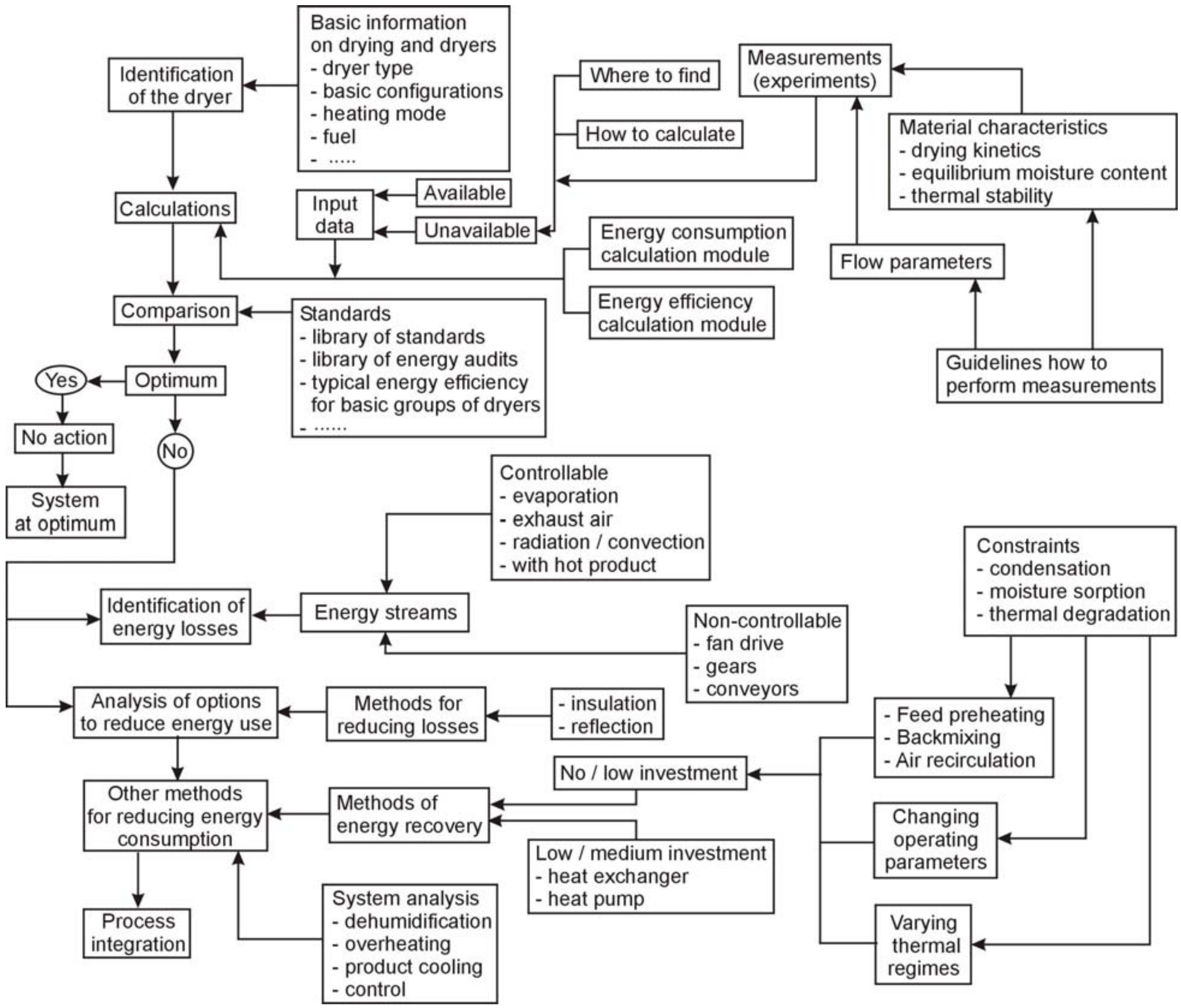

Figure 1. Block diagram of the energy calculation and analysis tool.

Essentially, the calculation of drying energy consumption is based on the drying gas parameters. However, determination of the attainable top-line dryer for indices such as specific energy consumption and energy efficiency, as well as an analysis of options for reducing energy consumption are based on material properties (e.g., specific heat, sorption isotherms). As such properties are not readily available, the tool allows calculation of needed parameters or, at least, the use of properties of the materials most similar to the drying material. An example is the equilibrium moisture content tabulated for representative materials.

Because of the page format constraints, a more detailed description of the tool will be presented in the paper published in a special edition of Drying Technology.

The tool was developed in Excel-VBA, but after thorough verification, it will migrated to a VB.net platform.

3. CALCULATIONS OF ENERGY PERFORMANCE

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

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

Regarding only the energy used to heat drying air which enters a single-pass theoretical convective dryer, Equation 1 can be rewritten as

$$\eta^t = \frac{\Delta H}{W^*(I_1 - I_a)} = \frac{\Delta H(Y_2 - Y_a)}{I_1 - I_a} = \frac{\Delta H(Y_2 - Y_a)}{I_2 - I_a} \tag{2}$$

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

$$W^* = \frac{W_g}{W_{ev}} = \frac{1}{Y_2 - Y_a} \tag{3}$$

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 inlet material temperature is equal to 0°C. Thus, the energy efficiency of a real dryer can be determined from the following relation:

$$\eta = \frac{\Delta H}{W^*\left(I_2 - I_a\right) + \Sigma Q_l} \tag{4}$$

or expressed in terms of the theoretical dryer

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

For low humidity and low temperature convective drying, the energy efficiency can be approximated by thermal efficiency (η_T)

$$\eta_T = \frac{T_1 - T_2}{T_1 - T_a} \tag{6}$$

The thermal (energy) efficiency does not indicate how good the dryer is unless it is compared to the maximum thermal efficiency ($\eta_{T,\,max}$)

$$\eta_{T,max} = \frac{T_1 - T_{WB}}{T_1 - T_a} = \frac{T_1 - T_{AS}}{T_1 - T_a} \tag{7}$$

The departure of a thermal efficiency of a real dryer from the maximum one is quantified by the efficiency ratio

$$\chi = \frac{\eta_T}{\eta_{T,\,max}} = \frac{T_1 - T_2}{T_1 - T_{WB}} = \frac{T_1 - T_2}{T_1 - T_{AS}} \tag{8}$$

For a given evaporation rate, saturation of the exhaust air (Y_2^{sat}) can be attained when the air flow is minimal, yet securing both heat and hydrodynamic requirements. Thus,

$$\eta_{max} = \frac{\Delta H\left(Y_2^{sat} - Y_a\right)}{I_2 - I_a} \tag{9}$$

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 saturation but by the equilibrium humidity (Y_2^{sat}) determined from sorption isotherms

$$\eta_{max} = \frac{\Delta H\left(Y_2^{eq} - Y_a\right)}{I_2 - I_a} \tag{10}$$

An alternative measure of dryer efficiency is the specific energy consumption defined as the heat input to the dryer per unit mass of evaporated water. Because for convective dryers the heat input is given as power supplied to the heater then

$$E_s = \frac{Q_h}{W_{ev}} = \frac{Q_h}{F(X_1 - X_2)} \tag{11}$$

Baker and McKenzie (2005) 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

$$E_s = c_g\left(\frac{T_2/(1-\eta_l) - T_a}{Y_2 - Y_a}\right) + \Delta H_{ref}\left(\frac{Y_2/(1-\eta_l) - Y_a}{Y_2 - Y_a}\right) \tag{12}$$

where ΔH_{ref} is the latent heat of evaporation at 0°C, taken as the reference temperature.

The parameter η_l in Equation 12 is called the thermal loss factor of the dryer, and defined as

$$\eta_l = \frac{Q_l}{W_g I_1} \tag{13}$$

For an adiabatic dryer $\eta_l = 0$ so Equation 12 reduces to

$$E_{s,a} = c_g\left(\frac{T_2 - T_a}{Y_2 - Y_a}\right) + \Delta H_{ref} \tag{14}$$

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 (Baker and McKenzie, 2005)

$$E_{s,x} = E_s - E_{s,a} \tag{15}$$

The concept of using specific energy consumption to evaluate the performance of indirectly-heated spray dryers presented by Baker and McKenzie (2005) and extended to fluidized bed dryers (Baker, 2005; Baker *et al*., 2006; Baker and Al-Adwani, 2007) was successfully validated by the authors of this paper for other single-stage convective dryers such as pneumatic and rotary dryers, and various combined dryers including filtermat dryer, and spray dryer with integrated fluidized bed. This concept also holds for gas-fired dryers, if the combustion air is accounted for.

4. EXAMPLES OF INPUT AND OUTPUT DATA

Figures 2 and 3 provide examples of the input data and results of calculations. Detailed presentation of the tool will be given at the IADC conference.

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6. NOTATION

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 (dry basis), kg/s
ΔH	Latent heat of vaporization, kJ/kg
I	Enthalpy, kJ/kg
ΣQ_l	Heat losses, kJ/kg H_2O
Q	Heat rate, kJ/s
t	Time, s
T	Temperature, K (°C)
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	Air humidity, kg H_2O/kg dry air
η	Efficiency, -
χ	Efficiency ratio -

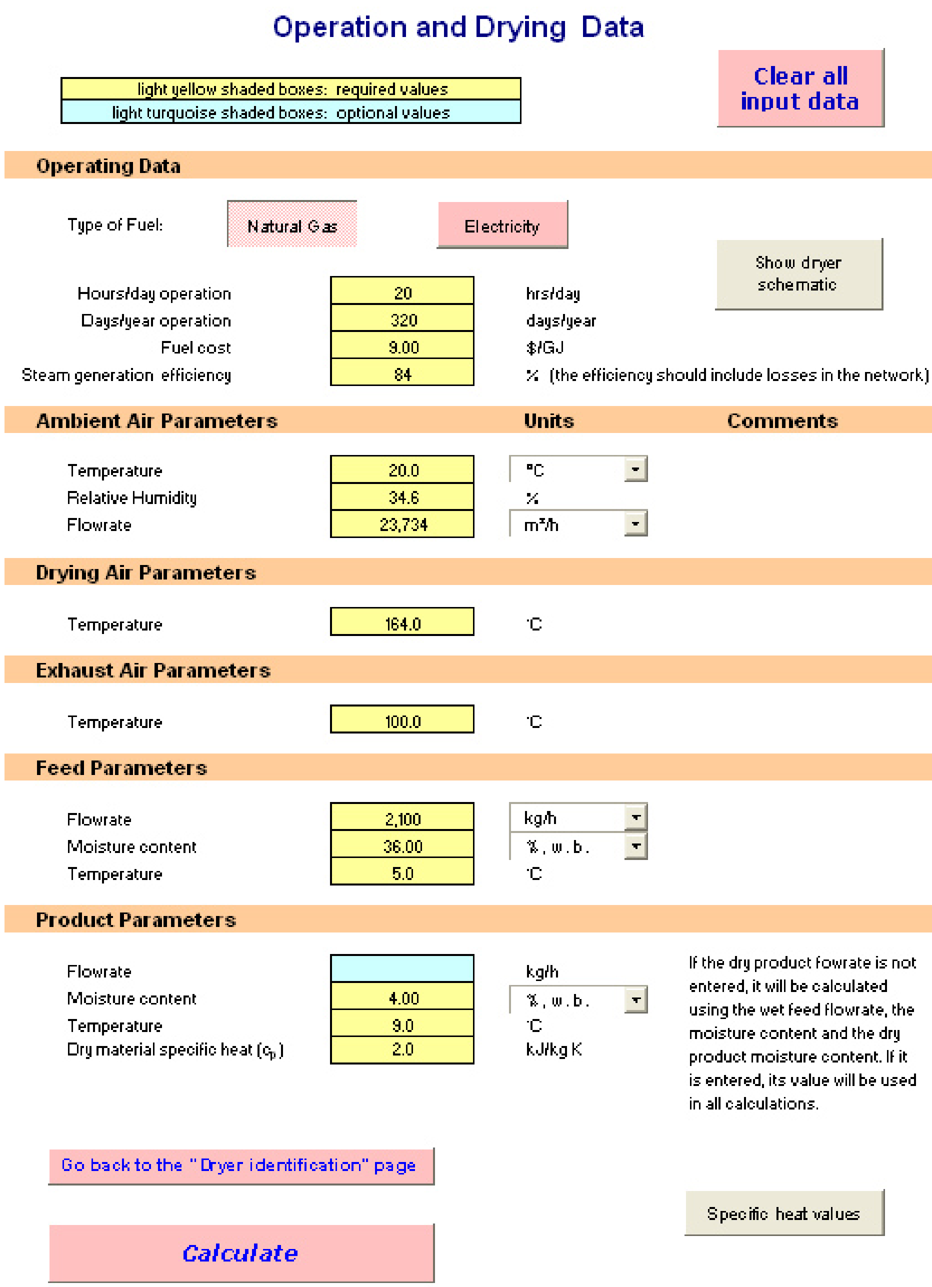
Subscripts

a	Ambient
AS	Adiabatic saturation
ev	Evaporation
g	Gas (air)
h	Heater
l	Losses
max	Maximum
ref	Reference
t	Total
T	Thermal

WB	Wet bulb
1	Inlet
2	Outlet

Superscripts

eq	Equilibrium
t	Theoretical
sat	Saturation



Operation and Drying Data

light yellow shaded boxes: required values
light turquoise shaded boxes: optional values

Clear all input data

Operating Data

Type of Fuel: Natural Gas | Electricity

Show dryer schematic

Hours/day operation	20	hrs/day
Days/year operation	320	days/year
Fuel cost	9.00	$/GJ
Steam generation efficiency	84	% (the efficiency should include losses in the network)

Ambient Air Parameters		Units	Comments
Temperature	20.0	°C	
Relative Humidity	34.6	%	
Flowrate	23,734	m³/h	
Drying Air Parameters			
Temperature	164.0	°C	
Exhaust Air Parameters			
Temperature	100.0	°C	
Feed Parameters			
Flowrate	2,100	kg/h	
Moisture content	36.00	%, w.b.	
Temperature	5.0	°C	
Product Parameters			
Flowrate		kg/h	If the dry product fowrate is not entered, it will be calculated using the wet feed flowrate, the moisture content and the dry product moisture content. If it is entered, its value will be used in all calculations.
Moisture content	4.00	%, w.b.	
Temperature	9.0	°C	
Dry material specific heat (c_p)	2.0	kJ/kg K	

Go back to the "Dryer identification" page

Specific heat values

Calculate

Fig. 2. Input data sheet.

Dryer energy efficiency model

Dryer name: Dryer1
Date:

light yellow shaded boxes: user values
white boxes: calculated values

Dryer Characteristics

Dryer type:	Spray	Drying medium:	Hot air
Operation mode:	Continuous	Number of stages:	Multiple stages
Heating mode:	Indirect	Cycle type:	Closed cycle
Dryer location:	Outside		

Ambient Air Parameters

Temperature	20.0	°C
Pressure	101.3	kPa
Relative humidity	34.6	%
Absolute humidity	0.0050	kg vapor/kg dry air
Density	1.20	kg/m³
Specific heat	1.01	kJ/kg K
Flowrate	23,734	m³/h
Dry air flowrate	28,408	kg/h
Vapor flowrate	142	kg/h

Drying Air Parameters

Temperature	164.0	°C
Absolute humidity	0.0050	kg vapor/kg dry air
Flowrate	35,399	m³/h

Exhaust Air Parameters

Temperature	100.0	°C
Absolute humidity	0.0296	kg vapor/kg dry air
Flowrate	31,070	m³/h
Dry air flowrate	28,408	kg/h
Vapor flowrate	842	kg/h

Feed Parameters

Flowrate	2,100	kg/h
Moisture content	36.0	%, w. b.
	0.5625	kg/kg, d. b.
Water flowrate	756	kg/h
Dry matter flowrate	1,344	kg/h
Temperature	5.0	°C

Product Parameters

Flowrate	1,400	kg/h
Moisture content	4.0	%, w. b.
	0.0417	kg/kg, d. b.
Water flowrate	56	kg/h
Dry matter flowrate	1,344	kg/h
Temperature	9.0	°C

Energy Reduction and Savings

Dryer evaporative load	700	kg/h
Ideal heater capacity	1,149.0	kW
Dryer efficiency	38.24	%
Ideal dryer energy consumption	5,768.8	kJ/kg
Actual dryer energy consumption	5,909.2	kJ/kg
Dryer energy savings scope	140.4	kJ/kg
Ideal energy consumption cost	232,599	$/year
Actual energy consumption cost	238,258	$/year
Energy savings scope	5,659	$/year

Energy consumption explanation

Fig. 3. Results of calculations.