60 Symprosys
Software for Dryer Calculations

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60.1 INTRODUCTION

Over the past 25 years, considerable effort has been devoted to the development of various software programs applicable to the design, operation, and optimization of drying systems (Marinos-Kouris et al., 1996; Menshutina and Kudra, 2001; Kemp et al., 2004; Kemp, 2007). However, few commercial drying software products have been available on the market and well accepted by the industry. In fact, the most prominent one is proprietary and available only to the sponsors.

In view of the skyrocketing energy costs in recent years and the looming concerns over global climate change caused by greenhouse gas emission, energy conservation technology is once again a very important aspect for the industry. It has a direct bearing on carbon footprint as well as life cycle costs of dryers and drying operations.

Drying is one of the most commonly found important unit operations in chemical, food, biochemical, pharmaceutical, pulp and paper, wood, and several other industries. Thermal drying is an extremely energy-intensive unit operation that ultimately contributes to the emission of greenhouse gases. The energy used in the drying operations is on the order of 15%–20% of the total energy used for industrial production in developed countries (Mujumdar, 2006; Kudra and
AQ1 Mujumdar, 2009; Jangam and Mujumdar 2010). This can be attributed to various reasons such as poor design of dryers, nonuniform distribution of drying media that results in inefficient heat utilization, poor insulation of dryers, improper control of dryers, and of course the high latent heat of vaporization of water (Baker, 2005). In addition, in conventional drying systems using convection mode of heat transfer, the evaporated moisture is usually vented off along with the drying medium, resulting in loss of both sensible and latent heat of vaporization of moisture. With industrial dryer efficiencies ranging from just 30% to 60%, there is a great potential for improvements, especially in view of rising energy costs and sustainability issues related to carbon footprint as well as environmental constraints on greenhouse gas emissions from the burning of fossil fuels. If countries adopt caps on carbon emissions, such as the one recently adopted by the United Kingdom to reduce CO_2 emissions by 50% from their 1990 level by 2050, there is no doubt every industrial and agricultural drying operation will come under scrutiny and will be subject to legislative limits on carbon footprints allowed.

Access to reliable drying software is cost-effective not only for the energy aspects but also for other aspects of design, analysis, and troubleshooting as well as control and optimization of drying systems. Kemp and Gardiner (2001) showed that even a simple heat and mass balance calculation can yield important benefits for a convective dryer in a troubleshooting practice. Drying software can not only make sophisticated calculations readily feasible but also help improve significantly the productivity and efficiency of engineers related to drying designs and practices. Indeed, it may even be possible to use such software for automated control purposes.

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60.2 IDEAL DRYING SOFTWARE SPECIFICATIONS

For convective thermal drying, which constitutes over 90% of industrial dryers in operation today according to some estimates, wet material and hot gas exchange heat and mass in a dryer to get the material dried.

To design a drying system for a material, lab-scale experiments are generally needed to obtain the material properties and desirable operating conditions. Once the design requirements are specified, the dryer needs to be carefully selected first. Then a drying flowsheet must be laid out to meet the design requirements. Next, heat and mass balances of the flowsheet need to be calculated to obtain the necessary process parameters such as the air flow rate to the dryer, the capacity and power requirements for the blower, the heat duty of the heater, and the exhaust dust concentration of the cyclone or scrubber. Finally, equipment and processing conditions can be selected according to the balance calculation results. Then equipment and operating cost of the drying system can be estimated.

For the design of some dryers, for example, rotary, spray, flash, and fluid bed dryers, scoping may be needed in addition to heat and mass balance calculations; sometimes, scale-up is needed after lab experiments for dryers such as fluid bed dryer according to Kemp and Oakley (2002). This is a separate but important issue by itself.

Drying kinetics analysis (numerical methodology such as finite element or finite difference solutions of governing equations) of the transient coupled heat and mass transfer inside the material under different boundary conditions can help to determine drying time and optimal drying conditions that are essential to the design of dryers. Such analysis can greatly reduce experimental cost.

For the design of some specific dryers, for example, impinging jet, spray, and flash dryers, computational (such as computational fluid dynamics known as CFD) analysis of the complex gas–particle two-phase flow with inter-gas–particle heat and mass transfer can help understand the effects of dryer geometries to the drying process and make better design decisions.

Based on various aspects of design, analysis, and troubleshooting as well as control and optimization of drying systems, ideal drying software should be a comprehensive *drying suite* consisting of a drying material database and interrelated units that share the same material model, drying gas model, and dryer equipment model. Each unit in the suite covers different aspects for design, analysis, and troubleshooting as well as control and optimization of drying systems.

With such a *drying suite*, users can process their experimental data. They can select an appropriate dryer or get the appropriate dryers recommended after material characteristics (such as moister contents, particle distributions, and experimental drying curves), and product requirements (such as final moisture content, product quality requirements) are specified. They then can perform relevant heat/mass/pressure balance calculations for not only the dryer(s) but also the ancillary unit operations of the drying operation. Users should be able to further carry out scoping, on the basis of the balance calculations, or scaling up of the dryer(s), based on lab experimental results, or dryer rating. Users should further be able to estimate the equipment and operating cost for a drying system. They should also be able to do advanced simulations for drying kinetics analysis and computational analysis of the gas–particle two-phase flow with coupled heat and mass transfer for some typical dryers such as spray dryers and flash dryers.

The ideal *drying suite* should consist of four essential units for design and process engineers and two advanced units for R&D engineers and researchers, as is displayed in Figure 60.1.

The four essential units are as follows:

1. An experiment processor that can be used to process experimental data and store them into the material database.
2. A dryer selector that can be used to get appropriate dryers recommended or an appropriate dryer selected.
3. A process simulator that can be used to lay out drying flowsheets and carry out heat/mass/pressure balance calculations to obtain all necessary process parameters. With the dryer model of the process simulator, users should be able to further drill down, on the basis of the balance calculations, to scoping, scaling up, or dryer rating.
4. A cost estimator that can be used to estimate the equipment cost and operating cost based on the process simulation results.

The two advanced units are as follows:

1. A set of simulators that can be used to simulate the coupled heat and mass transfer within the drying material for drying controlled by internal diffusion
2. A set of simulators that can be used to simulate gas–material interaction (such as gas–particle two-phase flow) with the inter gas–material heat and mass transfer

The experiment processor is used to establish a material model, which is needed by the dryer selector and process simulator. The dryer equipment model is shared by the process simulator and the cost estimator. The material model, drying gas model, and dryer equipment model can be shared by the process simulator and the simulators in the two advanced units.

With the four essential units of the *drying suite*, design engineers should be able to design any drying system incorporating any typical dryer; process engineers should be able to simulate any drying process or drying plant to optimize or troubleshoot their drying operations.

With the two advanced units of the *drying suite*, R&D engineers and researchers can carry out cost-effective simulations for better design, optimization, and control. With simulation of the internal heat and mass transfer, drying time under different operating conditions can be predicted to help both process and dryer designs. With simulation of the inter-gas–material heat and mass transfer, geometry and details inside the dryer

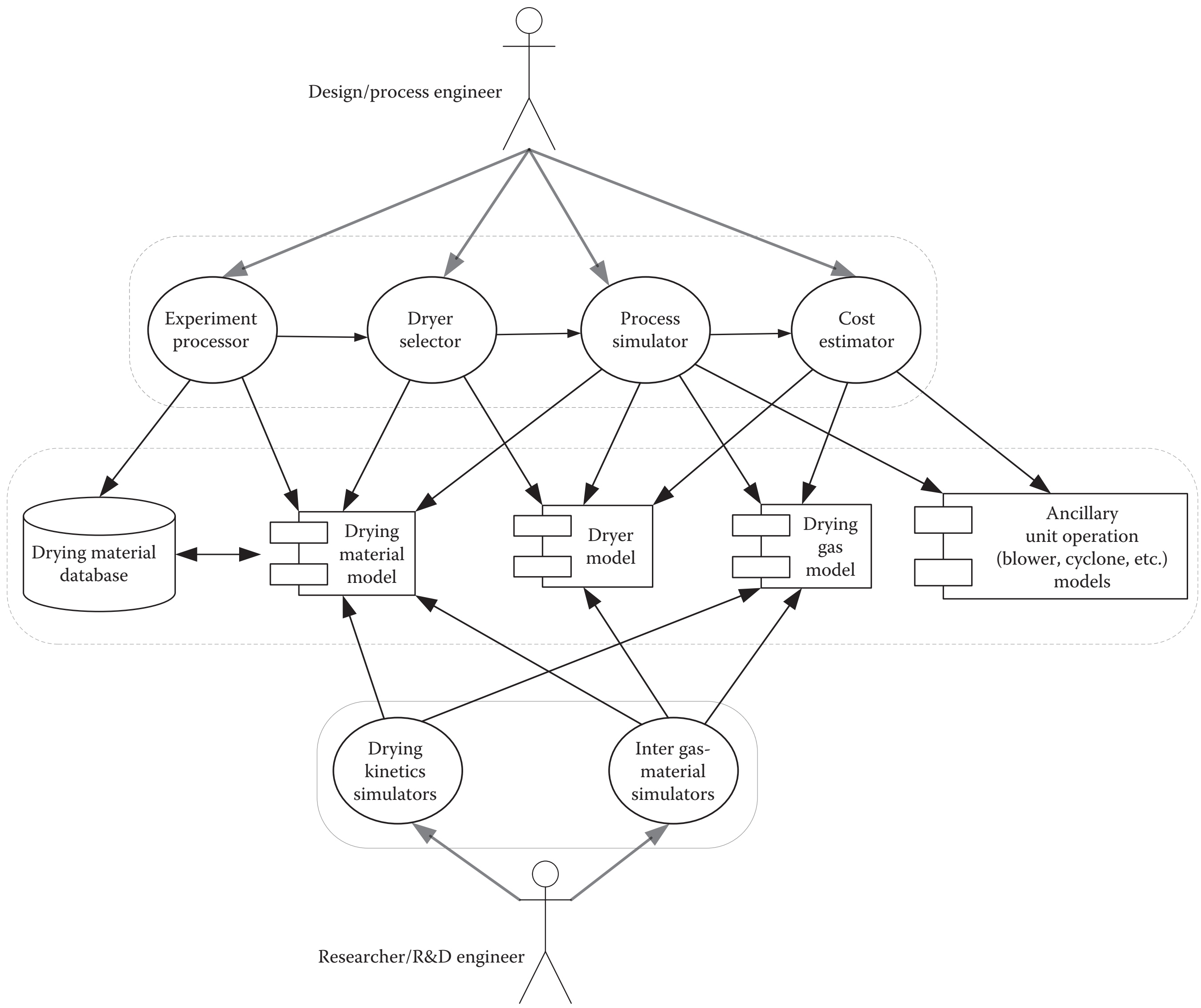

FIGURE 60.1 Top-level architecture of *drying suite*.

can be experimented under different heat and flow conditions to optimize and refine the dryer geometries and drying conditions. Researchers can use the two advanced units to effectively develop innovative concepts and ideas in drying as is proposed by Huang and Mujumdar (2005) and Mujumdar and Wu (2008).

60.3 AVAILABLE DRYING SOFTWARE

A search identified only three commercial software packages are specifically intended for drying. They are *Simprosys*, dryPAK, and DrySel. After a brief introduction of dryPAK and DrySel, focus will be put on the latest *Simprosys*.

dryPAK is a DOS-based software package that does dryer design calculations including heat and mass balance and drying kinetics calculations (Pakowski, 1994). The equilibrium method or the characteristic drying curve method can be combined to model the process kinetics. Mass transfer coefficients and other kinetic data can be entered to calculate the dryer length. DrySel is an expert system for dryer selection (Kemp et al., 2004). It lists and compares many options for over 50 different types of dryer to perform a chosen drying duty. It is a proprietary software package.

It is worthwhile to mention that a general-purpose spray dryer modeling software package, called DrySPEC2 (DRYer System for Property and Energy Control), developed by NIZO food research (the Netherlands), can model the processing conditions, energy usage, powder properties, etc., for a two-stage spray drying system (Verdurmen et al., 2002; Straatsma et al., 2007). This model uses heat and mass balance equations, sorption equations, etc., and needs some calibration data before parametric studies can be carried out. This software has been successfully tested in spray drying of milk, whey permeate, etc. For a detailed model based on CFD, NIZO has also developed a software package entitled DrySim. Such a model can be very useful in examining effects of geometry, flow conditions, etc., which can be useful for troubleshooting (Straatsma et al., 1999). Recently, Kudra et al. (2009) have developed an Excel spreadsheet template for the analysis of energy performance of convective dryers.

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Although many CFD-based models for dryers such as spray, fluid bed, flash, and impinging jet have been developed as parts of R&D projects in academia, they are not openly available and often not user-friendly. They are also of limited validity over parameter ranges tested.

Free software available on the Internet for humidity and psychrometric calculations is of limited value for practical drying calculations such as dryer flowsheet calculations since drying problems are much more complicated. AQ3

60.4 SIMPROSYS

Simprosys is a Windows-based process simulator developed by Simprotek Corporation (www.simprotek.com). It was developed with the expertise of the authors on drying, process simulation, and software development. It is developed using the most advanced software technology, viz. Microsoft. Net and C#.

Simprosys 3.0 contains 20 unit operation modules and 2 utilities as displayed in Figure 60.2. The 20 unit operation modules include solid dryer, liquid dryer, burner, cyclone, air filter, bag filter, electrostatic precipitator, wet scrubber, scrubber condenser, fan/blower, compressor, steam jet ejector, pump, valve, heater, cooler, heat exchanger that can also be used as an evaporator, liquid–vapor separator, mixer, and tee. The 2 utility modules are the humidity charts utility and unit converter utility.

Simprosys 3.0 provides a comprehensive and integrated but simple and easy tool not only for the calculation of humid gas properties of 14 solvent–gas systems (including combustion gases from any specified fossil fuel) but also for the process modeling and simulation of these 14 solvent–gas drying systems.

In addition to the most commonly encountered water–air and water–combustion systems, *Simprosys 3.0* can also model and simulate the following 13 solvent–gas systems:

1. Ethanol–nitrogen
2. Acetic acid–nitrogen
3. Acetone–nitrogen
4. Methanol–nitrogen
5. *N*-Propanol–nitrogen
6. Isopropanol–nitrogen
7. *N*-Butanol–nitrogen
8. Isobutanol–nitrogen
9. Ethanol–air
10. Acetic acid–air
11. Carbon tetrachloride–air
12. Benzene–air
13. Toluene–air

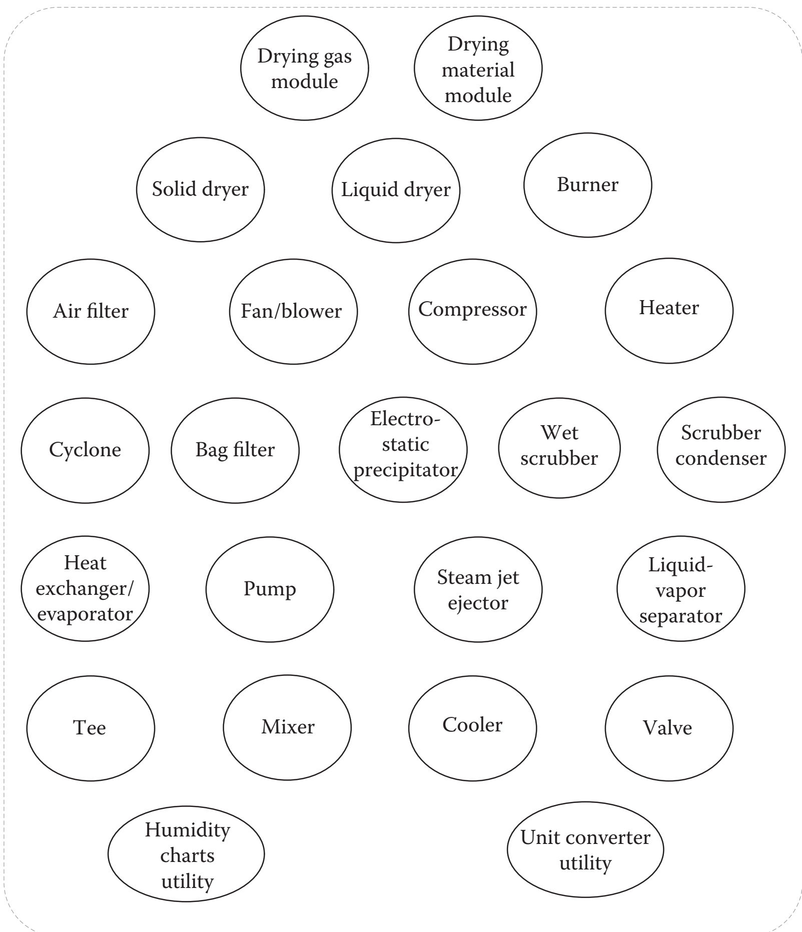

FIGURE 60.2 Modules in *Simprosys 3.0.*

The burner unit operation of *Simprosys* can not only be combined with the dryer and other unit operations to simulate combustion drying systems but also be used for design of new burners and evaluation of existing burners.

60.5 BASICS OF SIMPROSYS

Simprosys is based on extensive studies presented in the most authoritative drying technology journal; handbooks in drying by Mujumdar (2007), Masters (1985), and Perry (1977); and many other handbooks on chemical engineering calculations and unit operations such as Chopey (2003), Reynolds et al. (2002), Walas (1990), Ibarz and Barbosa-Canovas (2002), and Kuppan (2000).

60.5.1 Drying Gas Model

The calculations of absolute humidity, relative humidity, wet-bulb temperature, dew point temperature, humid volume, humid heat, and humid enthalpy are based on information found in Pakowski and Mujumdar (2007) and Moyers and Baldwin (1997).

For water–air system, the properties (including saturation pressure) of water are calculated according to the 1967 ASME steam tables; the properties of dry air are based on Liley et al. (1997). For other solvent–gas systems such as ethanol–nitrogen, the properties of both the solvent and the gas are based on Liley et al. (1997), Yaws (1999), and Yaw and Gabbula (2003).

Figure 60.3 shows the software interface of a gas stream based on the drying gas model. It should be noted that values in white cells are specified by the user and values in gray cells are calculated by *Simprosys*.

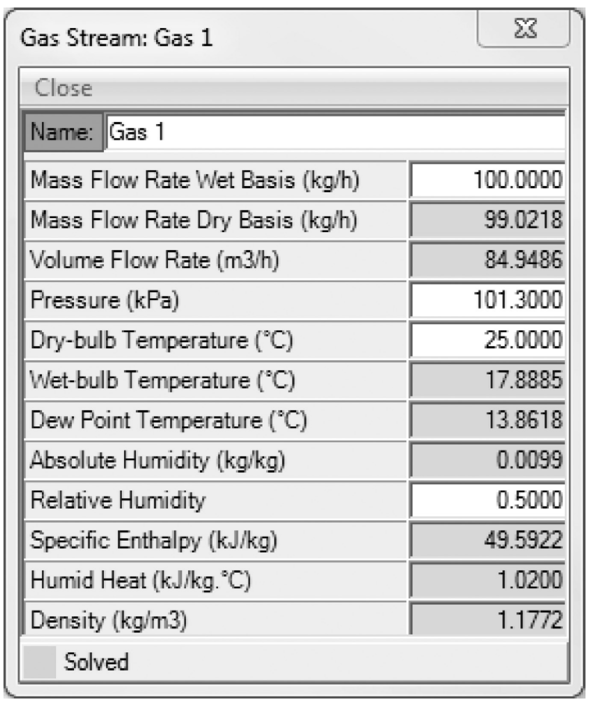

FIGURE 60.3 Software interface of gas stream.

On the drying gas stream interface, one can specify pressure, one of the three temperature parameters (either dry-bulb temperature, wet-bulb temperature, or dew point temperature), and one of the two humidity parameters (either absolute humidity or relative humidity); then all the other thermal physical property variables are automatically calculated by *Simprosys* and displayed on the interface. Whenever one of the flow rate parameters (either mass flow rate wet basis, mass flow rate dry basis, or volume flow rate) is specified and the state of the moist air is determined, the other AQ4 flow rates are automatically calculated and displayed on the gas stream's interface.

60.5.2 Dryer Models

The heat and mass balance calculations of the solid and liquid dryers of *Simprosys* are based on the following two equations (Pakowski and Mujumdar, 2007):

$$W_G\left(Y_O - Y_I\right) = W_{ev} = W_S\left(X_I - X_O\right) \tag{60.1}$$

$$W_G\left(I_{GI} - I_{GO}\right) + Q_c + \Delta Q_t + Q_m = W_S\left(I_{SO} - I_{SI}\right) + Q_l \tag{60.2}$$

where

- W_G is the gas mass flow rate (dry basis)
- Y_O *and* Y_I are gas outlet and inlet absolute humidity, respectively
- W_S is the solid throughput (mass flow rate dry basis)
- X_I and X_O are the inlet and outlet moisture content (dry basis), respectively
- I_{GI} and I_{GO} are gas inlet and outlet specific enthalpy, respectively
- I_{SI} and I_{SO} are solid inlet and outlet specific enthalpy, respectively
- Q_c is heat indirectly supplied to the dryer
- Q_l is heat loss of the dryer
- ΔQ_t is net heat carried in by transport device
- Q_m is mechanical energy input

Figure 60.4 shows the software interface of the solid dryer. It should be noted that values in white cells are specified by the user and values in gray cells are calculated by *Simprosys*.

In the *Simprosys* solid dryer model, you can specify the hot gas (inlet) temperature and humidity (either absolute or relative) and either the exhaust gas (outlet) temperature or the exhaust gas humidity (either absolute or relative) to calculate how much drying air is needed. You can also specify the hot gas flow rate, temperature, and humidity to calculate the exhaust gas temperature and humidity.

From Figure 60.4 one can see that the *thermal efficiency* and *specific heat consumption* of the dryer are automatically obtained with the heat and mass balance calculations.

Since design, optimization, and troubleshooting of a dryer or drying system may require knowledge of various process parameters, the dryer unit operation is designed for multiple different use cases so that the user can specify different process parameters in different scenarios for convenience.

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Table 60.1 lists some typical use cases that *Simprosys* supports for both the solid and liquid dryers. Each row in Table 60.1 represents a use case. In each of the cases in Table 60.1, the *Specified* columns are major process parameters user can specify, and the *Calculated* colums are major process parameters calculated by *Simprosys* with user-specified values.

Take case 2 in Table 60.1, for example. One can calculate the needed gas outlet temperature of a dryer by specifying the desired exhaust gas relative humidity as is displayed in Figure 60.5.

Due to space limitation, we cannot list all the supported use cases of the dryer models. Interested readers are encouraged to visit www.simprotek.com and download a trial version of *Simprosys 3.0* and try it out.

In addition to the heat and mass balance calculations, the *Simprosys* dryers (solid and liquid) also have a simple scoping model based on Kemp and Oakley (2002). After heat and mass balance calculation, one can input the drying gas velocity in the dryer to get the size of the dryer calculated.

60.5.3 Burner Model

The stoichiometry relationships used to determine the compositions of combustion in the burner model of *Simprosys* are based on Gary (2003). The enthalpy of formation of chemical compounds is based on Yaw and Gabbula (2003).

The calculation of theoretical flame temperature is based on the assumption that combustion process is an adiabatic constant volume process. Since the temperature of the combustion in drying is, in general, not very high, dissociations are not taken into consideration in the calculation of flame temperature of the burner model.

The specific heat of each component of the air and combustion is temperature dependent and based on Liley et al. (1997), Yaws (1999), and Yaw and Gabbula (2003). The specific heat of combustion for the calculation of flame temperature is calculated as an integral average in the temperature range of the combustion from the starting to end temperatures.

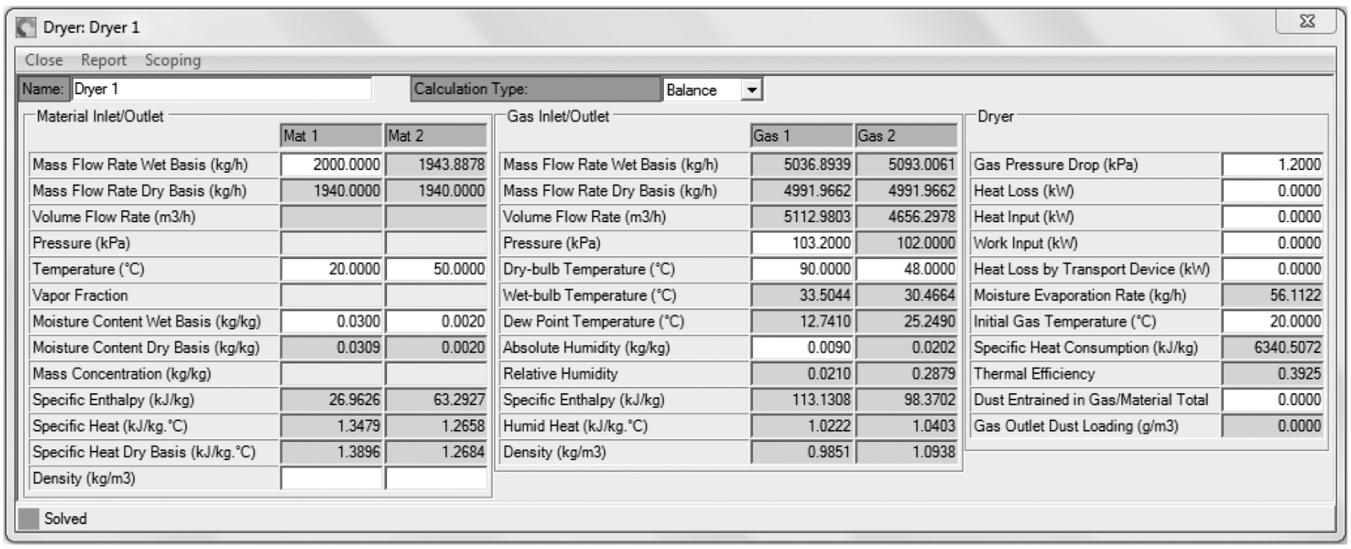

FIGURE 60.4 Software interface of solid dryer.

TABLE 60.1
Typical Use Cases of Solid and Liquid Dryer Models

Case	Specified	Specified	Specified	Specified	Calculated	Calculated
1	Gas inlet temperature	Gas inlet humidity	Gas outlet temperature	Material inlet mass flow rate	Gas outlet humidity	Gas inlet mass flow rate
2	Gas inlet temperature	Gas inlet humidity	Gas outlet humidity	Material inlet mass flow rate	Gas outlet temperature	Gas inlet mass flow rate
3	Gas inlet temperature	Gas inlet humidity	Gas inlet mass flow rate	Material inlet mass flow rate	Gas outlet temperature	Gas outlet humidity
4	Gas inlet mass flow rate	Gas inlet absolute humidity	Gas outlet temperature	Material inlet mass flow rate	Gas inlet temperature	Gas outlet humidity
5	Gas inlet absolute humidity	Gas outlet temperature	Gas outlet absolute humidity	Material inlet mass flow rate	Gas inlet temperature	Gas inlet mass flow rate
6	Gas inlet temperature	Gas inlet humidity	Gas inlet mass flow rate	Gas outlet temperature	Material inlet mass flow rate	Gas outlet humidity

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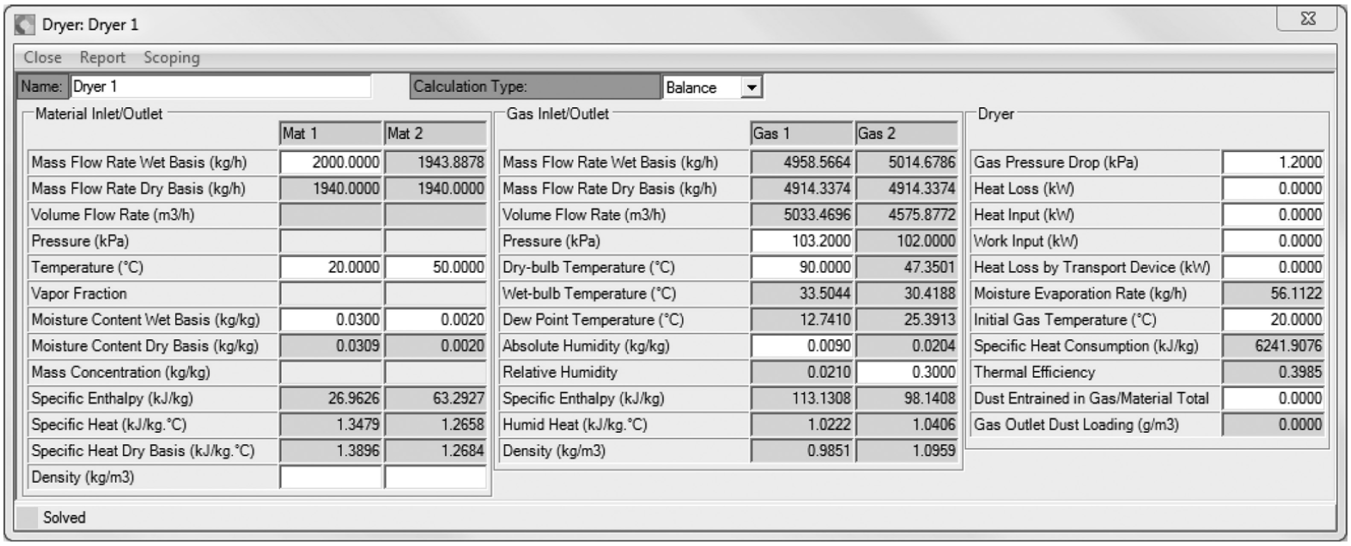


FIGURE 60.5 Simulation of dryer design for required exhaust gas relative humidity.

Figure 60.6 shows the software interface of the burner. It should be noted that values in white cells are specified by the user and values in gray cells are calculated by *Simprosys*.

From Figure 60.6, one can see that the user can choose a fuel from a list of predefined fuels (the fuel is defined in the fuel catalog of *Simprosys*). Then he or she can specify the mass flow rate, pressure, and temperature of the drying fuel; then the pressure, temperature, and relative humidity of air; the pressure of the flue gas; and the excess air% and heat loss% of the burner. *Simprosys* calculates the flow rates of the required air and the temperature, moisture contents, and flow rates of the flue gas, etc.

Since design, optimization, and troubleshooting of a drying system or a burner may require knowledge of various process parameters, the burner unit operation is designed for multiple different use cases so that the user can specify different process parameters in different scenarios for convenience.

Table 60.2 lists all possible use cases that *Simprosys* supports for the burner unit operation. Each row in Table 60.2 represents a use case. In each of the cases in Table 60.2, the *Specified* columns are major process parameters user can specify, and the *Calculated* colums are major process parameters calculated by *Simprosys* with user-specified values.

Take case 2 in Table 60.2, for example. One can evaluate the heat loss of a burner by measuring the actual flue gas AQ5
temperature and excess air% and then input these measured AQ6
values into the unit operation model to get the heat loss% of the burner calculated as displayed in Figure 60.7.

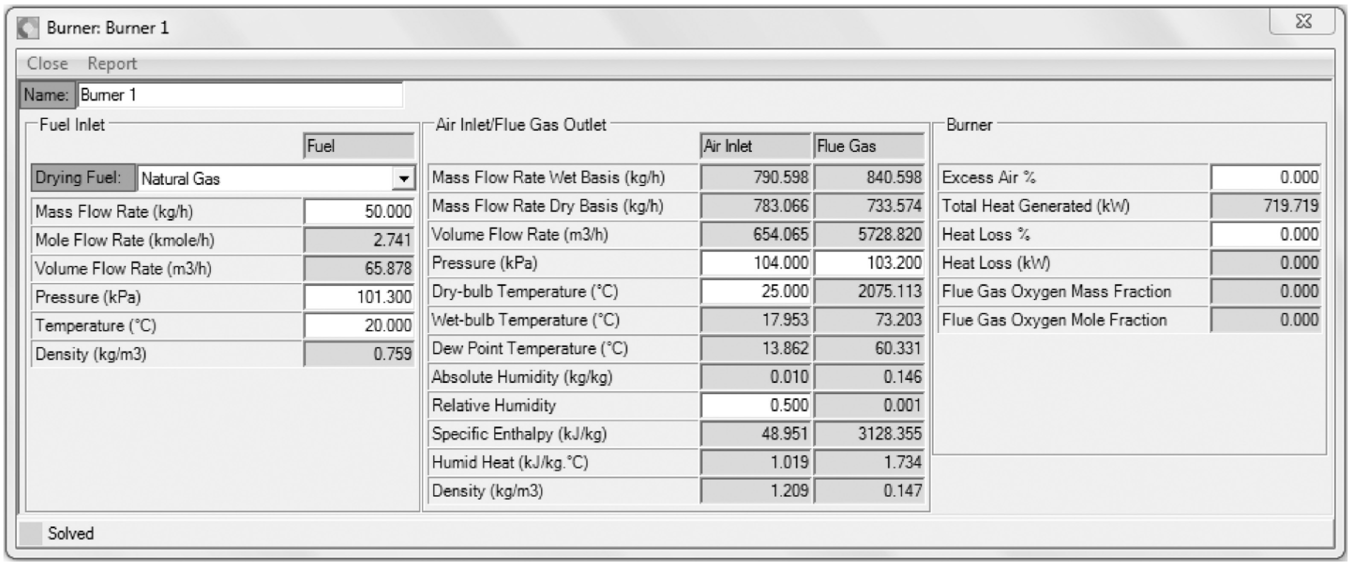


FIGURE 60.6 Software interface of burner.

TABLE 60.2
Use Cases of Burner Model

Case	Specified	Specified	Specified	Calculated	Calculated
1	Fuel mass flow rate	Excess air	Heat loss	Flue gas temperature	Flue gas mass flow rate
2	Fuel mass flow rate	Flue gas temperature	Excess air	Flue gas mass flow rate	Heat loss
3	Fuel mass flow rate	Flue gas temperature	Heat loss	Flue gas mass flow rate	Excess air
4	Flue gas temperature	Flue gas mass flow rate	Excess air	Fuel mass flow rate	Heat loss
5	Flue gas temperature	Flue gas mass flow rate	Heat loss	Fuel mass flow rate	Excess air
6	Flue gas mass flow rate	Excess air	Heat loss	Flue gas temperature	Fuel mass flow rate

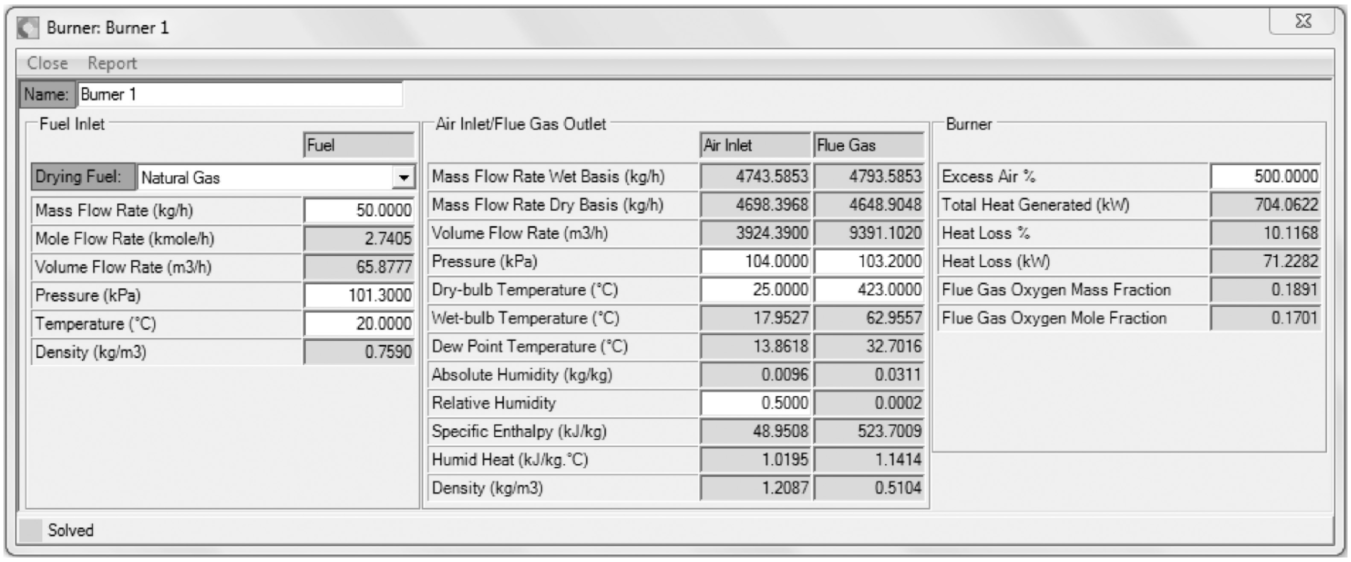


FIGURE 60.7 Heat loss evaluation of burner.

60.5.4 Material Property Model

Current material model in *Simprosys* supports two types of materials. One is generic material type and the other is generic food type.

For drying-related balance simulation of a generic material, you only need to provide the specific heat of the bone dry material. The specific heat of the material with moisture content is calculated as a weighted average of the bone dry material and the moisture as follows:

$$c_{wm} = (1.0 - w)c_{dm} + wc_{moisture} \quad (60.3)$$

where

c_{wm}, c_{dm}, $c_{moisture}$ represent the specific heats of wet material, bone dry material, and liquid moisture, respectively
w stands for the moisture content (wet basis) of the material

When evaporation-related balance simulation is involved,
AQ7 Durhing lines of the material solution to account for boiling point rise are required as input in addition to the specific heat of the bone dry material.

For a generic food material, the basic composition of the material needs to be specified. Five basic components constitute a generic food material in addition to its moisture. They are carbohydrate, ash, fiber, fat, and protein.

The specific heat of a generic food material without moisture content is calculated as a weighted average of each of the five basic components. The specific heat as a function of temperature for each of the five basic components is based on Ibarz and Barbosa-Canovas (2002) and Heldman (2001) and is listed in Table 60.3.

TABLE 60.3
Specific Heats of Generic Food Components

Carbohydrate	$c_p = 1.5488 + 1.9625 \times 10^{-3}T - 5.9399 \times 10^{-6}T^2$
Ash	$c_p = 1.0926 + 1.8896 \times 10^{-3}T - 3.6817 \times 10^{-6}T^2$
Fiber	$c_p = 1.8459 + 1.8306 \times 10^{-3}T - 4.6509 \times 10^{-6}T^2$
Fat	$c_p = 1.9842 + 1.4733 \times 10^{-3}T - 4.8008 \times 10^{-6}T^2$
Protein	$c_p = 2.0082 + 1.2089 \times 10^{-3}T - 1.3129 \times 10^{-6}T^2$

The unit of temperature T is °C and that of c_p is kJ/kg °C in Table 60.3.

For drying-related balance simulation, you need to specify the mass fraction for each of the five basic components to obtain the specific heat of the bone dry material. The specific heat of a generic food material with moisture is calculated as a weighted average of the bone dry food material and the moisture according to Equation 60.3.

60.5.5 Nonaqueous Systems

The psychrometric ratio model of the nonaqueous systems is based on the following governing equation (Equation 60.4) of wet-bulb temperature (Keey, 1978; Pakowski and Mujumdar, 2007):

$$\frac{t - t_{WB}}{Y - Y_{s,WBT}} = -\frac{\Delta h_{v,WBT}}{c_H} Le^{-2/3}\phi \tag{60.4}$$

where

t and t_{WB} are the dry-bulb and wet-bulb temperatures, respectively
Y is the absolute humidity
$Y_{s,\ WBT}$ is the saturation humidity at wet-bulb temperature
$\Delta h_{v,WBT}$ is the latent heat of evaporation at wet-bulb temperature
c_H is the humid heat

Le and ϕ are Lewis number and humidity-potential coefficient defined by

$$Le = \frac{\lambda_g}{c_P \rho_g D_{AB}} \tag{60.5}$$

and

$$\phi = \frac{M_A/M_B}{Y^* - Y} \ln\left(1 + \frac{Y^* - Y}{M_A/M_B + Y}\right) \tag{60.6}$$

where

λ_g, c_P, and ρ_g are the thermal conductivity, specific heat, and density of the humid gas, respectively
M_A and M_B are the molar mass of the moisture and dry gas, respectively
Y^* is the saturation humidity
D_{AB} is the binary diffusivity between the moisture and the gas

For water–air system, $Le^{-2/3}\phi \approx 1$, and it is well accepted $Le^{-2/3}\phi = 1$.

For carbon tetrachloride–air, benzene–air, and toluene–air systems, the values of 0.51, 0.54, and 0.47 are used in *Simprosys* for $Le^{-2/3}\phi$ (Moyers and Baldwin, 1997).

For any other solvent–gas systems, the value of $Le^{-2/3}\phi$ is calculated according to Equations 60.5 and 60.6. The value of D_{AB} in Equation 60.5 is based on Fuller et al. (1966, 1969) and Poling et al. (2001):

$$D_{AB} = \frac{0.01013T^{1.75}\left(\frac{1}{M_A} + \frac{1}{M_B}\right)^{1/2}}{P\left[\left(\Sigma_A v_i\right)^{1/3} + \left(\Sigma_B v_i\right)^{1/3}\right]^2} \tag{60.7}$$

where

T and P are the temperature and pressure of the liquid–gas system
T and P are K and Pa, respectively, with the resulting diffusivity in m^2/s

All v_i are group contribution values for the subscript component summed over atoms, groups, and structural features given in Table III of Fuller et al. (1969) or Table 60.1 of Poling et al. (2001).

Please refer to Gong and Mujumdar (2010) for details about the calculations of nonaqueous drying systems.

60.5.6 Other Unit Operation Models

The heat exchanger models in *Simprosys* are based on Knudsen et al. (1997), Richard et al. (1997), Walas (1990), Kuppan (2000), Kakac and Liu (2002), McCabe et al. (2000), and Chopey (2003). The cyclone models are based on Pell and Dunson (1997), Zenz (1999), and Reynolds et al. (2003). The electrostatic precipitator model is based on Pell and Dunson (1997) and Reynolds et al. (2003). The wet scrubber model is based on Pell and Dunson (1997) and Schifftner and Hesketh (1983). All the other unit operation models of *Simprosys* are based on Perry (1997).

60.6 SAMPLE APPLICATIONS OF SIMPROSYS

Using the unit operation modules provided by *Simprosys*, one can readily construct any drying- and evaporation-related process. One can also readily explore different arrangements of unit operations and experiment with different operating conditions to optimize alternate designs and operations. With *Simprosys*, one can simulate both design and rating problems and it is extremely easy to switch back and forth between design and rating simulations.

Design engineers can use *Simprosys* to design drying- and evaporation-related plants. Based on design requirements, they can quickly lay out the flowsheet and compute the heat/mass/pressure balance of the whole plant and obtain the necessary process parameters such as the air flow rate to the dryer, the capacity and power requirements for the blower, and the heat duty of the heater. As part of the heat and mass balance calculation results, the *thermal efficiency* and *specific heat consumption* of the dryer(s) are automatically obtained. For combustion drying, they can obtain the needed process parameters such as the required drying fuel *flow rate* and corresponding air flow rate of the burner to the dryer, and the *capacity* and *power* requirements for the blower. They can explore various arrangements of the unit operations and experiment with different operating conditions to reach an optimized design. After the balance calculation is finalized, they then can choose equipment according to the simulation results.

Process engineers can simulate existing plant by easily laying out the plant on a flowsheet and input the operating conditions to obtain the heat and mass balance calculation results. They can see how efficient current operation is according to the calculated *thermal efficiency* and *specific heat consumption* of the dryer(s). They can try different operating conditions to optimize the operation. They can also use *Simprosys* as an effective troubleshooting tool to find which unit is not working as designed.

University instructors will find *Simprosys* an efficient teaching tool for undergraduate and postgraduate students working on design and research projects in chemical engineering unit operations, food process engineering, agricultural engineering, etc. They can show students the effects of the input parameters on the output parameters of a typical plant. With *Simprosys*, students can do what-if analysis, which otherwise would take an unrealistically long time to accomplish. Thus, this software can be used by creative instructors as a valuable teaching tool as well.

Practicing engineers and scientists can use *Simprosys* as a self-learning tool.

Since different units may be used in different countries, *Simprosys* has an extremely convenient unit conversion system. Users can convert the inputs and outputs of a large flowsheet from one set of units to another with just one mouse click.

The humidity chart utility can be used to visualize either the state of a drying gas or an isenthalpic drying process. The unit converters utility can do unit conversion from one unit to any another unit for any chemical engineering variable.

Simprosys has an intuitive and user-friendly interface with maximum protection to prevent users from making simple mistakes. It also has an effective tutorial to teach users step by step to use the software to simulate typical drying- and evaporation-related problems. Users of this software will require minimal self-training and effort to use it effectively. Typical calculations of a process that may take a skilled engineer several weeks to carry out can now be accomplished in several hours with *Simprosys*.

60.7 EXAMPLES OF SIMPROSYS

Five examples and two applications are selected here to demonstrate the applications of *Simprosys*. The first example is a two-stage drying flowsheet with the exhaust gas from the second dryer mixed with fresh air as the first dryer's inlet gas. The second one is a typical drying flowsheet with a recycled material stream. The third is a combined two-effect evaporation and two-stage drying flowsheet. The fourth is a simple combustion drying flowsheet. The fifth one is a closed-loop ethanol–nitrogen drying flowsheet. The first application is a parametric study for coal drying. The second one is an energy audit of a fiberboard drying production line.

Readers can develop their own flowsheet within a short time of self-training.

Example 60.1: A drying flowsheet with recycled exhaust gas stream

The drying material is a liquid. Feed solid mass content = 57% wet basis. Feed temperature = 97°C. Feed pressure = 101.3 kPa. The material goes through a spray dryer to be dried to a moisture content of 8.5% wet basis. Material outlet temperature is 50°C. Then it goes through a vibrated fluidized bed dryer to get the product dried to the final moisture content of 0.3% wet basis. Material product temperature is 52°C. Specific heat of the bone dry material = 1.26 kJ/kg·°C. Mass flow rate of wet material = 5000 kg/h.

Drying air has the following conditions: Initial pressure = 101.3 kPa. Initial temperature (dry bulb) = 22°C. Initial relative humidity = 40%. Mass flow rate of fresh air = 42000 kg/h.

Drying air to the spray dryer goes through an air filter with a pressure drop of 0.3 kPa. Assume dust volume concentration is 0.1 g/m^3, collection efficiency of the air filter is 99.8%, and filtration velocity is 2.5 m/s. The drying air then goes through a blower (the efficiency is 0.75) to gain 3.4 kPa static pressure, then through a heater to be heated to 140°C, and then to the spray dryer. Pressure drop of air in the heater and the spray dryer is 1.0 and 1.2, respectively. The exhaust air entrains 0.1% of the total material in both dryers. Exhaust gas from the spray dryer goes through a cyclone to collect 95% of the entrained dust material. Pressure drop of gas in the cyclone is 0.6 kPa.

Drying air to the vibrated fluidized bed dryer goes through an air filter with the same operating conditions as the air filter for the spray dryer. It then goes through a blower (the efficiency is 0.75) to gain 2.0 kPa static pressure, then through a heater to be heated to 90°C, and then to the vibrated fluidized bed dryer. Relative humidity of the exhaust air from the fluidized bed is 40%. Pressure drop of air in the heater and the fluidized bed dryer is 0.6 and 1.0, respectively. The exhaust air entrains 0.1% of the total material in both dryers. Exhaust air from the vibrated fluidized bed dryer goes through a cyclone to collect 95% of the entrained dust material. Pressure drop of gas in the cyclone is 0.6 kPa. Exhaust air coming out of the cyclone goes through a blower (the efficiency of the blower is 0.75) to be compressed to 103.4 kPa and then is mixed with the fresh air coming out of the air heater for the spray dryer and sent to the spray dryer inlet.

The established flowsheet using *Simprosys* is displayed in Figure 60.8. The simulated result is shown in Figure 60.9.

With current flowsheet, one can specify the absolute humidity of the fresh air instead of the relative humidity or specify the heating duty of the heaters rather than the air inlet temperatures of the dryers to simulate either design mode or operation mode. One can also change the material inlet temperature and/or moisture content to see how the air outlet temperature and humidity change.

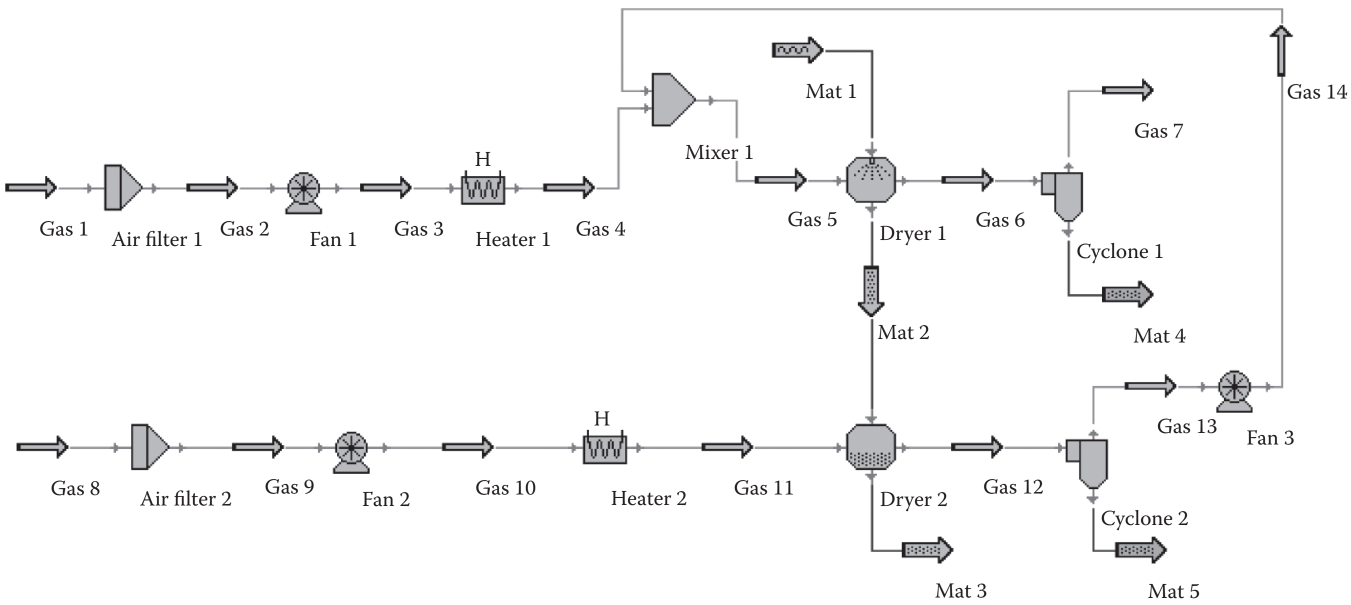
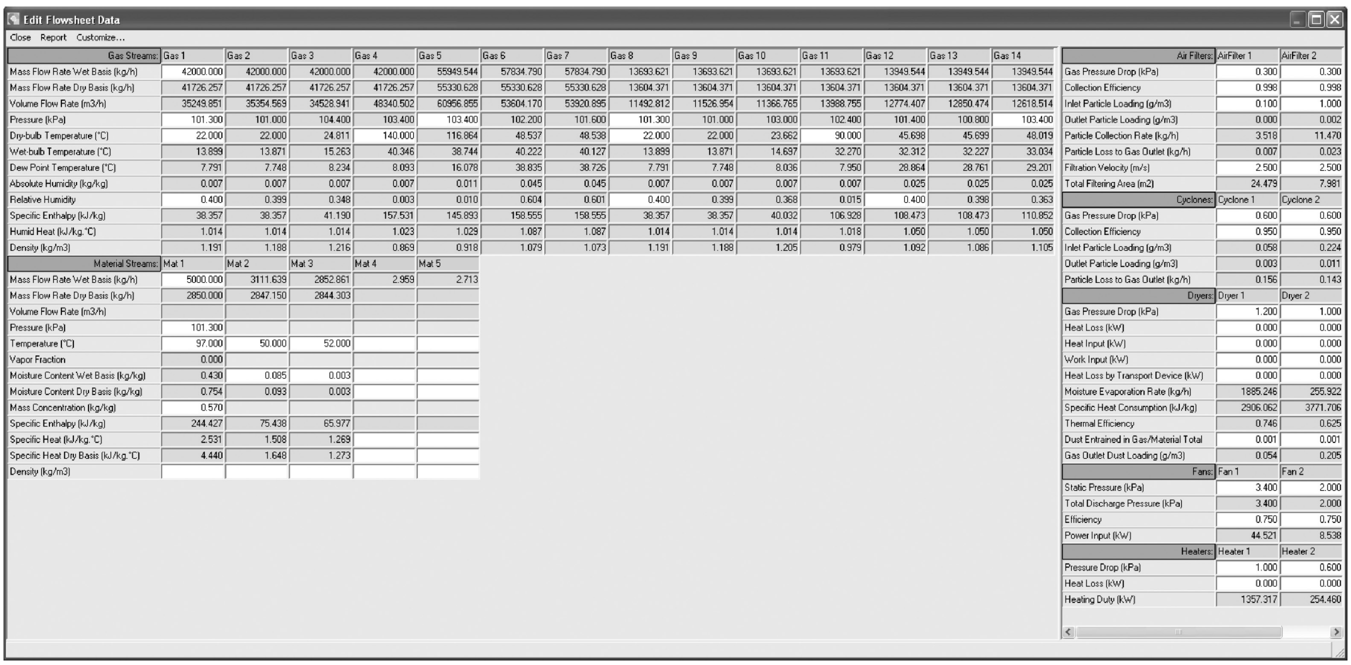


FIGURE 60.8 Flowsheet with recycled exhaust gas stream.



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Gas Streams:	Gas 1	Gas 2	Gas 3	Gas 4	Gas 5	Gas 6	Gas 7
Mass Flow Rate Wet Basis (kg/h)	42000.000	42000.000	42000.000	42000.000	55949.544	57834.790	57834.790
Mass Flow Rate Dry Basis (kg/h)	41726.257	41726.257	41726.257	41726.257	55330.628	55330.628	55330.628
Volume Flow Rate (m3/h)	35249.851	35354.569	34528.941	48340.502	60956.855	53604.170	53920.895
Pressure (kPa)	101.300	101.000	104.400	103.400	103.400	102.200	101.600
Dry-bulb Temperature (°C)	22.000	22.000	24.811	140.000	116.864	48.537	48.538
Wet-bulb Temperature (°C)	13.899	13.871	15.263	40.346	38.744	40.222	40.127
Dew Point Temperature (°C)	7.791	7.748	8.234	8.093	16.078	38.835	38.726
Absolute Humidity (kg/kg)	0.007	0.007	0.007	0.007	0.011	0.045	0.045
Relative Humidity	0.400	0.399	0.348	0.003	0.010	0.604	0.601
Specific Enthalpy (kJ/kg)	38.357	38.357	41.190	157.531	145.893	158.555	158.555
Humid Heat (kJ/kg.°C)	1.014	1.014	1.014	1.023	1.029	1.087	1.087
Density (kg/m3)	1.191	1.188	1.216	0.869	0.918	1.079	1.073

Gas Streams:	Gas 8	Gas 9	Gas 10	Gas 11	Gas 12	Gas 13	Gas 14
Mass Flow Rate Wet Basis (kg/h)	13693.621	13693.621	13693.621	13693.621	13949.544	13949.544	13949.544
Mass Flow Rate Dry Basis (kg/h)	13604.371	13604.371	13604.371	13604.371	13604.371	13604.371	13604.371
Volume Flow Rate (m3/h)	11492.812	11526.954	11366.765	13988.755	12774.407	12850.474	12618.514
Pressure (kPa)	101.300	101.000	103.000	102.400	101.400	100.800	103.400
Dry-bulb Temperature (°C)	22.000	22.000	23.662	90.000	45.698	45.699	48.019
Wet-bulb Temperature (°C)	13.899	13.871	14.697	32.270	32.312	32.227	33.034
Dew Point Temperature (°C)	7.791	7.748	8.036	7.950	28.864	28.761	29.201
Absolute Humidity (kg/kg)	0.007	0.007	0.007	0.007	0.025	0.025	0.025
Relative Humidity	0.400	0.399	0.368	0.015	0.400	0.398	0.363
Specific Enthalpy (kJ/kg)	38.357	38.357	40.032	106.928	108.473	108.473	110.852
Humid Heat (kJ/kg.°C)	1.014	1.014	1.014	1.018	1.050	1.050	1.050
Density (kg/m3)	1.191	1.188	1.205	0.979	1.092	1.086	1.105

Material Streams:	Mat 1	Mat 2	Mat 3	Mat 4	Mat 5
Mass Flow Rate Wet Basis (kg/h)	5000.000	3111.639	2852.861	2.959	2.713
Mass Flow Rate Dry Basis (kg/h)	2850.000	2847.150	2844.303		
Volume Flow Rate (m3/h)					
Pressure (kPa)	101.300				
Temperature (°C)	97.000	50.000	52.000		
Vapor Fraction	0.000				
Moisture Content Wet Basis (kg/kg)	0.430	0.085	0.003		
Moisture Content Dry Basis (kg/kg)	0.754	0.093	0.003		
Mass Concentration (kg/kg)	0.570				
Specific Enthalpy (kJ/kg)	244.427	75.438	65.977		
Specific Heat (kJ/kg.°C)	2.531	1.508	1.269		
Specific Heat Dry Basis (kJ/kg.°C)	4.440	1.648	1.273		
Density (kg/m3)					

Air Filters:	AirFilter 1	AirFilter 2
Gas Pressure Drop (kPa)	0.300	0.300
Collection Efficiency	0.998	0.998
Inlet Particle Loading (g/m3)	0.100	1.000
Outlet Particle Loading (g/m3)	0.000	0.002
Particle Collection Rate (kg/h)	3.518	11.470
Particle Loss to Gas Outlet (kg/h)	0.007	0.023
Filtration Velocity (m/s)	2.500	2.500
Total Filtering Area (m2)	24.479	7.981
Cyclones:	**Cyclone 1**	**Cyclone 2**
Gas Pressure Drop (kPa)	0.600	0.600
Collection Efficiency	0.950	0.950
Inlet Particle Loading (g/m3)	0.058	0.224
Outlet Particle Loading (g/m3)	0.003	0.011
Particle Loss to Gas Outlet (kg/h)	0.156	0.143
Dryers:	**Dryer 1**	**Dryer 2**
Gas Pressure Drop (kPa)	1.200	1.000
Heat Loss (kW)	0.000	0.000
Heat Input (kW)	0.000	0.000
Work Input (kW)	0.000	0.000
Heat Loss by Transport Device (kW)	0.000	0.000
Moisture Evaporation Rate (kg/h)	1885.246	255.922
Specific Heat Consumption (kJ/kg)	2906.062	3771.706
Thermal Efficiency	0.746	0.625
Dust Entrained in Gas/Material Total	0.001	0.001
Gas Outlet Dust Loading (g/m3)	0.054	0.205
Fans:	**Fan 1**	**Fan 2**
Static Pressure (kPa)	3.400	2.000
Total Discharge Pressure (kPa)	3.400	2.000
Efficiency	0.750	0.750
Power Input (kW)	44.521	8.538
Heaters:	**Heater 1**	**Heater 2**
Pressure Drop (kPa)	1.000	0.600
Heat Loss (kW)	0.000	0.000
Heating Duty (kW)	1357.317	254.460

FIGURE 60.9 Simulation results for Example 60.1.

Example 60.2: A drying flowsheet incorporating a recycled material stream

The material to be dried is in the form of solid particles. Initial moisture content = 25% wet basis. Final moisture content = 0.2% wet basis. Initial temperature = 20°C. Product temperature = 48°C. Specific heat of the bone dry material = 1.26 kJ/kg·°C. Mass flow rate of wet material = 1000 kg/h.

Drying air has the following conditions: Initial pressure = 101.3 kPa. Initial temperature = 20°C. Initial relative humidity = 45%. Mass flow rate of humid air = 10000 kg/h.

Drying air goes through an air filter. Pressure drop in the air filter is 0.3 kPa. Assume dust volume concentration is 0.1 g/m^3, collection efficiency of the air filter is 99.8%, and filtration velocity is 2.5 m/s. Drying air then goes through a blower (the efficiency of the blower is 0.7) to gain 3 kPa static pressure, then through a heater to be heated to 110°C. Pressure drop of air in heater and dryer is 0.8 and 1.2 kPa, respectively. The exhaust air of the dryer entrains 0.1% of the total material. The gas outlet stream needs to go through a cyclone to collect the entrained dust material. Collection efficiency of the cyclone is 95%. Pressure drop of air in the cyclone is 0.6 kPa.

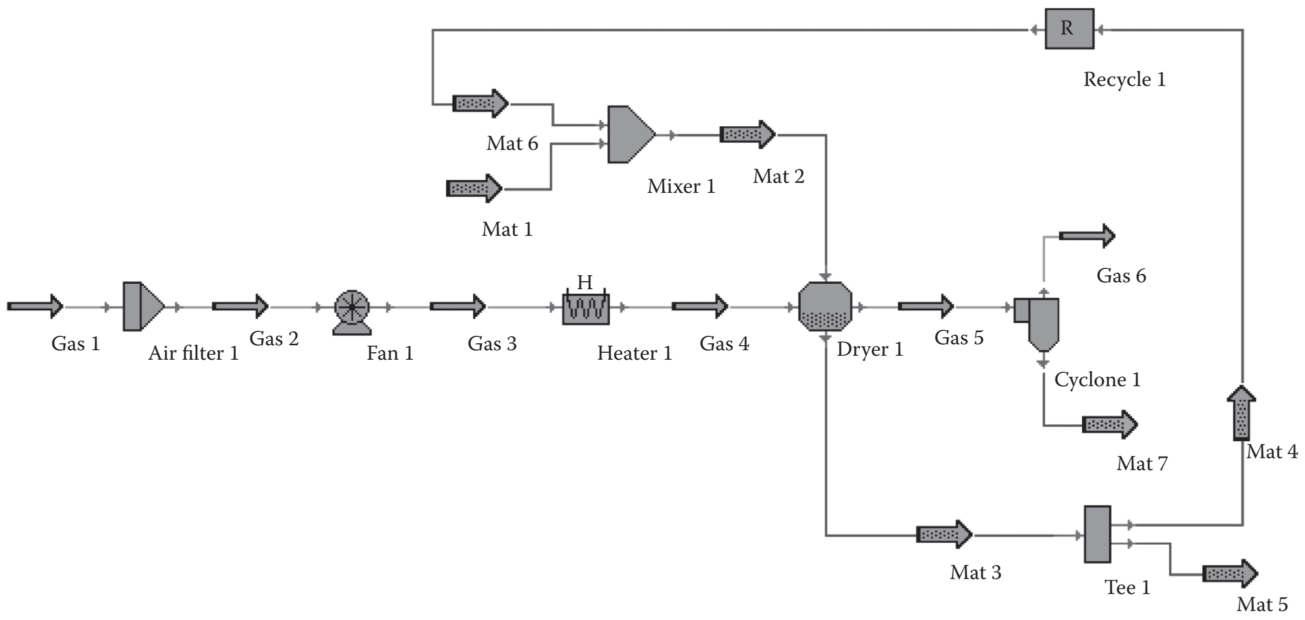

FIGURE 60.10 Flowsheet with recycled material stream.

The dryer requires that the feed moisture content (wet basis) be less than 15%. As is known, initial moisture content (wet basis) of the material is 25%. One solution is to mix a portion of the dried material product with the fresh material to decrease the moisture content to the required moisture content level and then feed the dryer.

A tee is required to split the product material into two streams. One stream goes through a recycle and mixes with the fresh material in a mixer and then is introduced into the dryer material inlet. The established flowsheet is displayed in Figure 60.10. The simulated result is shown in Figure 60.11.

Simulation results indicate that about one half of the dry product from the dryer needs to be mixed with the original material to satisfy the material inlet moisture content requirement.

With this flowsheet, the designer can easily specify the absolute humidity of the fresh air instead of the relative humidity, or specify the heating duty of the heater rather than the air inlet temperature of the dryer to simulate different use cases of the flowsheet. It is also possible to change the material inlet temperature and/or moisture content or the dry product ratio recycled (e.g., 40% or 60% dry product to be recycled) to see how the air outlet temperature and humidity are affected.

Example 60.3: Combined evaporation and two-stage drying

Liquid material of 4000 kg/h flow rate is initially at a solid mass content of 13% and a temperature of 3°C. It needs to be concentrated to a solid content (mass concentration) of about 57% before it is sent to a spray dryer. Material density is 720 kg/m^3 at initial temperature. Concentration process needs to be performed at around atmospheric pressure. Specific heat of the material without moisture is 1.26 kJ/kg·°C. The boiling point rise of the material solution can be described by the following Durhing lines expressed in Table 60.4.

Concentrated liquid material is dried through a two-stage drying process. It first goes through a spray dryer to be dried to a moisture content of 8% wet basis. It then goes through a vibrated fluidized bed dryer to be dried to a moisture content of 4% wet basis. The drying air of the spray dryer is at 103.2 kPa and 140°C. The exhaust air of the spray dryer is at 68°C. Dried material from the spray dryer is at 55°C. The drying air of the vibrated fluidized bed dryer is at 103.8 kPa and 85°C. The exhaust air of the vibrated fluidized bed dryer is at 45°C. Dried material from the vibrated fluidized bed dryer is at 52°C. Part of the secondary vapor from the second effect evaporator is used to preheat the drying air.

Concentration of the liquid can be achieved by a two-effect falling film evaporation process. The initial liquid material is first preheated using part of the secondary vapor from the second effect evaporation to about 81°C. Then part of the thermally compressed secondary vapor from the first effect is used to further heat the material to nearly the bubble point of the material. It then goes to the first falling film evaporator operating at a pressure of 106 kPa. Water vapor of 265 kPa is used as the heating steam for this evaporator. Vapor and liquid mixture coming out of the first evaporator goes to a liquid–vapor separator to separate the concentrated liquid with the vapor. Secondary vapor coming out of the separator is compressed with a fresh steam of 350 kPa using a steam jet ejector. A very small portion of the compressed secondary vapor is used to preheat the feeding material from 81°C to nearly the bubble point as indicated before. The majority of the compressed secondary vapor is used as the heating steam of the second effect evaporator. The second effect evaporator is operating at about 100 kPa. Liquid–vapor mixture coming out of the second effect evaporator goes to another liquid–vapor separator to

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Gas Streams:	Gas 1	Gas 2	Gas 3	Gas 4	Gas 5	Gas 6	
Mass Flow Rate Wet Basis (kg/h)	10000.0000	10000.0000	10000.0000	10000.0000	10248.4970	10248.4970	
Mass Flow Rate Dry Basis (kg/h)	9935.1579	9935.1579	9935.1579	9935.1579	9935.1579	9935.1579	
Volume Flow Rate (m3/h)	8335.7813	8360.5447	8187.7087	10694.3647	9372.3361	9427.8187	
Pressure (kPa)	101.3000	101.0000	104.0000	103.2000	102.0000	101.4000	
Dry-bulb Temperature (°C)	20.0000	20.0001	22.4673	110.0000	46.0343	46.0351	
Wet-bulb Temperature (°C)	13.0789	13.0516	14.2973	35.8829	35.0358	34.9474	
Dew Point Temperature (°C)	7.7161	7.6726	8.1023	7.9888	32.6121	32.5073	
Absolute Humidity (kg/kg)	0.0065	0.0065	0.0065	0.0065	0.0315	0.0315	
Relative Humidity	0.4500	0.4487	0.3971	0.0075	0.4870	0.4841	
Specific Enthalpy (kJ/kg)	36.2595	36.2595	38.7452	127.1024	123.6304	123.6304	
Humid Heat (kJ/kg.°C)	1.0135	1.0135	1.0136	1.0195	1.0613	1.0613	
Density (kg/m3)	1.1996	1.1961	1.2213	0.9351	1.0935	1.0870	
Material Streams:	**Mat 1**	**Mat 2**	**Mat 3**	**Mat 4**	**Mat 5**	**Mat 6**	**Mat 7**
Mass Flow Rate Wet Basis (kg/h)	1000.0000	1750.0002	1500.0017	750.0008	750.0008	750.0002	1.4264
Mass Flow Rate Dry Basis (kg/h)	750.0000	1498.5002	1497.0017	748.5008	748.5008	748.5002	
Volume Flow Rate (m3/h)							
Pressure (kPa)							
Temperature (°C)	20.0000	29.0526	48.0000	48.0002	48.0002	48.0002	
Vapor Fraction							
Moisture Content Wet Basis (kg/kg)	0.2500	0.1437	0.0020	0.0020	0.0020	0.0020	
Moisture Content Dry Basis (kg/kg)	0.3333	0.1678	0.0020	0.0020	0.0020	0.0020	
Mass Concentration (kg/kg)							
Specific Enthalpy (kJ/kg)	39.8887	48.8341	60.7610	60.7610	60.7610	60.7612	
Specific Heat (kJ/kg.°C)	1.9924	1.6810	1.2658	1.2659	1.2659	1.2658	
Specific Heat Dry Basis (kJ/kg.°C)	2.6566	1.9632	1.2684	1.2684	1.2684	1.2684	
Density (kg/m3)							

Air Filters:	AirFilter 1
Gas Pressure Drop (kPa)	0.3000
Collection Efficiency	0.9980
Inlet Particle Loading (g/m3)	1.0000
Outlet Particle Loading (g/m3)	0.0020
Particle Collection Rate (kg/h)	8.3191
Particle Loss to Gas Outlet (kg/h)	0.0167
Filtration Velocity (m/s)	2.5000
Total Filtering Area (m2)	5.7887
Cyclones:	**Cyclone 1**
Gas Pressure Drop (kPa)	0.6000
Collection Efficiency	0.9500
Inlet Particle Loading (g/m3)	0.1602
Outlet Particle Loading (g/m3)	0.0080
Particle Collection Rate (kg/h)	1.4264
Particle Loss to Gas Outlet (kg/h)	0.0751
Dryers:	**Dryer 1**
Gas Pressure Drop (kPa)	1.2000
Heat Loss (kW)	0.0000
Heat Input (kW)	0.0000
Work Input (kW)	0.0000
Heat Loss by Transport Device (kW)	0.0000
Moisture Evaporation Rate (kg/h)	248.4970
Initial Gas Temperature (°C)	20.0000
Specific Heat Consumption (kJ/kg)	3647.0216
Thermal Efficiency	0.6710
Dust Entrained in Gas/Material Total	0.0010
Gas Outlet Dust Loading (g/m3)	0.1465
Fans:	**Fan 1**
Static Pressure (kPa)	3.0000
Total Discharge Pressure (kPa)	3.0000
Efficiency	0.7000
Power Input (kW)	9.9530
Heaters:	**Heater 1**
Pressure Drop (kPa)	0.8000
Heat Loss (kW)	0.0000
Heating Duty (kW)	245.4365

FIGURE 60.11 Simulation results for Example 60.2.

TABLE 60.4
Durhing Lines

Mass Concentration (kg/kg)	Start Boiling Point (°C)		End Boiling Point (°C)	
	Solvent	Solution	Solvent	Solution
0.0	50	50	200	200
0.2	50	52	200	203
0.4	50	55	200	207
0.6	50	59	200	212

separate the concentrated liquid with the vapor. As is mentioned earlier, part of the secondary vapor is used to preheat the feeding material.

The established flowsheet is displayed in Figure 60.12. The results of the calculation are shown in Figure 60.13. Note that not all results are shown in the table due to space limitation in Figure 60.13. Interested readers may visit www.simprotek.com to download a trial version of *Simprosys 3.0* and load Example 12 in the tutorial to fully study this example.

Example 60.4: Combustion drying

The drying material is wet solid particles. Feed moisture content = 22% wet basis. Feed temperature = 20°C. Product temperature = 50°C. Product moisture content = 0.2% wet basis. Specific heat of the absolute dry material = 1.26 kJ/kg·°C. Mass flow rate wet basis = 2000 kg/h.

Air has the following conditions: Initial pressure = 101.3 kPa, initial temperature (dry bulb) = 20°C, and initial absolute humidity = 0.009 kg/kg.

Natural gas compositions are as listed in Table 60.5. Pressure = 101.3 kPa. Temperature = 20°C. Mass flow rate = 34 kg/h.

Air to the burner needs to go through an air filter first. Pressure drop in the air filter is 0.3 kPa. Assume dust volume concentration is 0.1 g/m^3, collection efficiency of the air filter is 99.8%, and filtration velocity is 2.5 m/s. Air then goes through a fan (the efficiency of the fan is 0.7) to gain 3 kPa static pressure and then enters a burner to generate the needed combustion for the dryer. Excess air% of the burner is 500%. Heat loss of the burner is 10%. Flue gas outlet pressure is 103.2 kPa. Pressure drop of flue gas in dryer is 1.2 kPa. The exhaust gas entrains 0.1% of the AQ8

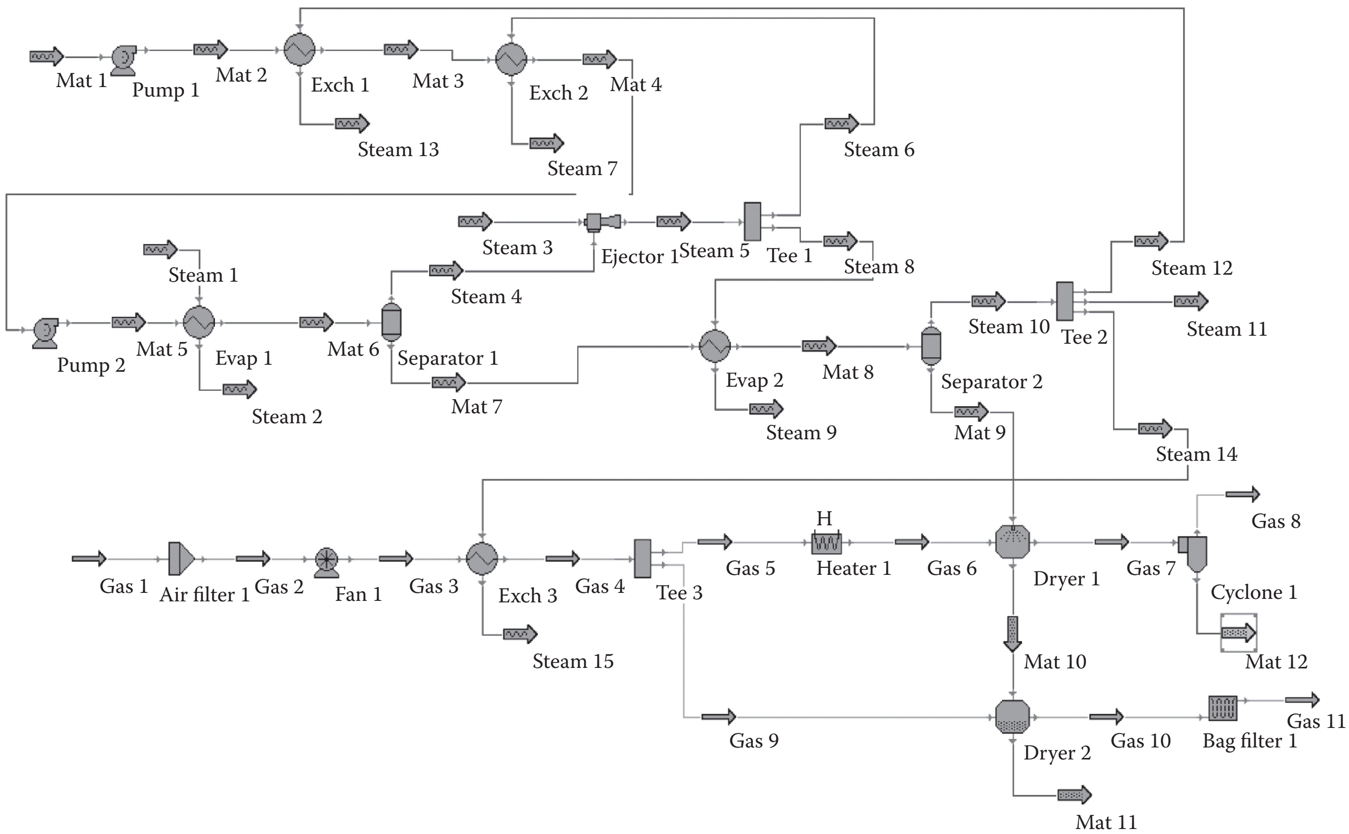
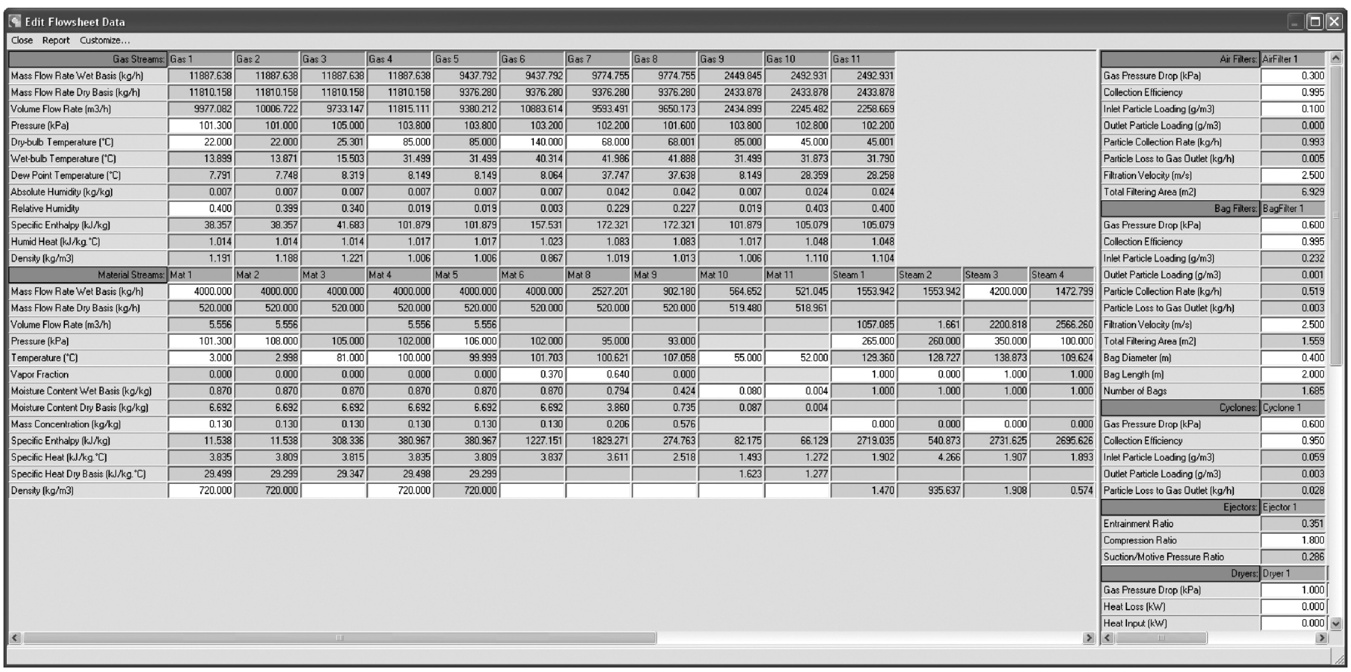


FIGURE 60.12 Combined evaporation and drying flowsheet.



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Gas Streams:	Gas 1	Gas 2	Gas 3	Gas 4	Gas 5	Gas 6	Gas 7	Gas 8	Gas 9	Gas 10	Gas 11
Mass Flow Rate Wet Basis (kg/h)	11887.638	11887.638	11887.638	11887.638	9437.792	9437.792	9774.755	9774.755	2449.845	2492.931	2492.931
Mass Flow Rate Dry Basis (kg/h)	11810.158	11810.158	11810.158	11810.158	9376.280	9376.280	9376.280	9376.280	2433.878	2433.878	2433.878
Volume Flow Rate (m3/h)	9977.082	10006.722	9733.147	11815.111	9380.212	10883.614	9593.491	9650.173	2434.899	2245.482	2258.669
Pressure (kPa)	101.300	101.000	105.000	103.800	103.800	103.200	102.200	101.600	103.800	102.800	102.200
Dry-bulb Temperature (°C)	22.000	22.000	25.301	85.000	85.000	140.000	68.000	68.001	85.000	45.000	45.001
Wet-bulb Temperature (°C)	13.899	13.871	15.503	31.499	31.499	40.314	41.986	41.888	31.499	31.873	31.790
Dew Point Temperature (°C)	7.791	7.748	8.319	8.149	8.149	8.064	37.747	37.638	8.149	28.359	28.258
Absolute Humidity (kg/kg)	0.007	0.007	0.007	0.007	0.007	0.007	0.042	0.042	0.007	0.024	0.024
Relative Humidity	0.400	0.399	0.340	0.019	0.019	0.003	0.229	0.227	0.019	0.403	0.400
Specific Enthalpy (kJ/kg)	38.357	38.357	41.683	101.879	101.879	157.531	172.321	172.321	101.879	105.079	105.079
Humid Heat (kJ/kg.°C)	1.014	1.014	1.014	1.017	1.017	1.023	1.083	1.083	1.017	1.048	1.048
Density (kg/m3)	1.191	1.188	1.221	1.006	1.006	0.867	1.019	1.013	1.006	1.110	1.104

Material Streams:	Mat 1	Mat 2	Mat 3	Mat 4	Mat 5	Mat 6	Mat 8	Mat 9	Mat 10	Mat 11	Steam 1	Steam 2	Steam 3	Steam 4
Mass Flow Rate Wet Basis (kg/h)	4000.000	4000.000	4000.000	4000.000	4000.000	4000.000	2527.201	902.180	564.652	521.045	1553.942	1553.942	4200.000	1472.799
Mass Flow Rate Dry Basis (kg/h)	520.000	520.000	520.000	520.000	520.000	520.000	520.000	520.000	519.480	518.961				
Volume Flow Rate (m3/h)	5.556	5.556		5.556	5.556						1057.085	1.661	2200.818	2566.260
Pressure (kPa)	101.300	108.000	105.000	102.000	106.000	102.000	95.000	93.000			265.000	260.000	350.000	100.000
Temperature (°C)	3.000	2.998	81.000	100.000	99.999	101.703	100.621	107.058	55.000	52.000	129.360	128.722	138.873	109.624
Vapor Fraction	0.000	0.000	0.000	0.000	0.000	0.370	0.640	0.000			1.000	0.000	1.000	1.000
Moisture Content Wet Basis (kg/kg)	0.870	0.870	0.870	0.870	0.870	0.870	0.794	0.424	0.080	0.004	1.000	1.000	1.000	1.000
Moisture Content Dry Basis (kg/kg)	6.692	6.692	6.692	6.692	6.692	6.692	3.860	0.735	0.087	0.004				
Mass Concentration (kg/kg)	0.130	0.130	0.130	0.130	0.130	0.130	0.206	0.576			0.000	0.000	0.000	0.000
Specific Enthalpy (kJ/kg)	11.538	11.538	308.336	380.967	380.967	1227.151	1829.271	274.763	82.175	66.129	2719.035	540.873	2731.625	2695.626
Specific Heat (kJ/kg.°C)	3.835	3.809	3.815	3.835	3.809	3.837	3.611	2.518	1.493	1.272	1.902	4.266	1.907	1.893
Specific Heat Dry Basis (kJ/kg.°C)	29.499	29.299	29.347	29.498	29.299				1.623	1.277				
Density (kg/m3)	720.000	720.000		720.000	720.000						1.470	935.637	1.908	0.574

Air Filters:	AirFilter 1
Gas Pressure Drop (kPa)	0.300
Collection Efficiency	0.995
Inlet Particle Loading (g/m3)	0.100
Outlet Particle Loading (g/m3)	0.000
Particle Collection Rate (kg/h)	0.993
Particle Loss to Gas Outlet (kg/h)	0.005
Filtration Velocity (m/s)	2.500
Total Filtering Area (m2)	6.929
Bag Filters:	**BagFilter 1**
Gas Pressure Drop (kPa)	0.600
Collection Efficiency	0.995
Inlet Particle Loading (g/m3)	0.232
Outlet Particle Loading (g/m3)	0.001
Particle Collection Rate (kg/h)	0.519
Particle Loss to Gas Outlet (kg/h)	0.003
Filtration Velocity (m/s)	2.500
Total Filtering Area (m2)	1.559
Bag Diameter (m)	0.400
Bag Length (m)	2.000
Number of Bags	1.685
Cyclones:	**Cyclone 1**
Gas Pressure Drop (kPa)	0.600
Collection Efficiency	0.950
Inlet Particle Loading (g/m3)	0.059
Outlet Particle Loading (g/m3)	0.003
Particle Loss to Gas Outlet (kg/h)	0.028
Ejectors:	**Ejector 1**
Entrainment Ratio	0.351
Compression Ratio	1.800
Suction/Motive Pressure Ratio	0.286
Dryers:	**Dryer 1**
Gas Pressure Drop (kPa)	1.000
Heat Loss (kW)	0.000
Heat Input (kW)	0.000

FIGURE 60.13 Simulation results of Example 60.3.

TABLE 60.5
Natural Gas Compositions

Component	Mass Fraction
Methane	0.8
Ethane	0.108
Propane	0.02
N-Butane	0.016
Carbon dioxide	0.04
Oxygen	0.002
Nitrogen	0.025
Hydrogen sulfide	0.025

total material. It needs to go through a cyclone to collect the entrained dust material. Collection efficiency of the cyclone is 95%. Pressure drop of the cyclone is 0.6 kPa.

The established flowsheet using *Simprosys* is displayed in Figure 60.14. The simulated results are shown in Figure 60.15.

From Figure 60.15, one can see that the calculated combustion temperature, mass flow rate, and absolute moisture content are 421.7°C, 3257.7 kg/h, and 0.031 kg/kg, respectively. The required air mass flow rate for combustion generation is 3223.7 kg/h. Total heat generation and heat loss of the burner are 478.8 kW and 47.9 kW, respectively.

With the same flowsheet as the one in Figure 60.14, different process parameters can be specified to simulate different cases. For example, one can specify the mass flow rate of the gas inlet stream (Gas 4) of the dryer to compute the mass flow rate of the fuel stream of the burner. One can also specify the dry-bulb temperature of gas inlet stream (Gas 4) of the dryer to get the heat loss% of the burner calculated. Such *what-if* computations can give a better feel about the process and lead to better design and operation as well.

Example 60.5: Nonaqueous drying

Drying of materials containing nonaqueous solvents is generally carried out in a closed-loop system so that the exhaust gas containing nonaqueous vapors is not discharged unto the atmosphere to pollute the air.

Simprosys is applied to the drying of a solid material containing ethanol. Due to the low flash (burning) point, nitrogen is used as the drying medium to prevent possible explosion hazard. In order not to lose both the ethanol and the nitrogen drying gas in the exhaust, a closed-loop drying system as displayed in Figure 60.16 is needed.

The input and output conditions of the drying material and nitrogen drying gas are as follows: Material feed temperature = 20°C. Feed moisture content = 8% wet basis. Wet material mass flow rate = 2000 kg/h. Product temperature = 50°C. Product moisture content = 0.2% wet basis. Nitrogen pressure at dryer inlet = 102.4 kPa. Temperature at dryer inlet = 120 °C. Mass flow rate wet basis at dryer inlet = 3000 kg/h.

Pressure drop of the dryer is 1.2 kPa. Dryer gas outlet stream goes through a fan to gain 1.5 kPa static pressure. Efficiency of the fan is 0.75. Exhaust gas coming from the fan goes through a scrubber/condenser to collect the dusts and remove the moisture carried in the exhaust gas. Temperature of the exhaust gas from the scrubber/condenser is 35°C. Gas pressure drop in scrubber/condenser is 1.0 kPa. Collection efficiency and liquid–gas ratio of the scrubber/condenser are 99% and 1.0%, respectively. Liquid inlet pressure and temperature of the scrubber/condenser are 101.3 kPa and 20°C, respectively. The gas coming out of the scrubber/condenser goes through a fan to gain some static pressure and then goes through a heater to be heated to the required dryer inlet temperature (120°C). The efficiency of the fan is set at 0.75. The pressure drop of gas in the heater is 0.6 kPa.

The flowsheet is constructed as shown in Figure 60.16. The simulation results produced using *Simprosys* are displayed in Figure 60.17.

Please be noted that one can use the heating duty of the heater, instead of the dry-bulb temperature of the dryer gas inlet, and/or the dry-bulb temperature of the dryer gas outlet, instead of the moisture content of the material inlet, as input parameter to simulate the operation of an existing drying system.

Example 60.6: Coal drying

In this case study, a simple drying flowsheet was initially simulated for drying of coal based on the assumed parameters. Most of the parameters such as initial moisture content, final expected moisture content, and drying temperature are selected based on reported values in the literature; the throughput is an individual choice. Coal with initial moisture content of 50% wet basis at 30°C

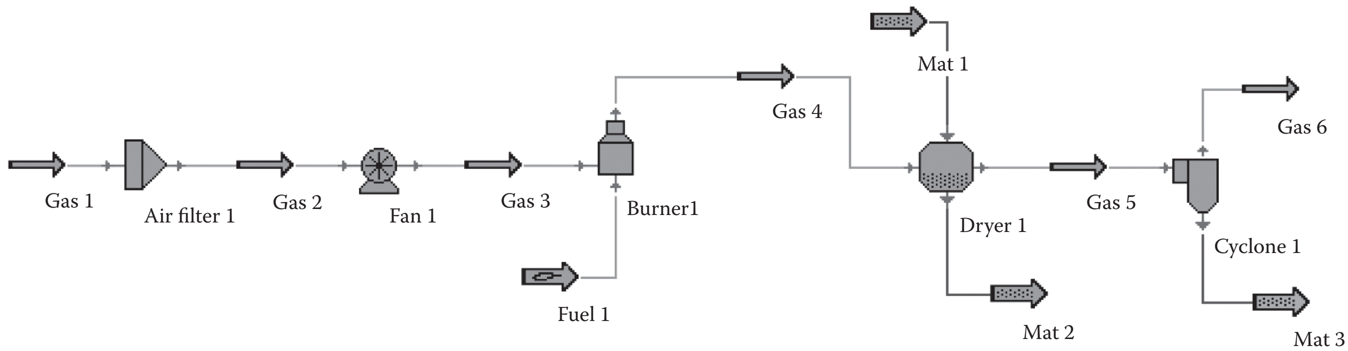

FIGURE 60.14 Combustion drying flowsheet.

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Gas Streams:	Gas 1	Gas 2	Gas 3	Gas 4	Gas 5	Gas 6
Mass Flow Rate Wet Basis (kg/h)	3223.6640	3223.6640	3223.6640	3257.6640	3694.5378	3694.5378
Mass Flow Rate Dry Basis (kg/h)	3194.9098	3194.9098	3194.9098	3161.2553	3161.2553	3161.2553
Volume Flow Rate (m3/h)	2691.1332	2699.1282	2643.3161	6367.7991	3897.3496	3920.4204
Pressure (kPa)	101.3000	101.0000	104.0000	103.2000	102.0000	101.4000
Dry-bulb Temperature (°C)	20.0000	20.0002	22.4658	421.6894	73.3694	73.3702
Wet-bulb Temperature (°C)	15.3826	15.3534	16.5422	62.8809	62.6285	62.5056
Dew Point Temperature (°C)	12.4578	12.4126	12.8588	32.3588	62.0243	61.8951
Absolute Humidity (kg/kg)	0.0090	0.0090	0.0090	0.0305	0.1687	0.1687
Relative Humidity	0.6181	0.6163	0.5455	0.0002	0.6074	0.6038
Specific Enthalpy (kJ/kg)	42.3769	42.3769	44.8667	520.5526	443.8123	443.8123
Humid Heat (kJ/kg.°C)	1.0182	1.0182	1.0182	1.1398	1.3247	1.3247
Density (kg/m3)	1.1979	1.1943	1.2196	0.5116	0.9480	0.9424

Material Streams:	Mat 1	Mat 2	Mat 3
Mass Flow Rate Wet Basis (kg/h)	2000.0000	1561.5631	1.4850
Mass Flow Rate Dry Basis (kg/h)	1560.0000	1558.4400	
Volume Flow Rate (m3/h)			
Pressure (kPa)			
Temperature (°C)	20.0000	50.0000	
Vapor Fraction			
Moisture Content Wet Basis (kg/kg)	0.2200	0.0020	
Moisture Content Dry Basis (kg/kg)	0.2821	0.0020	
Mass Concentration (kg/kg)			
Specific Enthalpy (kJ/kg)	38.1261	63.2927	
Specific Heat (kJ/kg.°C)	1.9045	1.2658	
Specific Heat Dry Basis (kJ/kg.°C)	2.4417	1.2684	
Density (kg/m3)			

Fuel Streams:	Fuel 1
Mass Flow Rate (kg/h)	34.0000
Mole Flow Rate (kmole/h)	1.8636
Volume Flow Rate (m3/h)	44.7968
Pressure (kPa)	101.3000
Temperature (°C)	20.0000
Density (kg/m3)	0.7590

Air Filters:	AirFilter 1
Gas Pressure Drop (kPa)	0.3000
Collection Efficiency	0.9980
Inlet Particle Loading (g/m3)	0.1000
Outlet Particle Loading (g/m3)	0.0002
Particle Collection Rate (kg/h)	0.2686
Particle Loss to Gas Outlet (kg/h)	0.0005
Filtration Velocity (m/s)	2.5000
Total Filtering Area (m2)	1.8688
Burner:	**Burner 1**
Excess Air %	500.0000
Total Heat Generated (kW)	478.7501
Heat Loss %	10.0000
Heat Loss (kW)	47.8750
Flue Gas Oxygen Mass Fraction	0.1892
Flue Gas Oxygen Mole Fraction	0.1702
Cyclones:	**Cyclone 1**
Gas Pressure Drop (kPa)	0.6000
Collection Efficiency	0.9500
Inlet Particle Loading (g/m3)	0.4011
Outlet Particle Loading (g/m3)	0.0199
Particle Collection Rate (kg/h)	1.4850
Particle Loss to Gas Outlet (kg/h)	0.0782
Dryers:	**Dryer 1**
Gas Pressure Drop (kPa)	1.2000
Heat Loss (kW)	0.0000
Heat Input (kW)	0.0000
Work Input (kW)	0.0000
Heat Loss by Transport Device (kW)	0.0000
Moisture Evaporation Rate (kg/h)	436.8737
Initial Gas Temperature (°C)	20.0000
Specific Heat Consumption (kJ/kg)	3081.2225
Thermal Efficiency	0.8230
Dust Entrained in Gas/Material Total	0.0010
Gas Outlet Dust Loading (g/m3)	0.4231
Fans:	**Fan 1**
Static Pressure (kPa)	3.0000
Total Discharge Pressure (kPa)	3.0000
Efficiency	0.7000
Power Input (kW)	3.2132

FIGURE 60.15 Simulation results of Example 60.4.

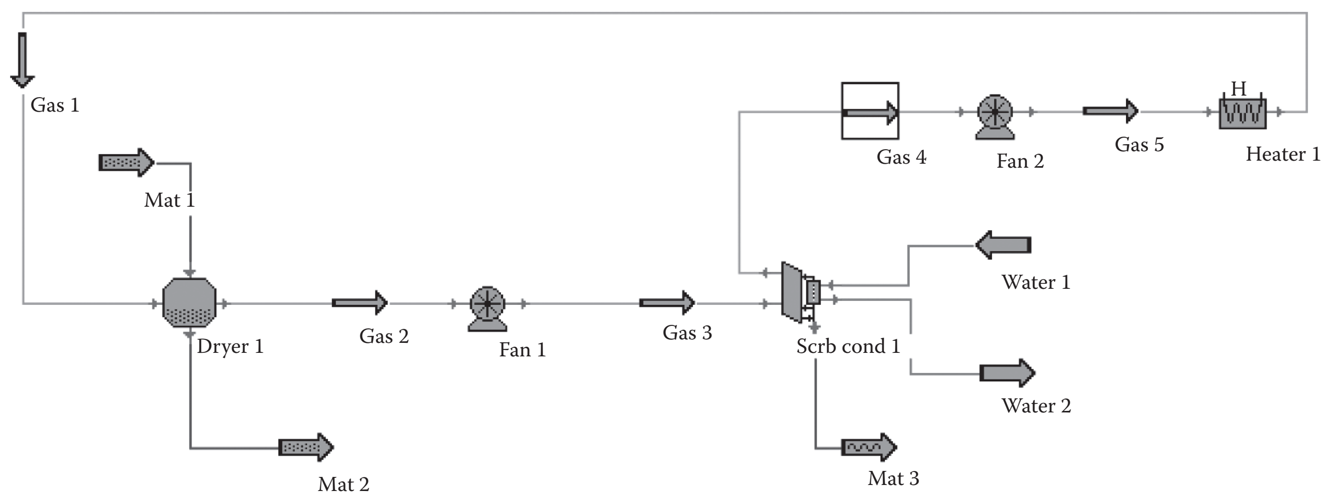

FIGURE 60.16 Closed-loop ethanol–nitrogen flowsheet.

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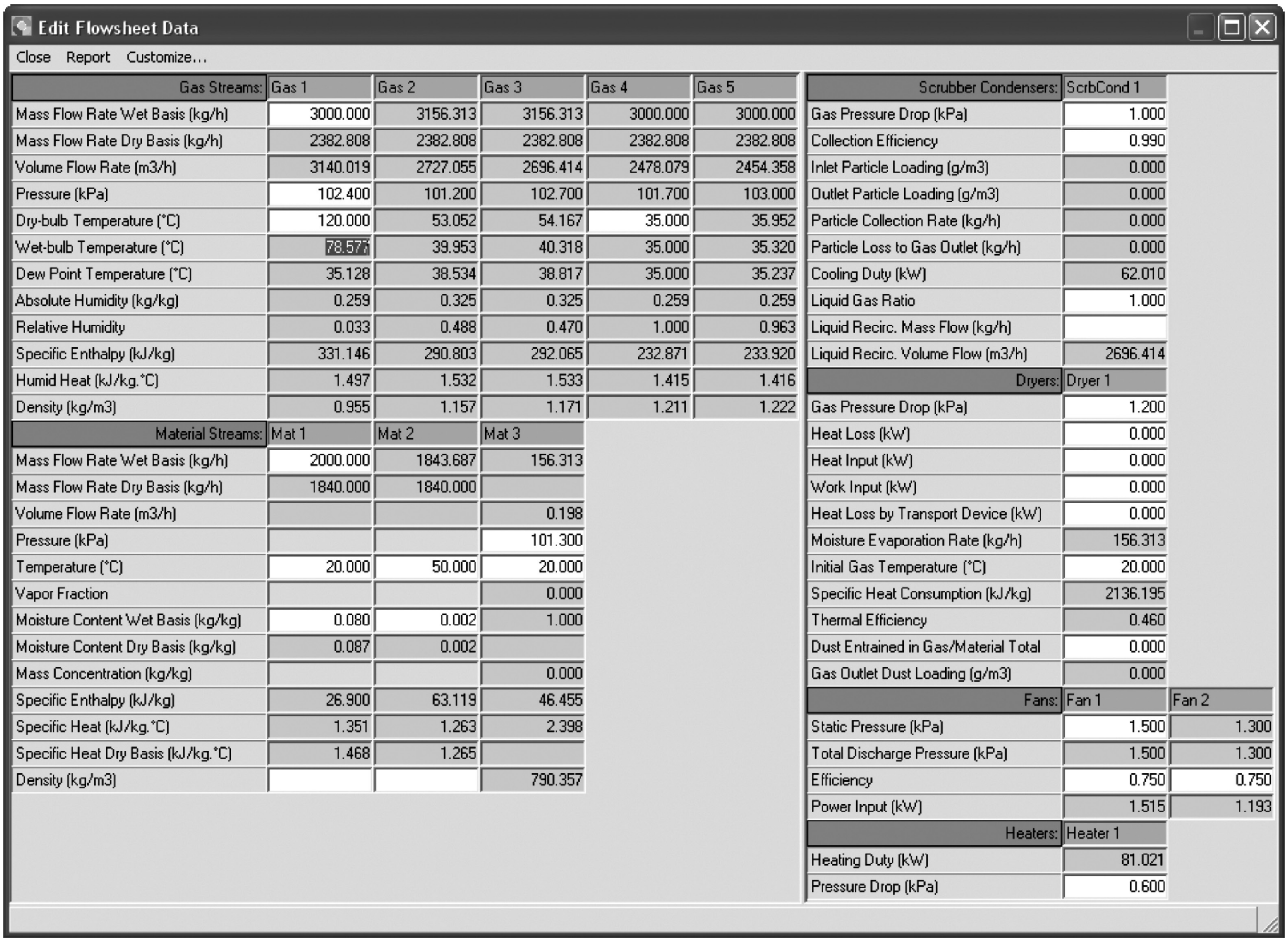

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Gas Streams:	Gas 1	Gas 2	Gas 3	Gas 4	Gas 5
Mass Flow Rate Wet Basis (kg/h)	3000.000	3156.313	3156.313	3000.000	3000.000
Mass Flow Rate Dry Basis (kg/h)	2382.808	2382.808	2382.808	2382.808	2382.808
Volume Flow Rate (m3/h)	3140.019	2727.055	2696.414	2478.079	2454.358
Pressure (kPa)	102.400	101.200	102.700	101.700	103.000
Dry-bulb Temperature (°C)	120.000	53.052	54.167	35.000	35.952
Wet-bulb Temperature (°C)	78.577	39.953	40.318	35.000	35.320
Dew Point Temperature (°C)	35.128	38.534	38.817	35.000	35.237
Absolute Humidity (kg/kg)	0.259	0.325	0.325	0.259	0.259
Relative Humidity	0.033	0.488	0.470	1.000	0.963
Specific Enthalpy (kJ/kg)	331.146	290.803	292.065	232.871	233.920
Humid Heat (kJ/kg.°C)	1.497	1.532	1.533	1.415	1.416
Density (kg/m3)	0.955	1.157	1.171	1.211	1.222

Material Streams:	Mat 1	Mat 2	Mat 3
Mass Flow Rate Wet Basis (kg/h)	2000.000	1843.687	156.313
Mass Flow Rate Dry Basis (kg/h)	1840.000	1840.000	
Volume Flow Rate (m3/h)			0.198
Pressure (kPa)			101.300
Temperature (°C)	20.000	50.000	20.000
Vapor Fraction			0.000
Moisture Content Wet Basis (kg/kg)	0.080	0.002	1.000
Moisture Content Dry Basis (kg/kg)	0.087	0.002	
Mass Concentration (kg/kg)			0.000
Specific Enthalpy (kJ/kg)	26.900	63.119	46.455
Specific Heat (kJ/kg.°C)	1.351	1.263	2.398
Specific Heat Dry Basis (kJ/kg.°C)	1.468	1.265	
Density (kg/m3)			790.357

Scrubber Condensers:	ScrbCond 1
Gas Pressure Drop (kPa)	1.000
Collection Efficiency	0.990
Inlet Particle Loading (g/m3)	0.000
Outlet Particle Loading (g/m3)	0.000
Particle Collection Rate (kg/h)	0.000
Particle Loss to Gas Outlet (kg/h)	0.000
Cooling Duty (kW)	62.010
Liquid Gas Ratio	1.000
Liquid Recirc. Mass Flow (kg/h)	
Liquid Recirc. Volume Flow (m3/h)	2696.414

Dryers:	Dryer 1
Gas Pressure Drop (kPa)	1.200
Heat Loss (kW)	0.000
Heat Input (kW)	0.000
Work Input (kW)	0.000
Heat Loss by Transport Device (kW)	0.000
Moisture Evaporation Rate (kg/h)	156.313
Initial Gas Temperature (°C)	20.000
Specific Heat Consumption (kJ/kg)	2136.195
Thermal Efficiency	0.460
Dust Entrained in Gas/Material Total	0.000
Gas Outlet Dust Loading (g/m3)	0.000

Fans:	Fan 1	Fan 2
Static Pressure (kPa)	1.500	1.300
Total Discharge Pressure (kPa)	1.500	1.300
Efficiency	0.750	0.750
Power Input (kW)	1.515	1.193

Heaters:	Heater 1
Heating Duty (kW)	81.021
Pressure Drop (kPa)	0.600

FIGURE 60.17 Simulation results of Example 60.5.

was to be dried to 8% wet basis. First, the air temperature at the dryer exit was set to determine the minimum airflow, which can be used for the set conditions. Although the dryer exit temperature will depend on numerous factors such as the drying kinetics and the residence time of solids in a dryer. *Simprosys* does not take into account these parameters. This is the reason why simulations were carried out for predefined exit air conditions to compare different options (Ong et al., 2010).

In this study, the inlet air temperature was varied over a certain range in order to evaluate the thermal performance of dryer at a fixed outlet air temperature—which increases as the outlet temperature is lowered, essentially using most of the energy available for drying. The main goal was to study various options to increase the energy efficiency by recycling a part of exit air, preheating the inlet air using a recycled air stream and the effect of indirect heating of the dryer. It was observed that substantial reduction in specific energy consumption can be achieved using recycled air stream (Figure 60.18); however, one cannot recycle the entire drying air in order to have drying air at relatively low humidity in order to achieve drying.

The use of indirect heating is useful for a product such as coal, which is highly susceptible to spontaneous combustion. The use of indirect heat can reduce the hazard as less air at lower temperatures can be used. The use of indirect heating can result in lower required air volume for drying. This can result in lower specific energy consumption, lower air pumping cost, as well as smaller ducting for drying air. Thus, efficient indirect heating offers a number of advantages. *Simprosys* offers the advantage of easily incorporating indirect heat for drying. This possibility was simulated for drying of low-rank coals with the existing case.

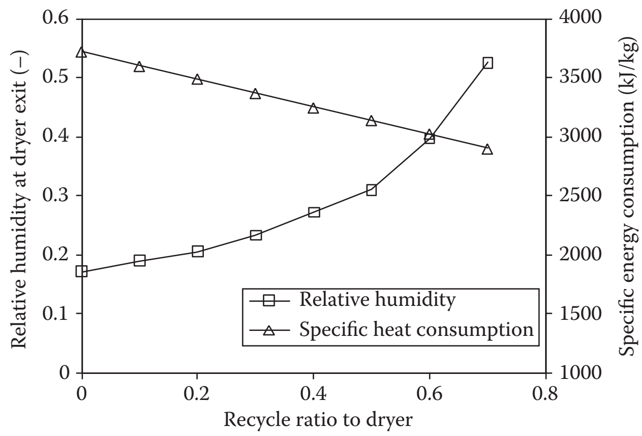

FIGURE 60.18 Effect of recycle ratio on exhaust air humidity and specific energy consumption.

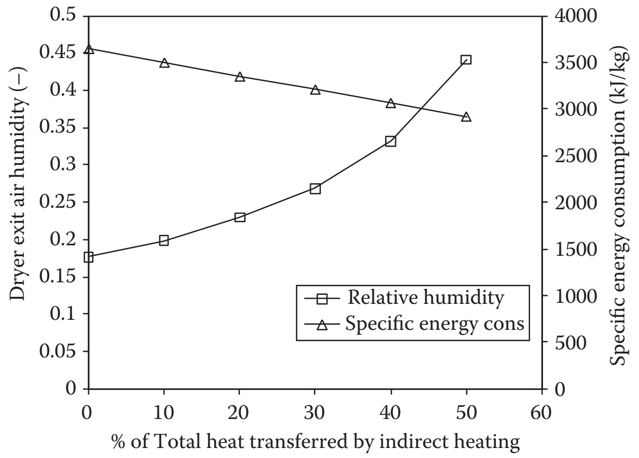

FIGURE 60.19 Effect of indirect heating on exit humidity and specific energy consumption.

Figure 60.19 shows the effect of percentage of total required heat supplied by indirect heating. It can be seen that the increase in the indirect heat results in higher dryer exit humidity and lower specific energy consumption. This is because of the lower quantity of required drying air. This indicates that the air is used more effectively. However, the extent of indirect heating will be limited by the dew point of the drying air.

Example 60.7: Energy audit of a fiberboard drying production line

An energy examination of the dryer and the drying system under current operating conditions is performed using *Simprosys 2.1* (Gong et al., 2011). The case of this study is an existing fiberboard drying production line of Smrečina Hofatex, a.s, Slovakia. The fiberboard products are thermo-insulating boards with length/width dimensions of dry boards at 5/2.5 m. The thickness of the products is in the range of 8–22 mm and the specific weight from 160 to 250 kg/m^3 depending on each product.

Softwood logs are cut into chips that are treated using thermomechanical process into water–fiber suspension. The suspension is dewatered, on a wired dewatering machine, into cake with a dryness of 35%–45%. Then it is cut into boards and fed to the production line at about 35°C. Final moisture content of the dry boards is about 5%. Fresh air is preheated to about 55°C by the exhaust air. Then it is heated by hot water to the needed inlet temperature at about 120°C. The left heat needed for the production line is provided by hot water through coil tubes under the production line. Drying time varies significantly (e.g., from 50 to 350 min) depending very much on product thickness. On the basis of current operating conditions, parametric studies are carried out to see how some major operating parameters such as the dryer heat input and fresh air inflow affect the energy consumption (Gong et al., 2011). However, it was found that the heat recovery was necessary in the existing process. Three possible ways to improve the dryer energy efficiency are as follows: decreasing heat loss by improving the insulation of the dryer and the hot water transport lines, effectively recovering the waste heat from the exhaust air, and shortening the drying time by increasing airflow in the dryer or by increasing hot water temperature or by doing both. Out of these options, energy recovery from exhaust air and increased airflow were tested using *Simprosys 2.1* (Gong et al., 2011).

To investigate the potential of heat recovery, three assumed exhaust air discharge temperatures are simulated. The simulation results are summarized in Table 60.6. It is obvious that the lower the discharge temperature of the exhaust air, the more the heat that can be recovered. However, with a decreased discharge temperature, the heat recovery cost will increase. Therefore, the discharge temperature is to be selected in such a way that the equipment cost is lower than the operating benefit.

An increased airflow in the dryer will enhance the heat transfer from the air to the fiberboard, which leads to an increased drying rate. This can be done either by increasing the fresh airflow or by increasing the exhaust recycle ratio. From Table 60.7, it is seen that with an increase of

TABLE 60.6
Heat Recovery in Fiberboard Drying

Exhaust Discharge Temperature (°C)	Sensible Heat Recovery above Dew Point (kW)	Heat Recovery below Dew Point (kW)	Possible Total Heat Recovery (kW)
70	127	480	607
60	127	869	996
50	127	1080	1307

TABLE 60.7
Effects of Exhaust Air Recycle Ratio

Exhaust Air Recycle Ratio (%)	Mixed Air Inlet Temperature (°C)	Mixed Air Inlet Relative Humidity (%)
0	122	1.6
30	132	6.5
50	138	7.9
70	143	8.6

the exhaust air recycle ratio, the mixed air inlet temperature is enhanced, but the mixed air inlet relative humidity drops. However, even in the case of 70% of recycle ratio, the relative humidity of the mixed air inlet is only 8.6%, which should not decrease the mass transfer rate of the water vapor into air. When airflow is increased in the dryer, the volume flow rate of the hot water needs to be increased accordingly so as to make up the increased heat input to the dryer.

60.8 CLOSING REMARKS

Drying is a widely used highly energy-intensive unit operation; software such as *Simprosys* can be used not only for better design of dryers and drying systems but also for troubleshooting and optimizing existing drying systems.

Simprosys is the first step toward the development of a comprehensive *drying suite*. It is an effort by the authors to provide affordable, yet powerful and easy-to-use software to benefit both drying industry and academia.

Demonstrated examples show only a fraction of the useful functionalities *Simprosys* possesses. Interested readers may visit www.simprotek.com to download a free trial version of *Simprosys* and follow the examples in the tutorial of the software package. They will find that *Simprosys* is an extremely intuitive, user-friendly, and useful tool in the analysis and design of dryers and drying-related engineering calculations.

REFERENCES

Baker C.G.J., 2005, Energy efficient dryer operation—An update on developments. *Drying Technology*, 23(9–11), 2071–2087.

Chopey N.P., 2003, *Handbook of Chemical Engineering Calculations*, 3rd edn., McGraw-Hill, New York.

Fuller E.N., Ensley K., Giddings J.C., 1969, Diffusion of halogenated hydrocarbons in helium the effect of structure on collision cross sections, *The Journal of Physical Chemistry*, 73(11), 3679–3685.

Fuller E.N., Shettler P.D., Giddings J.C., 1966, A new method for prediction of binary gas-phase diffusion coefficients, *Industrial and Engineering Chemistry*, 58(5), 19–27.

Gary J.H., 2003, Stoichiometry (Chapter 2), in *Handbook of Chemical Engineering Calculations*, 3rd edn., N.P. Chopey (Ed.), McGraw-Hill, New York.

AQ9 Gong Z., Mujumdar A.S., 2008, Software for design and analysis of drying systems, *Drying Technology*, 26(7), 884–894.

Gong Z., Mujumdar A.S., 2010, Simulation of drying nonaqueous systems—An application of Simprosys software, *Drying Technology*, 28(1), 111–115.

AQ10 Gong Z., Mujumdar A.S., in press, Process simulation of combustion drying with Simprosys software, *Drying Technology*.

Gong Z., Stanovský J., Mujumdar A.S., 2011, Energy audit of a fiberboard drying production line using Simprosys software, *Drying Technology*, 29(4), 408–418.

Heldman D.R., 2001, Prediction models for thermophysical properties of foods, in *Food Processing Operations Modeling: Design and Analysis*, J. Irudayaraj (Ed.), Marcel Dekker, New York, pp. 1–23.

Huang L., Mujumdar A.S., 2005, Development of a new innovative conceptual design for horizontal spray dryer via mathematical modeling, *Drying Technology*, 23, 1169–1187.

Ibarz A., Barbosa-Canovas G., 2002, Thermal properties of food (Chapter 11), in *Unit Operations in Food Engineering*, CRC Press, Boca Raton, FL. AQ11

Jangam S.V., Mujumdar A.S., 2010, Heat pump assisted drying technology—Overview with focus on energy, environment and product quality, in *Modern Drying Technology*, Vol. 4, E. Tsotsas, A.S. Mujumdar (Ed.), Wiley-VCH-Wiley, Weinheim, Germany.

Kakaç S., Liu H., 2002, *Heat Exchangers: Selection, Rating and Thermal Design* (Chapter 4), 2nd edn., CRC Press, Boca Raton, FL.

Keey R.B., 1978, *Introduction to Industrial Drying Operations*, Pergamon Press, Oxford, U.K.

Kemp I.C., 2007, Drying software: Past, present and future, *Drying Technology*, 25, 1249–1263.

Kemp, I.C., Gardiner, S.P., 2001, An outline method for troubleshooting and problem-solving in dryers, *Drying Technology*, 19, 1875–1890.

Kemp I.C., Hallas N.J., Oakley D.E., August 2004, Developments in aspen technology drying software. *Proceedings of 14th International Drying Symposium* (*IDS*), Sao Paulo, Brazil, Vol. B, pp. 767–774.

Kemp I.C., Oakley D., 2002, Modeling of particulate drying in theory and practice, *Drying Technology*, 20, 1699–1750.

Knudsen J.G., Hottel H.C., Sarofim A.F., Wankat P.C., Knaebel K.S., 1997, Heat and mass transfer (Section 5), in *Perry's Chemical Engineers' Handbook*, 7th edn., R. Perry (Ed.), McGraw-Hill, New York.

Kudra T., Mujumdar A.S., 2009, *Advanced Drying Technologies*, CRC Press, New York.

Kudra T., Platon R., Navarri P., 2009, Excel-based tool to analyze the energy performance of convective dryers. *Drying Technology*, 27(10–12), 1302–1308.

Kuppan T., 2000, *Heat Exchanger Design Handbook* (Chapters 3 and 5), Marcel Dekker, New York.

Liley P.E., Thomson G.H., Friend D.G., Daubert T.E., Buck, E., 1997, Physical and chemical data (Section 2), in *Perry's Chemical Engineers' Handbook*, 7th edn., R. Perry (Ed.), McGraw-Hill, New York.

Marinos-Kouris D., Mroulis Z.B., Kiranoudis C.T., 1996, Computer simulation of industrial dryers, *Drying Technology*, 14, 971–1010.

Master K., 1985, *Spray Drying Handbook*, 4th edn., John Wiley & Sons, New York.

McCabe W.L., Smith J., Harriott P., 2000, *Unit Operations of Chemical Engineering* (Chapters 12, 13, 15 and 16), 6th edn., McGraw-Hill, New York.

Menshutina N.V., Kudra T., 2001, Computer aided drying technologies, *Drying Technology*, 19, 1825–1850.

Minton P.E., Morrison E.S.S., 2003, Heat transfer (Section 7), in *Handbook of Chemical Engineering Calculations*, 3rd edn., N.P. Chopey (Ed.), McGraw-Hill, New York.

Moyers C.G., Baldwin G.W., 1997, Psychrometry, evaporative cooling, and solids drying (Section 12), in *Perry's Chemical Engineers' Handbook*, 7th edn., R. Perry (Ed.), McGraw-Hill, New York.

Mujumdar A.S., 2006, *Handbook of Industrial Drying*, 3rd edn., CRC Press, Boca Raton, FL.

Mujumdar A.S., Wu Z., 2008, Thermal drying technologies—Cost-effective innovation aided by mathematical modeling approach, *Drying Technology*, 26, 146–154.

Ong M.J.Y., Jangam S.V., Kuma J.V., Gong Z., Mujumdar A.S., 2010, Improving energy efficiency and sustainability of industrial thermal drying systems using Simprosys software. *Proceedings of International Symposium on Innovative Materials for Processes in Energy Systems 2010—For Fuel Cells, Heat Pumps and Sorption Systems*, November 30–December 1, Singapore.

Pakowski Z., 1994, DryPAK v1.1 program for psychrometric and drying computation, *Drying Technology*, 12, 1765–1768.
Pakowski Z., Mujumdar A.S., 2007, Basic process calculations and simulations in drying (Chapter 3), in *Handbook of Industrial Drying*, 3rd edn., A.S. Mujumdar (Ed.), CRC Press, Boca Raton, FL.
Pell M., Dunson J.B., 1997, Gas-solid operations and equipment (Section 17), in *Perry's Chemical Engineers' Handbook*, 7th edn., R. Perry (Ed.), McGraw-Hill, New York.
Perry R., 1997, *Perry's Chemical Engineers' Handbook*, 7th edn., McGraw-Hill, New York.
Poling B.E., Prausnitz J.M., O'Connell J.P., 2001, *The Properties of Gases and Liquids*, 7th edn., McGraw-Hill, New York.
Reynolds J.P., Jeris J.S., Theodore L., 2002, *Handbook of Chemical and Environmental Engineering Calculations* (Chapter 15), John Wiley, New York.
Richard L., Shilling R.L., Bell K.J., Bernhagen P.M., Flynn T.M., Goldschmidt V.M., Hrnjak P.S., Standiford F.C., Timmerhaus K.D., 1997, Heat-transfer equipment (Section 11), in *Perry's Chemical Engineers' Handbook*, 7th edn., R. Perry (Ed.), McGraw-Hill, New York.
Schifftner K.C., Hesketh H.E., 1983, *Wet Scrubbers* (Chapter 1), Ann Arbor Science Publishers, Ann Arbor, MI.
Straatsma J., Van Houwelingen G., Meulman A.P., Steenbergen A.E., 2007, Dryspec2: A computer model of a two-stage dryer, *International Journal of Dairy Technology*, 44, 107–111.
Straatsma J., Van Houwelingen G., Steenbergen A.E., De Jong P., 1999, Spray drying of food products: 1. Simulation model, *Journal of Food Engineering*, 42, 67–72.
Verdurmen R.E.M., Straatsma H., Verschueren M., van Haren J.J., Smit E., Bargeman G., De Jong P., 2002, Modeling spray drying processes for dairy products, *Lait*, 82, 453–463.
Walas S.M., 1990, *Chemical Process Equipment: Selection and Design*, Butterworth-Heinemann, Boston, MA.
Yaws C.L., 1999, *Chemical Properties Handbook*, McGraw-Hill, New York.
Yaws C.L., Gabbula C., 2003, *Yaw's Handbook of Thermodynamic and Physical Properties of Chemical Compounds*, Knovel (eBook), New York.
Zenz F.A., 1999, Cyclone design (Chapter 12), in *Fluidization, Solids Handling, and Processing: Industrial Applications*, W. Yang (Ed.), Noyes Publications, Westwood, NJ.

AUTHOR QUERIES

[AQ1] The reference Jangam and Mujumdar (2011) has been changed into Jangam and Mujumdar (2010) as per the reference list. Please check.
[AQ2] Please provide expansion for "NIZO," if appropriate.
[AQ3] Please check if "problems are much more complicated" is okay as edited.
[AQ4] Please provide complete details for the following references: Mujumdar (2007), Perry (1977), Reynolds et al. (2003).
[AQ5] Please provide other options, if possible.
[AQ6] Please check if paragraph starting "Since design, optimization..." should be deleted as it seems to be a repetition of a previous entry.
[AQ7] Please check if "Durhing lines" should be changed to "Duhring lines." If so, please make the change throughout the chapter.
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[AQ9] Please provide in-text citation for references Gong and Mujumdar (2008, in press) and Minton and Morrison (2003).
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