CHAPTER
X

SOFTWARE FOR DRYING

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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 (Kemp, 2007; Kemp et al., 2004; Menshutina and Kudra, 2001; Marinos-Kouris et al., 1996). However, few commercial drying software products have been available on market and well accepted by industry. In fact the most prominent one is proprietary and available only to the sponsors.

In view of the skyrocketing energy price 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 industry.

Thermal drying consumes, according to various estimates, 10-20 percent of industrial energy in various developed countries, e.g., Canada, France, UK, Germany, Denmark, etc. as energy audits carried out in these countries have revealed. In developing countries the fraction is probably around 4-6 % and rising. Fossil fuels provide almost all of the energy needed in industrial drying. The energy consumption of thermal drying as well as the resulting environmental impact through greenhouse gas emissions is massive. With industrial dryer efficiencies ranging from just 30-60 percent, there is significant scope for improvement of existing drying operations. If countries adopt caps on carbon emissions, such as the one recently adopted by U.K. to reduce CO_2 emissions by 50 percent 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, trouble-shooting 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 trouble shooting 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.

2. IDEAL DRYING SOFTWARE SPECIFICATIONS

For convective thermal drying which constitutes over 90% percent 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, the exhaust dust concentration of the cyclone or scrubber, etc. 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, e.g., 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, e.g., impinging jet, spray and flash dryers, computational (such as Computational Fluid Dynamics (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 deign decisions.

Based on various aspects of design, analysis, trouble-shooting 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, trouble-shooting 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, on the basis of the balance calculations, scoping, 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 dryer 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 1.

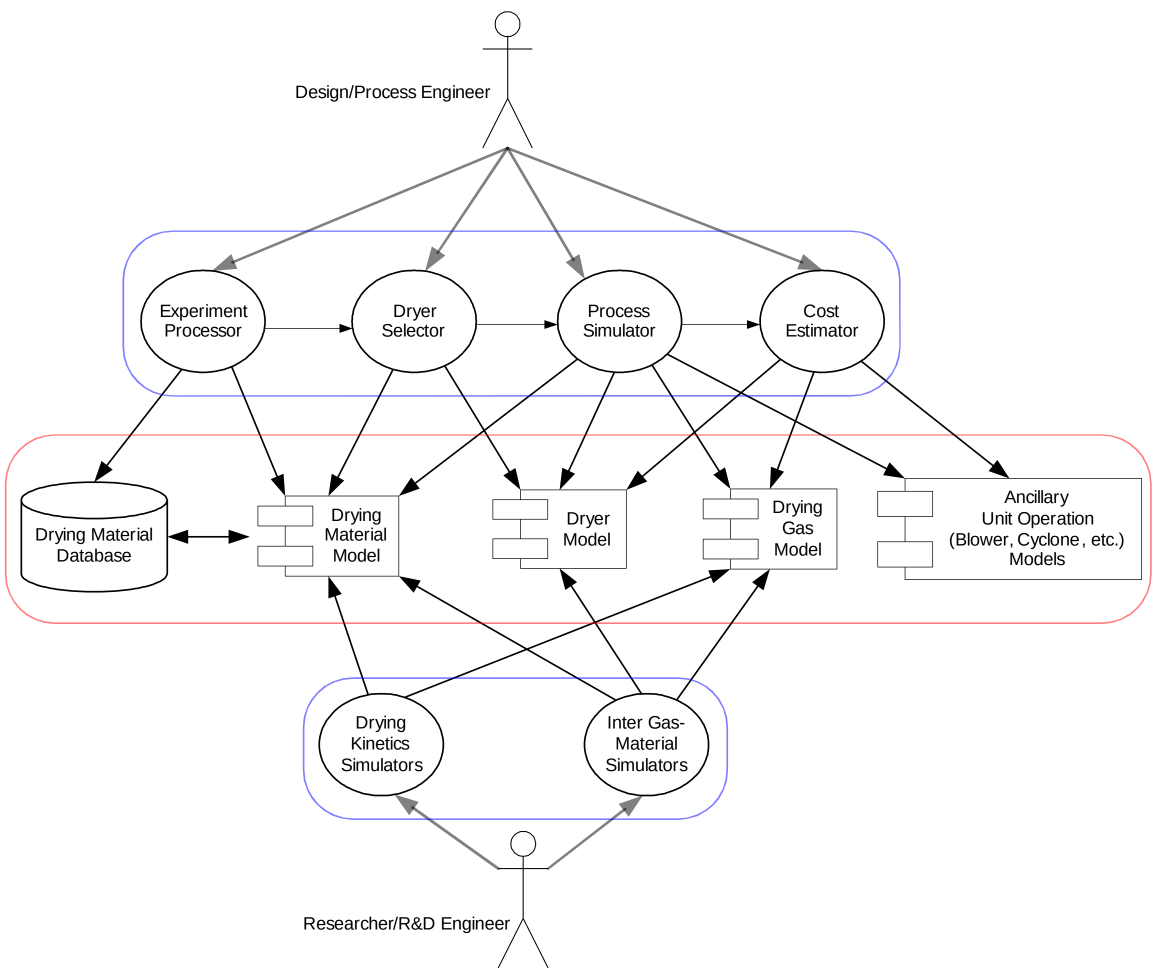


Figure 1 Top Level Architecture of ***Drying Suite***

The four essential units are as follows:

1. An experiment processor that can be used to process experimental data and store the experimental data 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, or scaling up or dryer rating.
4. A cost estimator that can be use to estimate the equipment cost and operating cost based on the process simulation results.

The two advanced units are:

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 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 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).

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 which 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 a 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 (Straatsma et al. 2007; Verdurmen, et al., 2002). 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).

Although many CFD-based models for dryers such as spray, fluid bed, flash, impinging jet, etc. 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 dryer flowsheet calculations since drying problems are much more than only humidity and psychrometric calculations.

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 can be used for flowsheet design and simulation of drying and evaporation systems. It can also be used for the design of dryers. It is developed using the most advanced software technology, viz. Microsoft .Net and C#.

Simprosys **1.01** contains 19 unit operation modules and 2 utilities as displayed in Figure 2. The 19 unit operation modules include solid dryer, liquid dryer, cyclone, air filter, bag filter, electro-static precipitator, wet scrubber, scrubber condenser, fan/blower, compressor, steam jet ejector, pump, valve, heater, cooler, heat exchanger which 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.

Users can construct any drying and evaporation related process to explore different arrangements of unit operations and experiment with different operating conditions with ***Simprosys***. ***Simprosys 1.01*** can also simulate recycled exhaust gas stream and product material stream in the process.

In addition to heat/mass/pressure balance calculations for all the unit operations, ***Simprosys*** **1.01** also contains a simple dryer scoping model, a detailed cyclone rating model as well as simple and complex heat exchanger rating models for single phase heat transfer.

Since different units may be used in different countries, ***Simprosys*** **1.01** 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 covers all chemical engineering units.

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***

Simprosys **1.01** covers only the air-water system and is used mainly for heat and mass balance calculations. Extension to other gas-organic liquid systems, to dryer scaling up is under development.

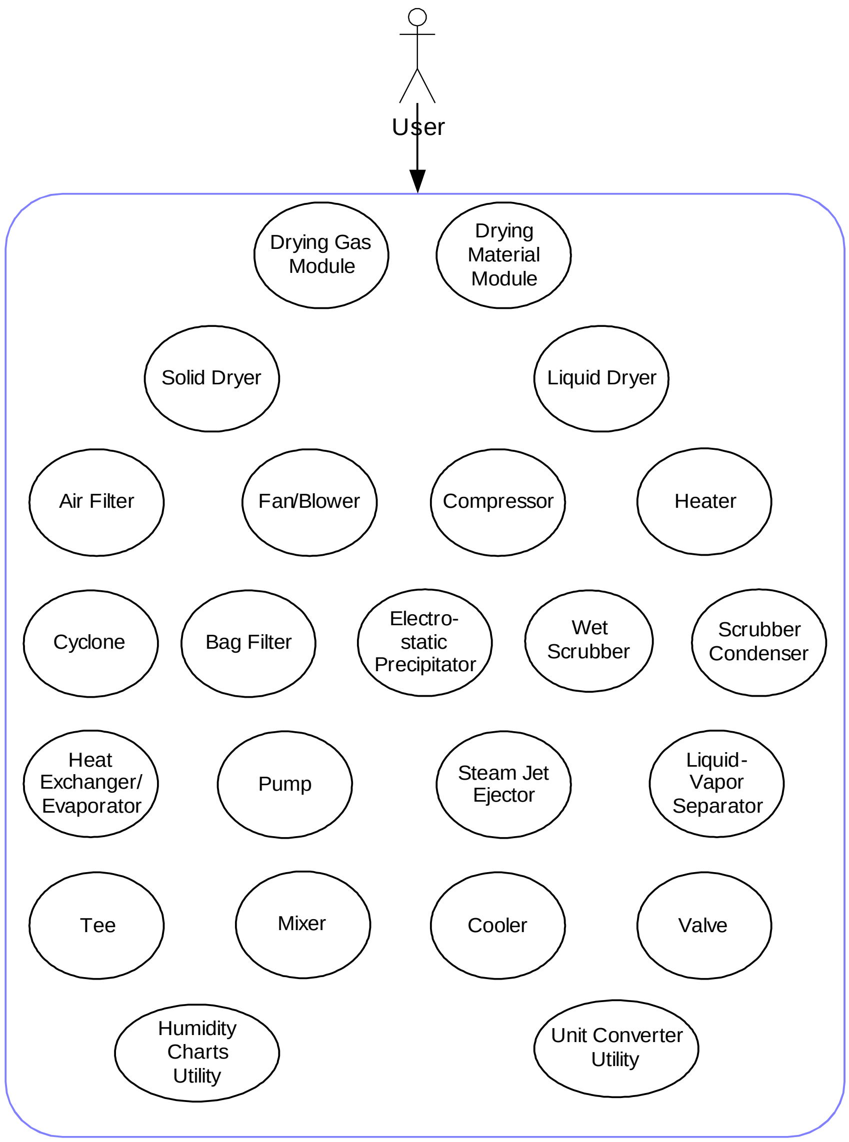


Figure 2 Modules in Simprosys 1.01

5. BASICS OF SIMPROSYS

Simprosys is based on extensive studies presented in the most authoritative handbooks in drying by Mujumdar (2007), Masters (1985) and Perry (1977).

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).

For air-water system, the properties (including saturation pressure) of liquid and steam of water are calculated according to the 1967 ASME Steam Tables. The properties of dry air are based on Perry (1997) (section 2, Physical and Chemical Data). For other solvent-gas systems (which are being developed) such as air-carbon tetrachloride, air-benzene and air-toluene, the liquid and steam peroperties of the solvent are based Perry (1997) (section 2, Physical and Chemical Data).

5.2 Dryer Models

In the ***Simprosys*** dryer model, you can automatically obtain the *Thermal Efficiency* and *Specific Heat Consumption* of the dryer with the heat and mass balance calculations.

You can specify the gas inlet temperature, absolute humidity, and either the gas outlet temperature or relative humidity or absolute humidity, to calculate how much drying air is needed. You can also specify the gas inlet flow rate, temperature and absolute humidity to calculate the gas outlet temperature and humidity. Due to space limitation we can not list all the functionalities of the dryer model. Interested readers are encouraged to visit www.simprotek.com and download a trial version of ***Simprosys*** **1.01** and try it out.

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

5.3 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 in Equation 1.

$$C_{WetMat} = (1.0 - w)C_{DryMat} + wC_{Moisture} \qquad (1)$$

where C_{WetMat}, C_{DryMat}, $C_{Moisture}$ represent the specific heats of wet material, bone dry material, and liquid moisture respectively and w stands for the moisture content (wet basis) of the material.

When evaporation related balance simulation is involved, During 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 5 basic components. The specific heat as a function of temperature for each of the 5 basic components is based on Ibarz and Barbosa-Canovas (2003) and Heldman (2001) and is listed in Table 1.

Table 1 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	$C_p = 1.0926 + 1.8896 \times 10^{-3} T - 3.6817 \times 10^{-6} T^2$
Fibe	$C_p = 1.8459 + 1.8306 \times 10^{-3} T - 4.6509 \times 10^{-6} T^2$
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 ^{o}C and that of C_p is kJ/kg. ^{o}C in Table 1.

For drying related balance simulation you need to specify the mass fraction for each of the 5 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 1.

5.4 Other Unit Operation Models

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

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 layout 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, the heat duty of the heater, etc. As part of the heat and mass balance calculation results the *Thermal Efficiency* and *Specific Heat Consumption* of the dryer(s) are automatically obtained. They can tweak the input and output values of different variables to optimize the dryer(s) and drying system. 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 unrealistically long time to accomplish. Thus this software can be used by creative instructors as a valuable teaching tool as well.

7. EXAMPLES OF SIMPROSYS

Three examples are selected here to demonstrate some simple 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 one is a combined two-effect evaporation and two stage drying flowsheet.

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

Example 1 -- A Drying Flowsheet with Recycled Exhaust Gas Stream

The drying material is a liquid. Feed solid content = 0.57 kg/kg wet basis. Feed temperature = 97 ^{o}C. Feed pressure = 101.3 kPa. The material goes through a spray dryer to be dried to a moisture content of 0.085 kg/kg wet basis. Material outlet temperature is 50 ^{o}C. Then it goes through a vibrated fluidized bed dryer to get the product dried to the final moisture content of 0.003 kg/kg wet basis. Material product temperature is 52 ^{o}C. Specific heat of the bone dry material = 1.26 kJ/kg ^{o}C. Mass flow rate of wet material = 5000 kg/hr.

Drying air has the following conditions: Initial pressure = 101.3 kPa. Initial temperature (dry-bulb) = 22 ^{o}C. Initial relative humidity = 40%. Mass flow rate of humid air = 42000 kg/hr.

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 ^{o}C and then goes 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 ^{o}C and then goes 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 3. The simulated result is shown in Figure 4.

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.

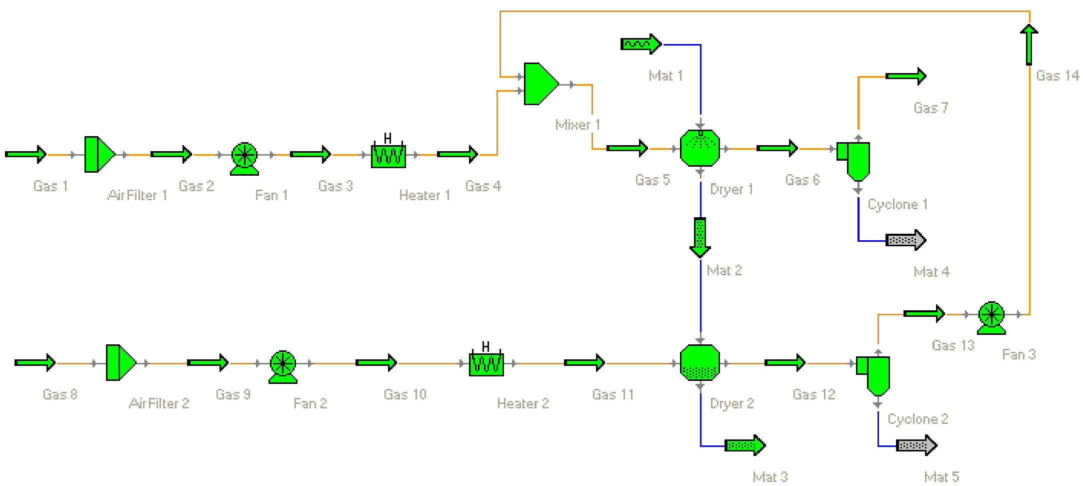
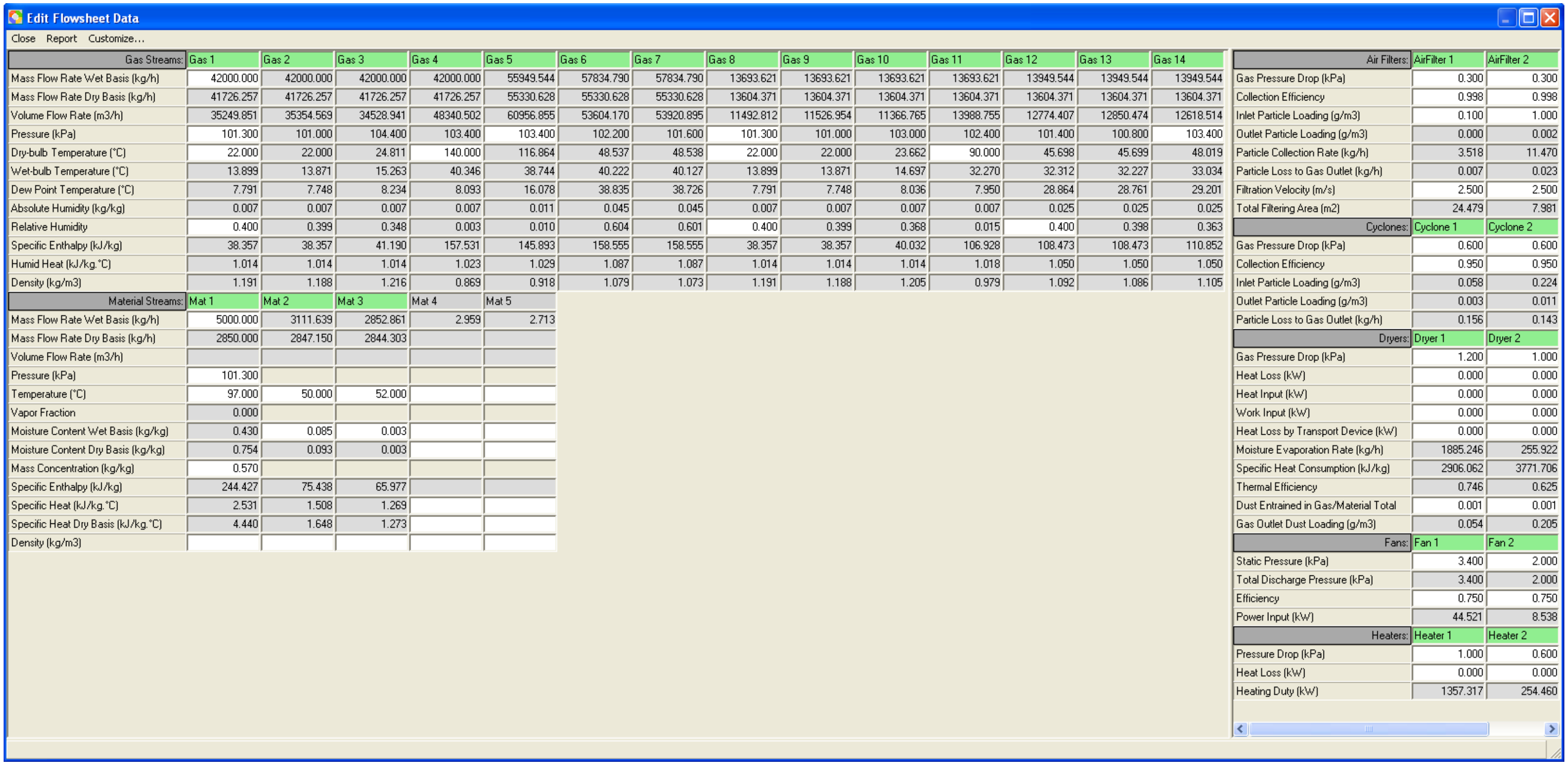


Figure 3 Flowsheet with Recycled Exhaust Gas Stream



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 4 Simulation Results for Example 1

Example 2 -- A Drying Flowsheet incorporating a Recycled Material Stream

The material to be dried is in the form of solid particles. Initial moisture content = 0.25 kg/kg wet basis. Initial temperature = 20 ^{o}C. Product temperature = 48 ^{o}C. Specific heat of the bone dry material = 1.26 kJ/kg ^{o}C. Mass flow rate of wet material = 1000 kg/hr.

Drying air has the following conditions: Initial pressure = 101.3 kPa. Initial temperature = 20 ^{o}C. Initial relative humidity = 45%. Mass flow rate of humid air = 10000 kg/hr. Dryer exhaust air relative humidity = 50%.

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 ^{o}C. Pressure drop of air in heater and dryer is 0.8 kPa 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.

The dryer requires that the feed moisture content (wet basis) is less than 0.15 kg/kg. As is known, initial moisture content (wet basis) of the material is 0.25 kg/kg. 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 goes through a recycle stream and mixes with the fresh material in a mixer and then introduced into the dryer material inlet. The established flowsheet is displayed in Figure 5. The simulated result is shown in Figure 6.

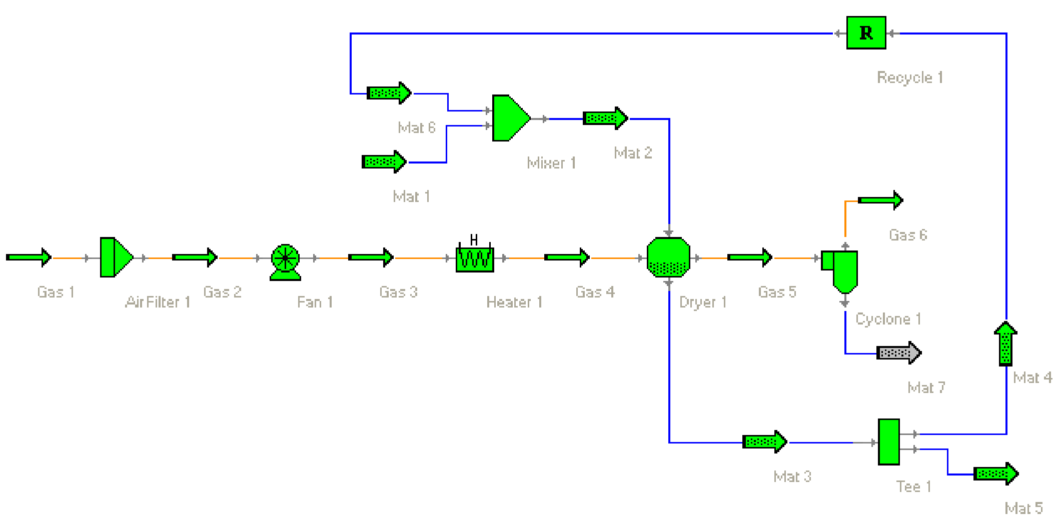
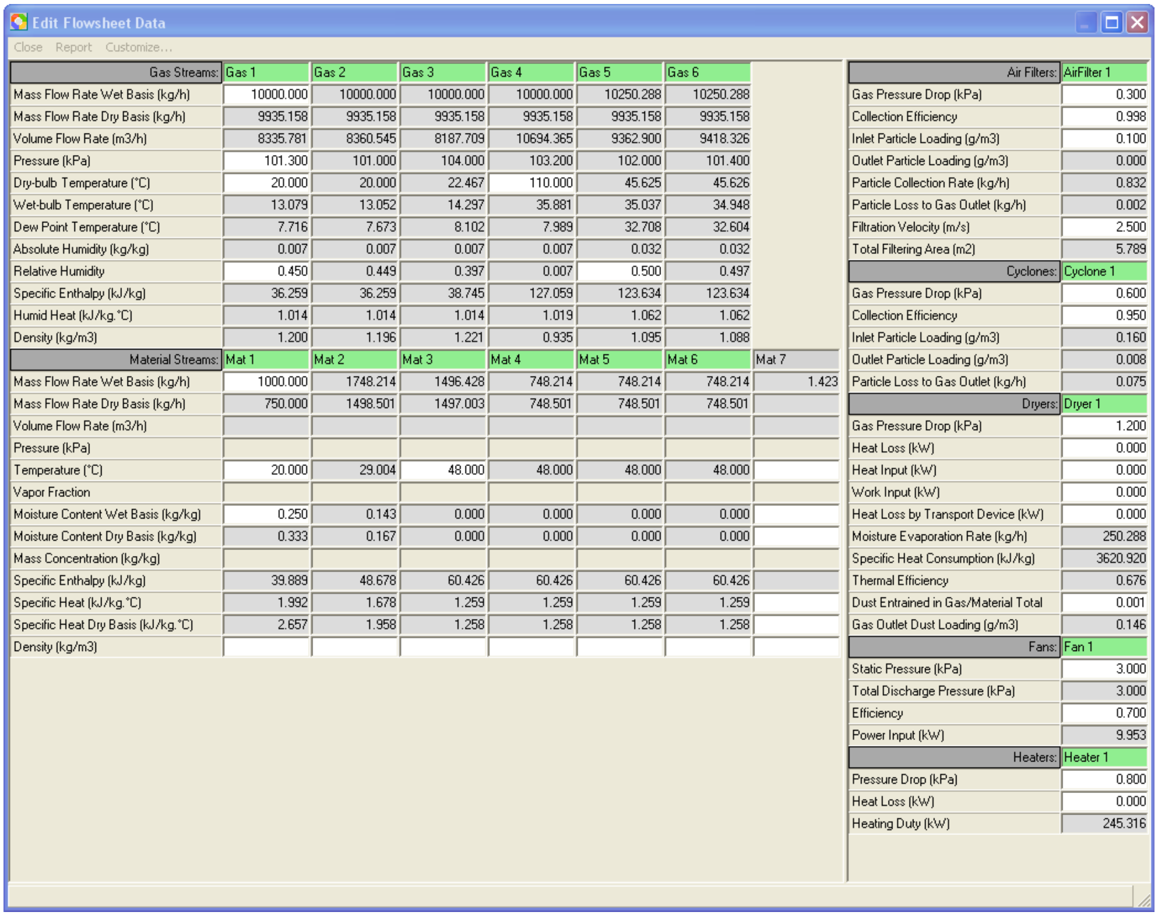


Figure 5 Flowsheet with Recycled Material Stream



Edit Flowsheet Data

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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)	10000.000	10000.000	10000.000	10000.000	10250.288	10250.288	
Mass Flow Rate Dry Basis (kg/h)	9935.158	9935.158	9935.158	9935.158	9935.158	9935.158	
Volume Flow Rate (m3/h)	8335.781	8360.545	8187.709	10694.365	9362.900	9418.326	
Pressure (kPa)	101.300	101.000	104.000	103.200	102.000	101.400	
Dry-bulb Temperature (°C)	20.000	20.000	22.467	110.000	45.625	45.626	
Wet-bulb Temperature (°C)	13.079	13.052	14.297	35.881	35.037	34.948	
Dew Point Temperature (°C)	7.716	7.673	8.102	7.989	32.708	32.604	
Absolute Humidity (kg/kg)	0.007	0.007	0.007	0.007	0.032	0.032	
Relative Humidity	0.450	0.449	0.397	0.007	0.500	0.497	
Specific Enthalpy (kJ/kg)	36.259	36.259	38.745	127.059	123.634	123.634	
Humid Heat (kJ/kg.°C)	1.014	1.014	1.014	1.019	1.062	1.062	
Density (kg/m3)	1.200	1.196	1.221	0.935	1.095	1.088	
Material Streams:	**Mat 1**	**Mat 2**	**Mat 3**	**Mat 4**	**Mat 5**	**Mat 6**	**Mat 7**
Mass Flow Rate Wet Basis (kg/h)	1000.000	1748.214	1496.428	748.214	748.214	748.214	1.423
Mass Flow Rate Dry Basis (kg/h)	750.000	1498.501	1497.003	748.501	748.501	748.501	
Volume Flow Rate (m3/h)							
Pressure (kPa)							
Temperature (°C)	20.000	29.004	48.000	48.000	48.000	48.000	
Vapor Fraction							
Moisture Content Wet Basis (kg/kg)	0.250	0.143	0.000	0.000	0.000	0.000	
Moisture Content Dry Basis (kg/kg)	0.333	0.167	0.000	0.000	0.000	0.000	
Mass Concentration (kg/kg)							
Specific Enthalpy (kJ/kg)	39.889	48.678	60.426	60.426	60.426	60.426	
Specific Heat (kJ/kg.°C)	1.992	1.678	1.259	1.259	1.259	1.259	
Specific Heat Dry Basis (kJ/kg.°C)	2.657	1.958	1.258	1.258	1.258	1.258	
Density (kg/m3)							

Air Filters:	AirFilter 1
Gas Pressure Drop (kPa)	0.300
Collection Efficiency	0.998
Inlet Particle Loading (g/m3)	0.100
Outlet Particle Loading (g/m3)	0.000
Particle Collection Rate (kg/h)	0.832
Particle Loss to Gas Outlet (kg/h)	0.002
Filtration Velocity (m/s)	2.500
Total Filtering Area (m2)	5.789
Cyclones:	**Cyclone 1**
Gas Pressure Drop (kPa)	0.600
Collection Efficiency	0.950
Inlet Particle Loading (g/m3)	0.160
Outlet Particle Loading (g/m3)	0.008
Particle Loss to Gas Outlet (kg/h)	0.075
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)	250.288
Specific Heat Consumption (kJ/kg)	3620.920
Thermal Efficiency	0.676
Dust Entrained in Gas/Material Total	0.001
Gas Outlet Dust Loading (g/m3)	0.146
Fans:	**Fan 1**
Static Pressure (kPa)	3.000
Total Discharge Pressure (kPa)	3.000
Efficiency	0.700
Power Input (kW)	9.953
Heaters:	**Heater 1**
Pressure Drop (kPa)	0.800
Heat Loss (kW)	0.000
Heating Duty (kW)	245.316

Figure 6 Simulation Results for Example 2

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 air inlet temperature of the dryer rather than the heating duty of the heater to simulate 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 3 – Combined Evaporation and Two Stage Drying

Liquid material of 4000 kg/hr flow rate is initially at a solid content of 0.13 kg/kg and a temperature of 3 ^{o}C. It needs to be concentrated to a solid content (mass concentration) of about 0.57 before it is sent to a spray dryer. Material density is 720 kg/m^3 at room temperature. Concentration process needs to be performed at around atmospheric pressure. Specific heat of the material without moisture is 1.26 kJ/kg ^{o}C. The boiling point rise of the material solution can be described by the following Durhing lines expressed in Table 2

Table 2 Durhing Lines

Mass concentration (kg/kg)	Start Boiling Point (^oC)		End Boiling Point (^oC)	
	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

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 0.08 kg/kg (wet basis). It then goes through a vibrated fluidized bed dryer to be dried to a moisture content of 0.04 kg/kg (wet basis). The drying air of the spray dryer is at 103.2 kPa and 140 ^oC. The exhaust air of the spray dryer is at 68 ^oC. Dried material from the spray dryer is at 55 ^oC. The drying air of the vibrated fluidized bed dryer is at 103.8 kPa and 85^oC. The exhaust air of the vibrated fluidized bed dryer is at 45 ^oC. Dried material from the vibrated fluidized bed dryer is at 52 ^oC. 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 85 ^oC. 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 potion of the compressed secondary vapor is used to preheat the feeding material from 85 ^oC 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 separate the concentrated liquid with the vapor. As is mentioned above, part of the secondary vapor is use to preheat the feeding material.

The established flowsheet is displayed in Figure 7. The results of the calculation are shown in Figure 8. Note that not all results are shown in the table due to space limitation in Figure 8. Interested readers may visit www.simprotek.com to download a trial version of ***Simprosys* 1.01** and load Example 11 in the Tutorial to fully study this example.

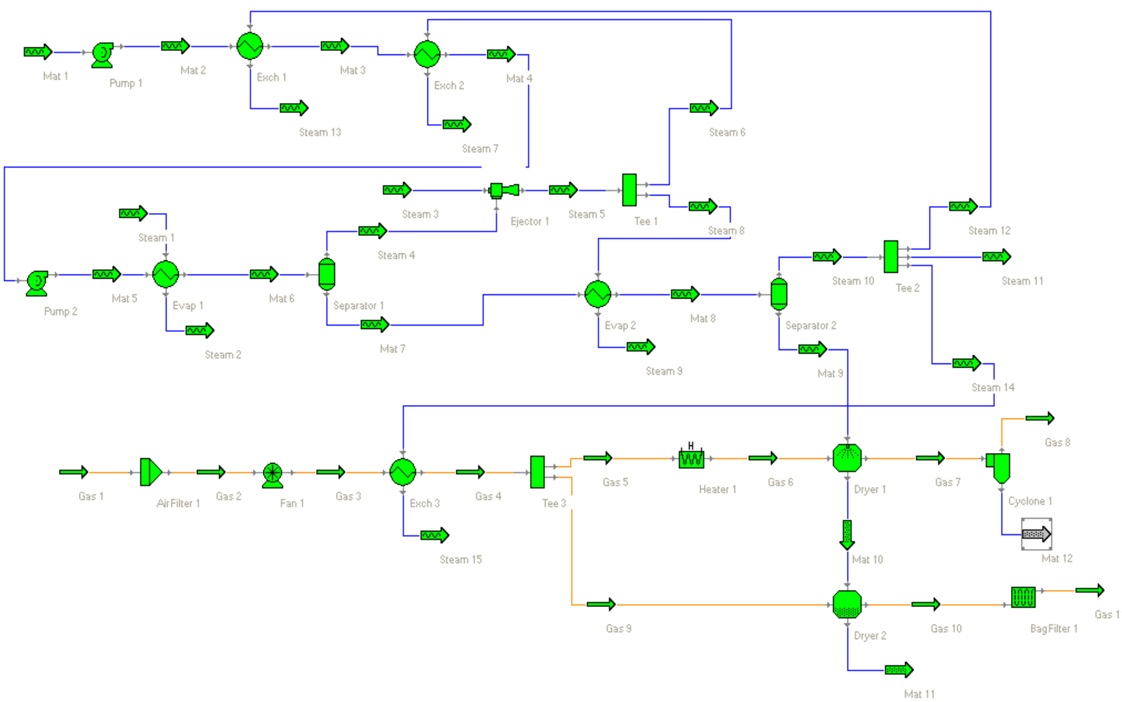

Figure 7 Combined Evaporation and Drying Flowsheet

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 towards 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 very small part of the 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.

Edit Flowsheet Data

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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	128.727	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 8 Simulation Results of Example 3

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