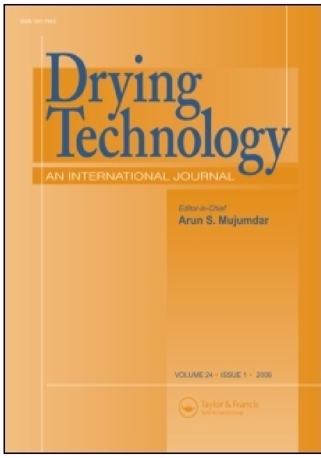

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Software for Design and Analysis of Drying Systems

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Available commercial software to simulate flowsheets incorporating drying is reviewed briefly. Such software can be very cost effective in the design, analysis, trouble-shooting, as well as control and optimization of drying systems. A new comprehensive drying software suite is proposed and analyzed. Key factors to the success of drying software products are discussed. Motivation, principles, and applications of the new drying software package, Simprosys, which represents a major step toward development of a comprehensive drying software suite, are presented.

Keywords Dryer design; Drying simulation; Drying suite; Simprosys; Software

INTRODUCTION

Since the emergence of modern electronic computers in early 1980s, knowledge developed in science and engineering has found a ready and effective way to be applied to industrial practice with the help of computers. Computer software made solutions to difficult and complex problems readily available. In almost all industrial sectors, engineers today use computer software every day to do their calculations and design tasks instead of going through dozens of handbooks to look up the needed engineering data and do the calculations "manually" or using custom-designed programs. Properly designed computer software can help increase significantly the efficiency and productivity of not only industry but also academia as well.

Over the past 30 years, considerable effort has been devoted to the development of various software programs applicable to thermal drying.[1–4] However, few commercial software packages related to drying and drying system design have been developed successfully or are well accepted by industry.

In view of the necessity to reduce greenhouse gas emissions due to concerns over global climate change and the rapidly escalating cost of energy, energy conservation technologies will once again become a focal point for both industry and academia. Considering drying as a particularly energy-consuming unit operation, user-friendly software is needed by industry and academia to improve the energy efficiency of drying and reduce the carbon footprint of drying products.

COMPUTER SIMULATION OF DRYING SYSTEMS

For thermal drying, the wet material and hot gas pass through a dryer to exchange heat and mass to dry the wet material. Such direct dryers constitute over 90% of industrial dryers in operation today according to some estimates. When the exhaust gas comes out from the dryer, the entrained material in the exhaust gas must go through suitable dust collectors such as cyclones and baghouses to collect the entrained product and to satisfy the exhaust discharge regulations. The material, drying gas, and dryer are the key components that need to be considered in a drying process.

After the required material properties, product requirements, and production scale are known, the appropriate dryer type is selected. Selection of a dryer must take many aspects into consideration. Numerous rules and methodologies have been proposed in the literature on selection of dryers based on material characteristics and product requirements.[5,6] Dryer selection is often the most challenging part for the drying system design and is also critical to the success of the dryer. It is also necessary to be sure that for the selected dryer type and operating conditions, the product quality meets customer specifications. This cannot be derived from the thermodynamic calculations of heat and mass balance equations.

To design a drying system for a material, lab-scale experiments are generally needed to obtain the material properties and desirable operation conditions once the dryer type is selected carefully. Once the design requirements are specified, a drying flowsheet must be laid out to meet the design requirements. Next, heat and mass balances of the whole process need to be calculated to

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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.

For the design of some dryers, a scaling up calculation is needed after the relevant lab experiment is completed. Computational analysis of inter gas material heat and mass transfer, such as computational fluid dynamics (CFD) analysis of gas particle two-phase flow with coupled heat and mass transfer, may be required for better design and optimization of some specific dryers.[7]

When drying is controlled by internal diffusion, 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 significantly reduce experimental cost in determining the drying time and optimal drying conditions.

Based on various aspects of design, analysis, troubleshooting, as well as control and optimization of drying systems, computer software can be helpful in the following ways:

1. Process simulation and control of drying-centered process. A thermal dryer needs ancillary pieces of equipment, e.g., heaters, fans, cyclones, etc., to carry out the drying operation. For spray drying of liquids, one may need evaporators to concentrate the liquid to a certain degree before it is sent to a spray dryer. Simulation of the drying operation as a system (or the whole drying plant) can lead to optimized design and operation.
2. Dryer design calculations, which include basic heat and mass balance calculations, and related calculations such as scoping and scaling up, can be used to specify the dryer equipment.
3. Drying kinetics simulation that predicts the transient coupled heat and mass diffusion within the material. This is mainly used to simulate different drying (heating) conditions to determine the drying time. For example, this is particularly useful for optimization of major materials such as monolithic and prefabricated refractory castings[8,9] and lumber. It can also be used to determine the drying time of a single drying particle under the flow and heat conditions in a dryer.
4. Computational simulation of the inter gas material heat and mass transfer. CFD simulation of the gas particle two-phase flow with coupled heat and mass transfer is one of the examples of this type of simulation. Such simulation is mainly used for detailed design of some specific dryers such as spray and flash dryers.

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

Within such a drying suite, users can process their experimental data. They can also select an appropriate dryer or get a set of appropriate dryers recommended after material characteristics (such as moisture 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 pre- and postprocessing stages of the drying material and the ancillary unit operations. Users should be able to further carry out, on the basis of the balance calculations, scoping, scaling up of the dryer based on lab experiment results, or dryer rating. Users should further be able to calculate the equipment and operating cost for a drying system. They should also be able to do advanced simulations for drying kinetics analysis and inter gas material heat and mass transfer analysis such as computational fluid dynamics simulation of gas particle two-phase flow with coupled heat and mass transfer, depending on the type of dryer.

The ideal drying suite should contain four essential units for design and process engineers and two advanced units for researchers and R&D engineers. The four essential units should include all the necessary tools needed for the design of dryers and drying systems by engineers. They are

1. An experimental data processor that can be used to process experimental data.
2. A dryer selector that can be used to get a list of appropriate dryers recommended or appropriate dryer selected.
3. A process simulator that can be used to lay out drying flowsheets and carry out heat/mass balance calculations. 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, and dryer rating. Since flows of air and material are involved, it is typically necessary to estimate the air-handling power requirements as well.
4. A flowsheet 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 the inter gas material heat and mass transfer.

The data processor is used to establish a material model, which is needed by the dryer selector and process simulator. The equipment model is shared by the process simulator and the cost estimator. The material model, drying gas model, and 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 the drying operation.

With the two advanced units of the drying suite, researchers and R&D engineers can perform 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 dryer geometry and drying conditions. Researchers can use the two advanced units to effectively develop innovative concepts and ideas in drying.[10–12]

AVAILABLE DRYING SOFTWARE

Available commercial drying software is limited for various reasons.[1] A search identified only three commercial software packages specifically intended for drying. They are Simprosys, dryPAK, and DrySel. Here we will discuss these three packages very briefly with some emphasis on the latest one, Simprosys.

Simprosys

Simprosys is a Windows-based process simulator developed by Simprotek Corporation (www.simprotek.com). 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, .Net and C#.

Simprosys 1.01 covers 19 unit operations (solids 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. Users can construct any drying- and evaporation-related process to explore different arrangements of unit operations and experiment with different operating conditions. Simprosys 1.01 can also simulate recycled exhaust gas stream and product material stream in the process.

Simprosys has a user-friendly and intuitive user interface with maximum protection to prevent users from making simple mistakes. Users of this software require minimal self-training and effort to use it effectively.

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

dryPAK

dryPAK is a DOS based dryer design software package developed by the Technical University of Lodz.

dryPAK 3.6 does dryer design calculations including heat and mass balance and drying kinetics calculations. 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. Drying kinetics are based on Fick's diffusion equation for three basic geometries (plate, cylinder, and sphere) and two types of boundary conditions for isothermal or adiabatic case. It can also do ancillary psychometric calculations. It covers not only air–water systems but also many other gas–solvent systems. Interested readers can refer to Pakowski[13] for details about this software package.

dryPAK is a good drying-specific software package. However, it was developed on the DOS platform and has not been upgraded to Windows yet.

DrySel

DrySel is an expert system marketed by Aspen Technology for dryer selection. 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.

DrySel can provide a range of promising dryers with their advantages and disadvantages. It is an expert system but also contains some numerical calculation capabilities. After input data are obtained, major choices are then addressed, such as batch or continuous mode, contact or convective heating, basic type of feed and options for feed or product modification. In each case, the software tells users what factors should be considered when making the choice and offers advice. Users may keep all options open or concentrate on a selection. The software evaluates the overall merit factors for the selected dryers, based on over 50 rules covering material properties, specified throughput and moisture content, and safety and environmental factors. The output data are extensive and a number of options are provided. Dryers may be ranked in order of merit score, and both graphical and numerical displays are provided.

As is well known, selection of dryers is more of an art and experience than engineering and science. Even top drying experts might make different choices for the same material and design requirements since it relies much on the experience and gut feeling. Software application has been proven very effective for engineering and science problems. It is less effective for problems featuring art and experience due to its fuzzy and indetermination characteristics. However, DrySel is still a useful software tool to help process engineers make good design decisions.

Other Drying-Related Software

Many authors have developed CFD-based models of dryers; e.g., spray, fluid bed, flash, impinging jet, etc. Most are developed as parts of R&D projects in academia and are not openly available and often not user-friendly. They are also of limited validity over parameter ranges tested. Such models give detailed quantitative description of the flow, temperature and humidity fields, local particle temperatures and moisture contents, etc. Such information is obtained by solution of the governing differential equations of conservation of mass, energy, momentum, and species along with equations describing turbulence, particle motion, thermophysical property variations, etc. For dryer scoping, such detail is often not needed.

For spray dryer simulation, many research groups have carried out CFD studies. For general purpose use, NIZO Food Research (The Netherlands) has come up with a general-purpose spray dryer modeling software package called DrySPEC2 (DRYer System for Property and Energy Control), which models the processing conditions, energy usage, powder properties, etc., for a two-stage spray drying system.[14] 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. It has been used to raise capacity by up to 20% and hold product moisture content within 0.05%. 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.[15] Models for agglomeration are also included in this software.

In existing process simulators, Hysys does not include a dryer unit. Aspen Plus includes a dryer unit that appears to be too simplistic to be of much practical use. Popular process simulators like Hysys, Aspen Plus, and ProSim were designed mainly for materials of very well-defined chemical compositions. Their fundamental calculations are based on components' liquid–vapor equilibrium, which is calculated according to gas state equation. Therefore, the foundation of these process simulators, the stream model, is based on the flash calculations of pressure, temperature, and enthalpy. Such a stream model is extremely difficult to deal with drying-related simulations which need specific state variables such as absolute/relative humidity and wet-bulb/dew point temperature. The stream model of these process simulators also has difficulties in dealing with such materials as food and agricultural products, which do not have a well-defined molecular composition. Even if Hysys and Aspen Plus would be able to include reasonable dryer unit operations, they are not affordable for most, if not all, of the drying audience since the licensing fees of these software packages are rather steep.

It is worthwhile to mention that a Web-based online library, called Process Manual, includes drying as one of the 10 technical areas. Strictly speaking, Process Manual is an electronic library rather than a software package.

Another effort worth mentioning is that Microsoft Excel combined with Visual Basic is used to model and simulate dryer designs.[16] However, this cannot be regarded as mainstream drying software, although the approach may have some potential.

Although some software packages are available free on the Internet for humidity and psychrometric calculations, they all are of very limited value since real-world calculations related to drying are much more complicated than humidity and psychrometric calculations alone.

KEYS TO SUCCESS OF DRYING SOFTWARE

It is well recognized that application of properly designed drying software not only makes engineers much more productive but also leads to better designs and optimized operations. However, few commercial drying software products have been developed that are well accepted by the drying community. Kemp[1,2] attributed the lack of drying software to the following four reasons: (1) complexity of calculations, (2) difficulties in modeling solids, (3) limited market and lack of replicability, and (4) changes in operating system software.

In the authors' opinion, this is due to one major reason. The process of software development so far lacks the involvement of the global drying industry. If engineers' needs cannot be accurately captured, no matter how much effort is devoted, development of drying software would be difficult to implement commercially.

Inappropriate requirement capture is the major reason for software project failures. Accurate requirements must come from those who need the software. Software developers can not always guess what users need. They need related domain experts and potential users actively involved to know what they really need and to receive valuable feedback. Getting drying industry involved in the process of software development is the key to success of the resulting software.

Ease of use is an important factor for success of any drying software. An intuitive and easy-to-use interface will make the user's learning curve much shorter.

Making the software affordable is another key to the success of any drying software product. Although drying competes with distillation as one of the top energy-consuming unit operations, distillation-centered software products such as ASPEN Plus and Hysys are very successful and well accepted by industry. Easy modeling of liquid and replicability[1] may be some of the reasons for their success. However, the huge production scale of gasoline and other chemical products to which these software packages are applied is the major reason. With such a huge production scale as gasoline for a refinery plant, any improvements in energy efficiency through simulation can produce huge profits. Therefore, the refinery industry can afford very expensive software such as ASPEN Plus and Hysys. In contrast, drying products are so diversified and there is not a single product whose production scale can be comparable. Therefore, affordability of drying software is very important to the drying community.

MOTIVATION FOR SIMPROSYS DEVELOPMENT

Process simulators such as Hysys are very popular in both industry and academia. Hysys has very good philosophy to handle user interaction with the software. With Hysys it is easy for engineers to quickly lay out a flowsheet and do the necessary heat/mass/pressure balance calculations. They can easily study the effects of input parameters on output parameters in a big flowsheet that contains dozens of unit operations. However, Hysys is oil and gas process centered.

Application of the Hysys philosophy to drying-centered processes can generate an excellent software tool for handling drying-related problems. However, such a tool was not available heretofore. This planted the seed for development of Simprosys as a tool specifically geared to handle dryers and related ancillary equipment in complex flowsheets. Since drying is a unit operation found in almost all industrial sectors, we believe that it has lot of potential applications to improve energy economics and emission control.

Simprosys was developed using the most advanced software technology, Microsoft .Net and C#, to fill the void of process simulation for materials that do not have a clear definition of compositions. It started with drying and evaporation as its typical target processes. However, this does not limit the software only to such processes. It is useful for academic as well as industrial use.

PRINCIPLES OF SIMPROSYS

The drying flowsheet model and dryer model of Simprosys are based on extensive studies presented in some of the most authoritative handbooks by Mujumdar,[17] Masters,[18] and Perry.[19]

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.[20]

For an air–water system, the properties (including saturation pressure) of water as liquid and steam are calculated according to the 1967 ASME Steam Tables. The properties of dry air are based on Perry[19] (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 properties of the solvent are also based on Perry[19] (section 2, Physical and Chemical Data).

Dryer Models

For a continuous convective dryer, the heat and mass balance is as follows:

$$W_G(Y_O - Y_I) = W_{ev} = W_S(X_I - X_O) \tag{1}$$

$$W_G(I_{GI} - I_{GO}) + Q_c + W = W_S(I_{SO} - I_{SI}) + Q_l + \Delta Q_t + Q_m \tag{2}$$

in which 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; I_{SI} and I_{SO} are solid inlet and outlet specific enthalpy, respectively; Q_c is indirectly supplied heat to the dryer; Q_l is heat loss of the dryer; ΔQ_t is net heat carried in by transport device; and Q_m is mechanical energy input.

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

In addition to the heat and mass balance calculations, the Simprosys dryer also has a simple scoping model based on Kemp.[21] After heat and mass balance calculation you can input the drying gas velocity in the dryer to get the size of the dryer calculated.

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 a weighted average of the bone dry

TABLE 1
Specific heat 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	$C_p = 2.0082 + 1.2089 \times 10^{-3}\,T - 1.3129 \times 10^{-6}\,T^2$

material and the moisture:

$$C_{WetMat} = (1.0 - w)C_{DryMat} + wC_{Moisture} \tag{3}$$

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

When evaporation-related balance simulation is involved, Duhring 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 compositions of the material need 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 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 listed in Table 1.[22,23] The unit of temperature T is in °C and that of C_p is kJ/kg °C in Table 1.

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 a weighted average of the bone-dry food material and the moisture, which can be calculated by Eq. (3).

Other Unit Operation Models

The heat exchanger model in Simprosys is based on those found in the literature,[19,24–27] as is the cyclone model,[19,28,29] the electrostatic precipitator model,[19,29] and the wet scrubber models.[19,30] All the other unit operation models of Simprosys are based on Perry.[19]

SOME ILLUSTRATIVE APPLICATIONS OF SIMPROSYS

Using the unit operation modules provided by Simprosys, one can readily construct any drying- and evaporation-related process to model, design, and analyze. One can also readily explore different arrangements of unit operations and experiment with different operating conditions to optimize alternate designs and operations.

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, the heat duty of the heater, the exhaust dust concentration of the cyclone or scrubber, etc. They then can choose equipment according to the simulation results.

Process engineers can simulate an existing plant by easily laying out the plant on a flowsheet and inputting the operating conditions to see how efficient the current operation is. 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.

Three examples are selected here to demonstrate 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 in a short time of self-training.

Example 1—A Drying Flowsheet with Recycled Exhaust Gas Stream

The drying material is liquid. Feed solids content = 0.57 kg/kg wet basis. Feed temperature = 100°C. Feed pressure = 101.3 kPa. The material goes through a spray dryer to be dried to a moisture content of 0.08 kg/kg wet basis. 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. Specific heat of the bone dry material = 1.26 kJ/kg°C. Mass flow rate of wet material = 2000 kg/h. Drying air: Initial pressure = 101.3 kPa. Initial temperature (dry-bulb) = 20°C. Initial absolute humidity = 0.009 kg/kg. Mass flow rate of humid air = 15,000 kg/h.

Drying air 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 99.5%, and filtration velocity is 2.5 m/s. Drying air then goes through a blower (the efficiency is 0.73) to gain 4 kPa static pressure, then through a heater to be heated to 85°C before it is split into two streams; one goes directly to the vibrated fluidized bed dryer, the other is further heated through a

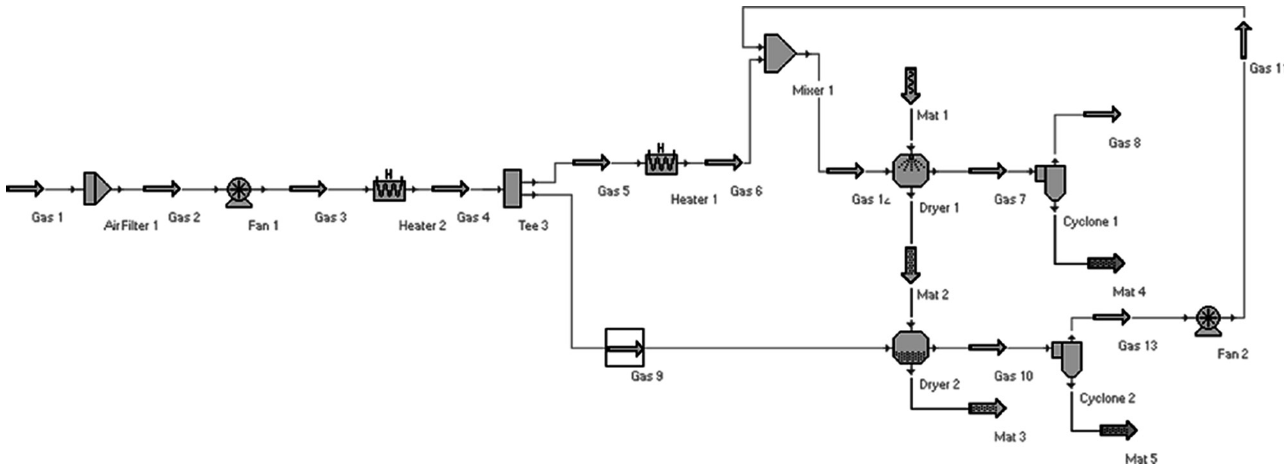


FIG. 1. Flowsheet with recycled exhaust gas stream.

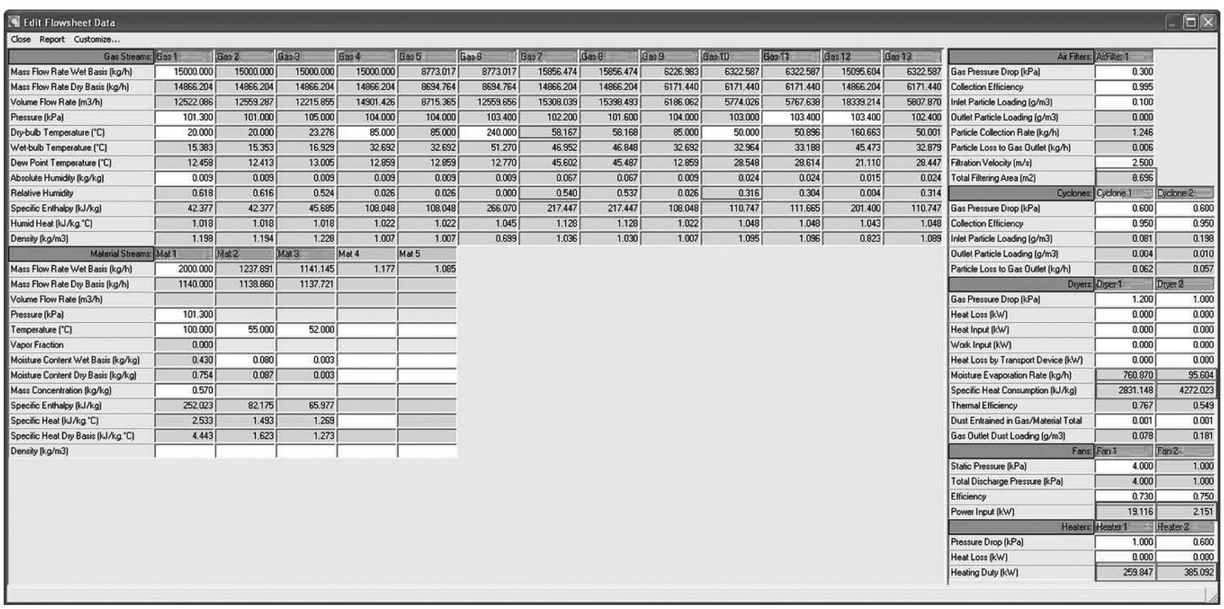
heater to 240°C and then goes to the spray dryer. Pressure drop of air in the first and second heater is 1.0 and 0.6 kPa, respectively. Pressure drop of air in the spray dryer and the fluidized bed dryer is 1.2 and 1.0 kPa, respectively. The exhaust air entrains 0.1% of the total material in both dryers. Exhaust gas from the spray dryer goes through a cyclone to collect 95% of the entrained dust material. Pressure drop of gas in this cyclone is 0.6 kPa. Exhaust gas from the vibrated fluidized bed dryer also goes through a cyclone to collect 95% of the entrained dust material. Pressure drop of gas in this cyclone is 0.6 kPa. Exhaust gas coming out of the cyclone goes through a blower (the efficiency of the fan is 0.7) to be compressed to 103.4 kPa and then is mixed with the fresh air coming out of heater 1 and sent to the spray dryer inlet.

The established flowsheet using Simprosys is displayed in Fig. 1. The simulated result is shown in Fig. 2.

With Simprosys it is easy to specify the absolute humidity of the fresh air instead of relative humidity or specify the heating duty of the heater rather than the air inlet temperature of the dryer to simulate the flowsheet. One can also change the material inlet temperature and/or moisture content to see how the air outlet temperature and humidity change.

Example 2—A Drying Flowsheet with 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°C. Product temperature = 75°C. Product



Edit Flowsheet Data

Close Report Customize...

Gas Streams:	Gas 1	Gas 2	Gas 3	Gas 4	Gas 5	Gas 6	Gas 7	Gas 8	Gas 9	Gas 10	Gas 11	Gas 12	Gas 13
Mass Flow Rate Wet Basis (kg/h)	15000.000	15000.000	15000.000	15000.000	8773.017	8773.017	15856.474	15856.474	6226.983	6322.587	6322.587	15095.604	6322.587
Mass Flow Rate Dry Basis (kg/h)	14866.204	14866.204	14866.204	14866.204	8694.764	8694.764	14866.204	14866.204	6171.440	6171.440	6171.440	14866.204	6171.440
Volume Flow Rate (m3/h)	12522.086	12559.287	12215.855	14901.426	8715.365	12559.656	15308.039	15398.493	6186.062	5774.026	5767.638	18339.214	5807.870
Pressure (kPa)	101.300	101.000	105.000	104.000	104.000	103.400	102.200	101.600	104.000	103.000	103.400	103.400	102.400
Dry-bulb Temperature (°C)	20.000	20.000	23.276	85.000	85.000	240.000	58.167	58.168	85.000	50.000	50.896	160.663	50.001
Wet-bulb Temperature (°C)	15.383	15.353	16.929	32.692	32.692	51.270	46.952	46.848	32.692	32.964	33.188	45.473	32.879
Dew Point Temperature (°C)	12.458	12.413	13.005	12.859	12.859	12.770	45.602	45.487	12.859	28.548	28.614	21.110	28.447
Absolute Humidity (kg/kg)	0.009	0.009	0.009	0.009	0.009	0.009	0.067	0.067	0.009	0.024	0.024	0.015	0.024
Relative Humidity	0.618	0.616	0.524	0.026	0.026	0.000	0.540	0.537	0.026	0.316	0.304	0.004	0.314
Specific Enthalpy (kJ/kg)	42.377	42.377	45.685	108.048	108.048	266.070	217.447	217.447	108.048	110.747	111.665	201.400	110.747
Humid Heat (kJ/kg.°C)	1.018	1.018	1.018	1.022	1.022	1.045	1.128	1.128	1.022	1.048	1.048	1.043	1.048
Density (kg/m3)	1.198	1.194	1.228	1.007	1.007	0.699	1.036	1.030	1.007	1.095	1.096	0.823	1.089

Material Streams:	Mat 1	Mat 2	Mat 3	Mat 4	Mat 5
Mass Flow Rate Wet Basis (kg/h)	2000.000	1237.891	1141.145	1.177	1.085
Mass Flow Rate Dry Basis (kg/h)	1140.000	1138.860	1137.721		
Volume Flow Rate (m3/h)					
Pressure (kPa)	101.300				
Temperature (°C)	100.000	55.000	52.000		
Vapor Fraction	0.000				
Moisture Content Wet Basis (kg/kg)	0.430	0.080	0.003		
Moisture Content Dry Basis (kg/kg)	0.754	0.087	0.003		
Mass Concentration (kg/kg)	0.570				
Specific Enthalpy (kJ/kg)	252.023	82.175	65.977		
Specific Heat (kJ/kg.°C)	2.533	1.493	1.269		
Specific Heat Dry Basis (kJ/kg.°C)	4.443	1.623	1.273		
Density (kg/m3)					

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)	1.246
Particle Loss to Gas Outlet (kg/h)	0.006
Filtration Velocity (m/s)	2.500
Total Filtering Area (m2)	8.696

Cyclones:	Cyclone 1	Cyclone 2
Gas Pressure Drop (kPa)	0.600	0.600
Collection Efficiency	0.950	0.950
Inlet Particle Loading (g/m3)	0.081	0.198
Outlet Particle Loading (g/m3)	0.004	0.010
Particle Loss to Gas Outlet (kg/h)	0.062	0.057

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)	760.870	95.604
Specific Heat Consumption (kJ/kg)	2831.148	4272.023
Thermal Efficiency	0.767	0.549
Dust Entrained in Gas/Material Total	0.001	0.001
Gas Outlet Dust Loading (g/m3)	0.078	0.181
Fans:	**Fan 1**	**Fan 2**
Static Pressure (kPa)	4.000	1.000
Total Discharge Pressure (kPa)	4.000	1.000
Efficiency	0.730	0.750
Power Input (kW)	19.116	2.151
Heaters:	**Heater 1**	**Heater 2**
Pressure Drop (kPa)	1.000	0.600
Heat Loss (kW)	0.000	0.000
Heating Duty (kW)	259.847	385.092

FIG. 2. Simulation results for example 1.

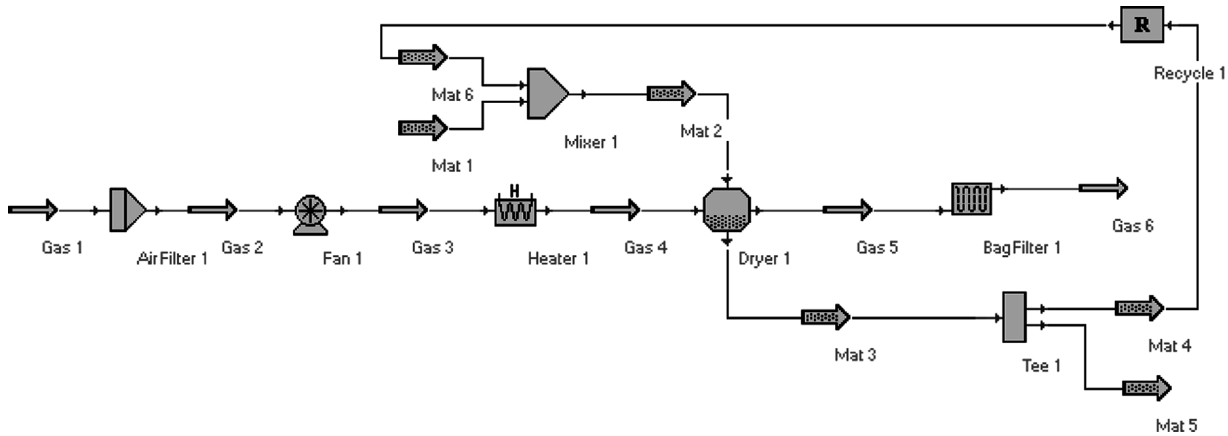
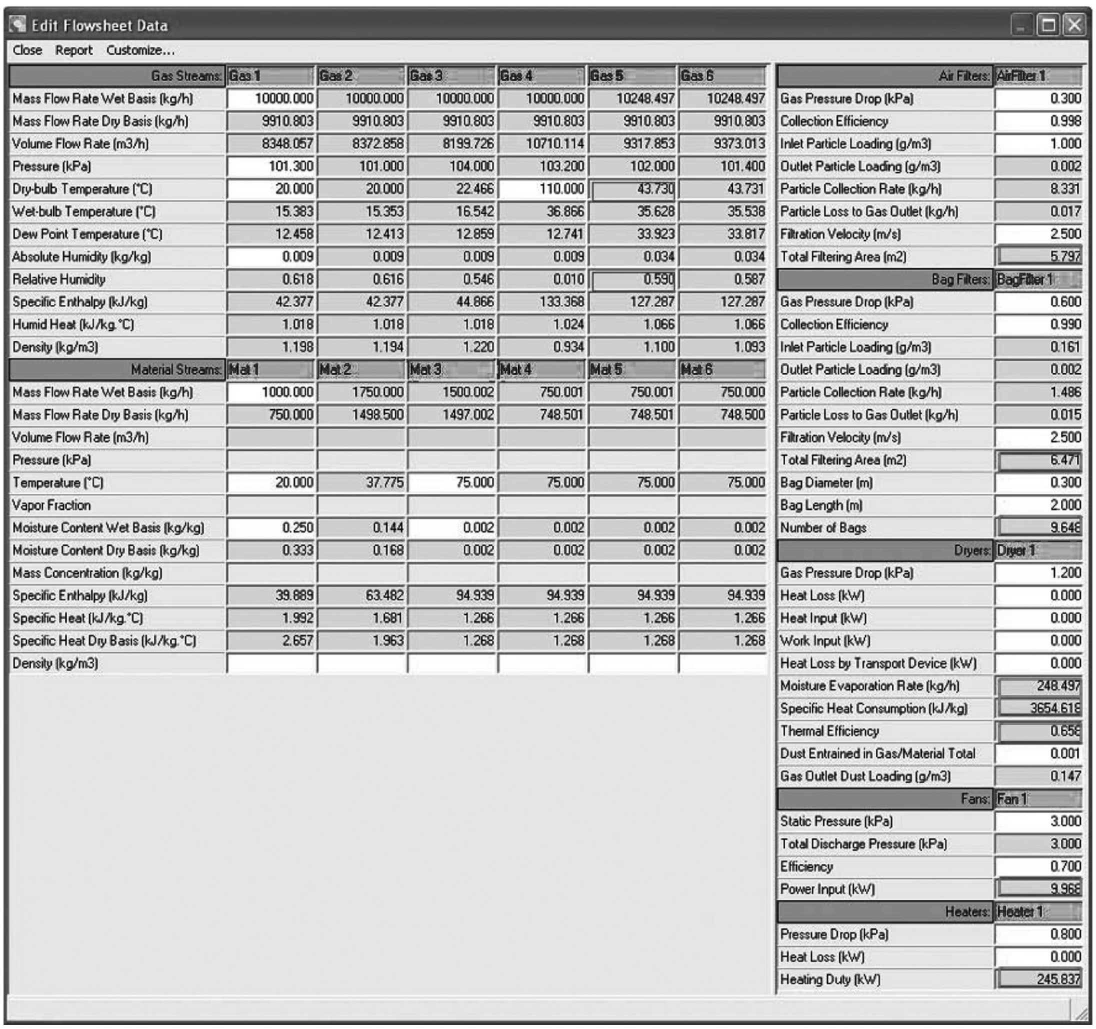


FIG. 3. Flowsheet with recycled material stream.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Gas Streams:	Gas 1	Gas 2	Gas 3	Gas 4	Gas 5	Gas 6
Mass Flow Rate Wet Basis (kg/h)	10000.000	10000.000	10000.000	10000.000	10248.497	10248.497
Mass Flow Rate Dry Basis (kg/h)	9910.803	9910.803	9910.803	9910.803	9910.803	9910.803
Volume Flow Rate (m3/h)	8348.057	8372.858	8199.726	10710.114	9317.853	9373.013
Pressure (kPa)	101.300	101.000	104.000	103.200	102.000	101.400
Dry-bulb Temperature (°C)	20.000	20.000	22.466	110.000	43.730	43.731
Wet-bulb Temperature (°C)	15.383	15.353	16.542	36.866	35.628	35.538
Dew Point Temperature (°C)	12.458	12.413	12.859	12.741	33.923	33.817
Absolute Humidity (kg/kg)	0.009	0.009	0.009	0.009	0.034	0.034
Relative Humidity	0.618	0.616	0.546	0.010	0.590	0.587
Specific Enthalpy (kJ/kg)	42.377	42.377	44.866	133.368	127.287	127.287
Humid Heat (kJ/kg.°C)	1.018	1.018	1.018	1.024	1.066	1.066
Density (kg/m3)	1.198	1.194	1.220	0.934	1.100	1.093
Material Streams:	**Mat 1**	**Mat 2**	**Mat 3**	**Mat 4**	**Mat 5**	**Mat 6**
Mass Flow Rate Wet Basis (kg/h)	1000.000	1750.000	1500.002	750.001	750.001	750.000
Mass Flow Rate Dry Basis (kg/h)	750.000	1498.500	1497.002	748.501	748.501	748.500
Volume Flow Rate (m3/h)						
Pressure (kPa)						
Temperature (°C)	20.000	37.775	75.000	75.000	75.000	75.000
Vapor Fraction						
Moisture Content Wet Basis (kg/kg)	0.250	0.144	0.002	0.002	0.002	0.002
Moisture Content Dry Basis (kg/kg)	0.333	0.168	0.002	0.002	0.002	0.002
Mass Concentration (kg/kg)						
Specific Enthalpy (kJ/kg)	39.889	63.482	94.939	94.939	94.939	94.939
Specific Heat (kJ/kg.°C)	1.992	1.681	1.266	1.266	1.266	1.266
Specific Heat Dry Basis (kJ/kg.°C)	2.657	1.963	1.268	1.268	1.268	1.268
Density (kg/m3)						

Air Filters:	AirFilter 1
Gas Pressure Drop (kPa)	0.300
Collection Efficiency	0.998
Inlet Particle Loading (g/m3)	1.000
Outlet Particle Loading (g/m3)	0.002
Particle Collection Rate (kg/h)	8.331
Particle Loss to Gas Outlet (kg/h)	0.017
Filtration Velocity (m/s)	2.500
Total Filtering Area (m2)	5.797
Bag Filters:	**BagFilter 1**
Gas Pressure Drop (kPa)	0.600
Collection Efficiency	0.990
Inlet Particle Loading (g/m3)	0.161
Outlet Particle Loading (g/m3)	0.002
Particle Collection Rate (kg/h)	1.486
Particle Loss to Gas Outlet (kg/h)	0.015
Filtration Velocity (m/s)	2.500
Total Filtering Area (m2)	6.471
Bag Diameter (m)	0.300
Bag Length (m)	2.000
Number of Bags	9.648
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)	248.497
Specific Heat Consumption (kJ/kg)	3654.618
Thermal Efficiency	0.658
Dust Entrained in Gas/Material Total	0.001
Gas Outlet Dust Loading (g/m3)	0.147
Fans:	**Fan 1**
Static Pressure (kPa)	3.000
Total Discharge Pressure (kPa)	3.000
Efficiency	0.700
Power Input (kW)	9.968
Heaters:	**Heater 1**
Pressure Drop (kPa)	0.800
Heat Loss (kW)	0.000
Heating Duty (kW)	245.837

FIG. 4. Simulation results for example 2.

moisture content = 0.002 kg/kg wet basis. 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 = 0.3. Mass flow rate of humid air = 10,000 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 fan (the efficiency of the fan is 0.7) to gain 3 kPa static pressure, then through a heater with a heating duty of 246 kW. Pressure drop of air in the 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 into the dryer's gas outlet stream. The gas outlet stream needs to go through a bag filter to collect the entrained dust material. Collection efficiency of the bag filter is 99%. Pressure drop of air in the bag filter 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 and mixes with the fresh material in a mixer and then is introduced into the dryer material inlet. The established flowsheet is displayed in Fig. 3. The simulated result is shown in Fig. 4.

Simulation results indicate that 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 Simprosys 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 50,000 kg/h flow rate is initially at a mass concentration of 0.13 kg/kg and a temperature of 3°C. It needs to be concentrated to a mass concentration of 0.57. 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 · °C. The boiling point rise of the material solution can be described by the Duhring lines expressed in Table 2.

TABLE 2
Duhring 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

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 fluid bed dryer to be dried to a moisture content of 0.03 kg/kg (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 fluid bed dryer is at 103.2 kPa and 85°C. The exhaust air of the vibrated fluid bed dryer is at 50°C. Dried material from the vibrated fluid bed dryer is at 52°C. Part of the liquid-vapor seperator of the second effect 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°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 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°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 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 Fig. 5. The results of the calculations are shown in Fig. 6. Note that not all results are shown in the table due to space

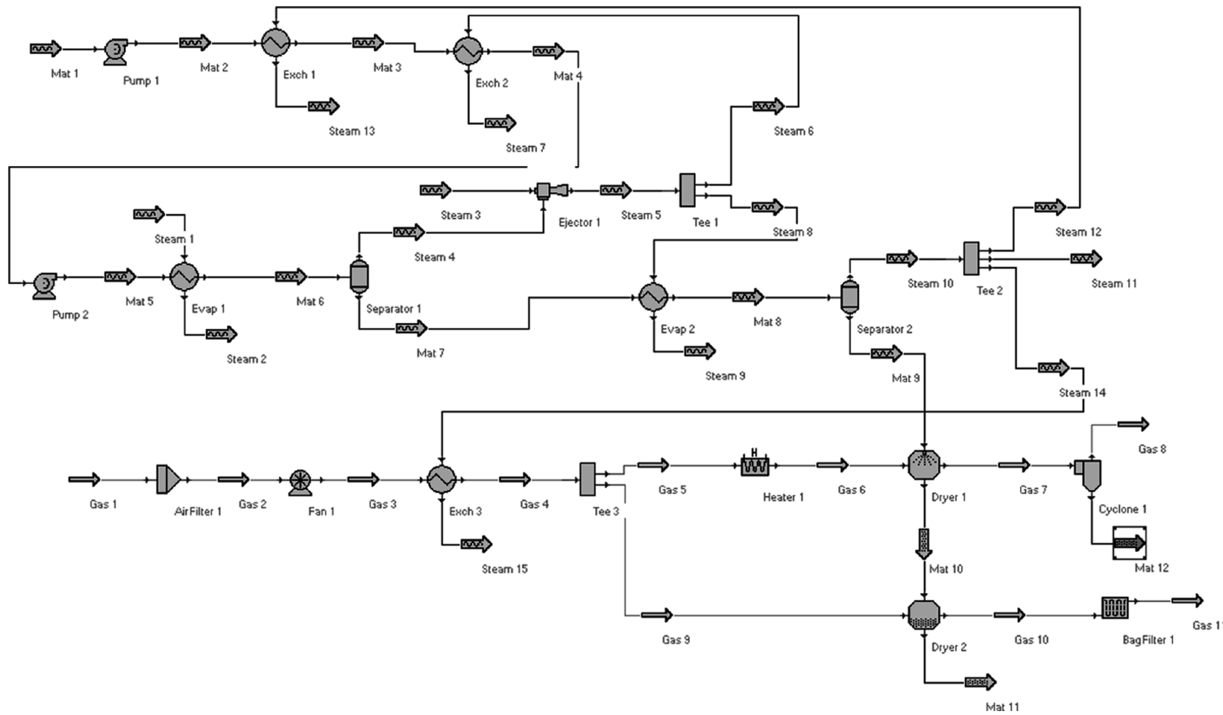

FIG. 5. Combined evaporation and drying flowsheet.

limitations in Fig. 6. 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.

CLOSING REMARKS

A comprehensive drying suite is an ideal solution for drying software. With such a drying suite, design engineers can do their designs of drying systems and dryers; process engineers can evaluate existing drying plants and optimize their operations; R&D engineers can do cost-effective simulations for better design, optimization, and control; and researchers can develop innovative concepts and ideas.

Simprosys is possibly the first step toward the 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.

Drying is such a widely used unit operation and such a huge energy consumer that the drying community must be able to nourish and sustain properly designed drying software. Software such as Simprosys can be widely used by academia for teaching and by industry. With concerns

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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)	153234.553	153234.553	153234.553	153234.553	117729.828	117729.828	121941.839	121941.839	35504.725	36049.839	36049.839
Mass Flow Rate Dry Basis (kg/h)	151867.744	151867.744	151867.744	151867.744	116679.710	116679.710	116679.710	116679.710	35188.033	35188.033	35188.033
Volume Flow Rate (m3/h)	127921.082	128301.120	123454.332	152520.870	117181.506	135962.623	119849.773	120551.678	35339.364	32986.127	33179.855
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)	20.000	20.000	20.097	85.000	85.000	140.000	68.000	67.983	85.000	50.000	50.001
Wet-bulb Temperature (°C)	15.383	15.353	15.772	32.664	32.664	41.124	42.723	42.622	32.664	32.935	32.850
Dew Point Temperature (°C)	12.458	12.413	13.005	12.829	12.829	12.741	38.774	38.665	12.829	28.514	28.413
Absolute Humidity (kg/kg)	0.009	0.009	0.009	0.009	0.009	0.009	0.045	0.045	0.009	0.024	0.024
Relative Humidity	0.618	0.616	0.637	0.026	0.026	0.004	0.242	0.241	0.026	0.316	0.314
Specific Enthalpy (kJ/kg)	42.377	42.377	42.477	108.048	108.048	163.817	178.432	178.414	108.048	110.747	110.747
Humid Heat (kJ/kg.°C)	1.018	1.018	1.018	1.022	1.022	1.028	1.088	1.088	1.022	1.048	1.048
Density (kg/m3)	1.198	1.194	1.241	1.005	1.005	0.866	1.017	1.012	1.005	1.093	1.086

Material Streams:	Mat 1	Mat 2	Mat 3	Mat 4	Mat 5	Mat 6	Mat 8	Mat 10	Mat 11	Steam 1	Steam 2	Steam 3	Steam 4	Steam 10
Mass Flow Rate Wet Basis (kg/h)	50000.000	50000.000	50000.000	50000.000	50000.000	50000.000	31590.009	7058.152	6506.526	19424.278	19424.278	4200.000	18409.990	20312.782
Mass Flow Rate Dry Basis (kg/h)	6500.000	6500.000	6500.000	6500.000	6500.000	6500.000	6500.000	6493.500	6487.007					
Volume Flow Rate (m3/h)	69.444	69.444		69.444	69.444					13213.564	20.760	2200.818	32078.255	37474.805
Pressure (kPa)	101.300	108.000	105.000	102.000	106.000	102.000	95.000			265.000	260.000	350.000	100.000	93.000
Temperature (°C)	3.000	2.998	81.000	100.000	99.999	101.703	100.621	55.000	52.000	129.360	128.727	138.873	109.624	103.761
Vapor Fraction	0.000	0.000	0.000	0.000	0.000	0.370	0.640			1.000	0.000	1.000	1.000	1.000
Moisture Content Wet Basis (kg/kg)	0.870	0.870	0.870	0.870	0.870	0.870	0.794	0.080	0.003	1.000	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	0.087	0.003					
Mass Concentration (kg/kg)	0.130	0.130	0.130	0.130	0.130	0.130	0.206			0.000	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	82.175	65.977	2719.035	540.873	2731.625	2695.626	2684.659
Specific Heat (kJ/kg.°C)	3.835	3.809	3.815	3.835	3.809	3.837	3.611	1.493	1.269	1.902	4.266	1.907	1.893	1.890
Specific Heat Dry Basis (kJ/kg.°C)	29.499	29.299	29.347	29.498	29.299			1.623	1.273					
Density (kg/m3)	720.000	720.000		720.000	720.000					1.470	935.637	1.908	0.574	0.542

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)	12.728
Particle Loss to Gas Outlet (kg/h)	0.064
Filtration Velocity (m/s)	2.500
Total Filtering Area (m2)	88.834
Bag Filters:	**BagFilter 1**
Gas Pressure Drop (kPa)	0.600
Collection Efficiency	0.995
Inlet Particle Loading (g/m3)	0.197
Outlet Particle Loading (g/m3)	0.001
Particle Collection Rate (kg/h)	6.480
Particle Loss to Gas Outlet (kg/h)	0.033
Filtration Velocity (m/s)	2.500
Total Filtering Area (m2)	22.907
Bag Diameter (m)	0.400
Bag Length (m)	2.000
Number of Bags	24.747
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)	[illegible]

FIG. 6. Simulation results for example 3.

about global warming, the possible implementation of carbon tax, and depleting energy resources, Simprosys can make an effective contribution to alleviating these problems.

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