

Software for Design and Analysis of Drying Systems

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ABSTRACT

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.

Key Words: Software; Drying Suite, Dryer Design, Drying Simulation, Simprosys

INTRODUCTION

Since the emergence of modern electronic computers in early 1980's, 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 [1-3]. However, few commercial software packages related to drying and drying system design have been developed successfully and 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 ninety percent 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 get the entrained product collected 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, 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. Dryer selection is often the most challenging part for the drying system design of a material 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 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 Dynamic (CFD) analysis of gas-particles two phase flow with coupled heat and mass transfer, may be required for better design and optimization.

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, trouble-shooting as well as control and optimization of drying systems, computer software can be helpful in 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 [4, 5] 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 that simulates 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 dryer 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, trouble-shooting 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 for the pre- and post-processing 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 for a drying operation. They should further 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 used 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 do cost-effective simulations for better design, optimization and control. They can also use them to effectively develop innovative concepts and ideas in drying [6].

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 viz. Symprosys.

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 viz. .Net and C#.

Simprosys 1.01 covers 19 unit operations (viz. 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. Symprosys 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, to dryer scaling up is under development.

dryPAK

dryPAK is a DOS based dryer design software package developed by 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 is 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 psychrometric calculations. It covers not only air-water system, but also many other gas-solvent systems.

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 not only is an expert system, but also contains some numerical calculation capabilities. After input data is obtained major choices are then addressed; 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, safety and environmental factors. The output data is extensive and a number of options are provided. Dryers may be ranked in order of merit score, and both graphical and numerical display is provided.

As is well known, selection of dryers is more of an art and experience than engineering and science. Even top dryer 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 featured by 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 flowfield, temperature and humidity fields, local particle temperatures and moisture contents etc. Such information 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 [22]. 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. 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 which appears to be too simplistic to be of much practical use. Popular process simulators like Hysys, Aspen Plus, 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 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 since they need specific state variables such as absolute and relative humidity, wet-bulb and 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 worthwhile to mention is that Microsoft Excel combined with Visual Basic is used to model and simulate dryer designs [7]. However, this can not be regarded as mainstream of 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 is much more complicated than only humidity and psychrometric calculations.

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 and 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; (4) changes in operating system software.

In 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 of 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 so as to know what they really need and to receive valuable feedback. Getting drying industry to be involved in the process of software development is the key to success of the resulting software.

Easy-to-use an important factors necessary for success of any drying software. An intuitive and easy-to-use interface will make users' 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 part 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 profit. Therefore, refinery industry can afford to very expensive software such as ASPEN Plus and Hysys. In contrary, 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 layout 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 process 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 is 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 [8], Masters [9] and Perry [10].

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 [11]

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 also based on Perry [9] (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 calculated according to Perry [9] (section 2, Physical and Chemical Data).

Dryer Models

The heat and mass balance calculations are based on Pakowski and Mujumdar [8] and Masters [11]. For a continuous convective dryer the heat and mass balance is as follows:

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

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

in which W_G is the gas mass flowrate (dry basis); Y_O and Y_I are gas outlet and inlet absolute humidity, respectively; W_S is the solid throughput (mass flowrate 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 to the dryer; Q_l is heat loss of the dryer; ΔQ_t is net heat carried in by transport device; Q_m is mechanical energy input.

In the Simprosys dryer model, you can specify the gas inlet temperature and humidity plus 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 limit we can not 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 [12]. 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 material and the moisture

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

Where C_{WetMat} , C_{DryMat} , $C_{Moisture}$ represent specific heats of wet material, bone dry material, and moisture liquid 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 needs to be specified. 5 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 5 basic components. The specific heat as a function of temperature for each of the 5 basic components is listed in Table 1 [13, 14].

| | |
|--------------|--|
| 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 | $C_p = 2.0082 + 1.2089 \times 10^{-3}T - 1.3129 \times 10^{-6}T^2$ |

Table 1 Specific Heat of Generic Food Components

The unit of temperature T is $^{\circ}\text{C}$ and that of C_p is $\text{kJ/kg.}^{\circ}\text{C}$ 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 a weighted average of the bone dry food material and the moisture, which can be calculated by Equation 1.

Other Unit Operation Models

The heat exchanger model in Simprosys is based on [9, 15-18]. The cyclone model is based on [9, 19, 20]. The electrostatic precipitator model is based on [9, 20]. The wet scrubber models are based [9, 21]. All the other unit operation models of Simprosys are based on Perry [9].

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.

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 mass concentration = 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 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 wet basis = 2000 kg/hr.

Drying air: Initial pressure = 101.3 kPa. Initial temperature (dry-bulb) = 20 °C. Initial absolute humidity = 0.009 kg/kg. Mass flow rate wet basis = 15000 kg/hr.

Drying air goes through an air filter with a pressure drop of 0.3 kPa. Assume dust volume concentration is 0.1 g/m³, 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 stream, one goes directly to the vibrated fluidized bed dryer; the other is further heated through a 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 the second heater and used as the sent to the spray dryer inlet.

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

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 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.

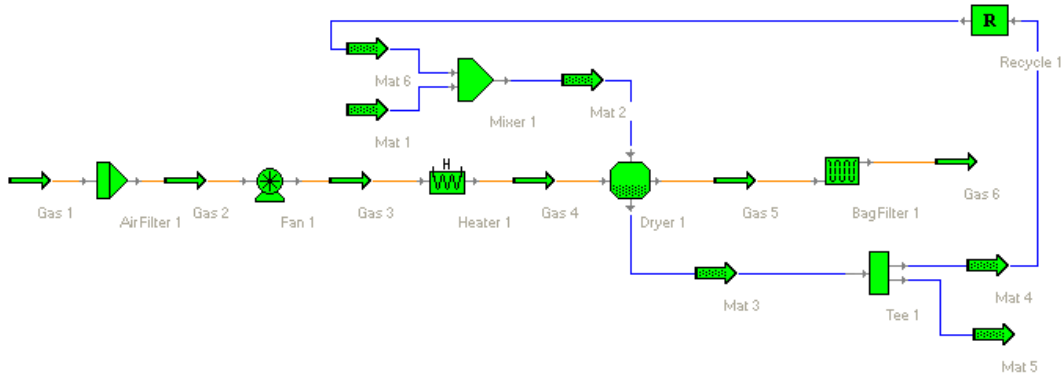


Figure 3 Flowsheet with Recycled Material Stream

| Edit Flowsheet Data | | | | | | | Air Filters: AirFilter 1 | |
|------------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|--------------------------------------|----------|
| 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 | Gas Pressure Drop (kPa) | 0.300 |
| Mass Flow Rate Dry Basis (kg/h) | 9910.803 | 9910.803 | 9910.803 | 9910.803 | 9910.803 | 9910.803 | Collection Efficiency | 0.998 |
| Volume Flow Rate (m3/h) | 8348.057 | 8372.858 | 8199.726 | 10710.114 | 9317.853 | 9373.013 | Inlet Particle Loading (g/m3) | 1.000 |
| Pressure (kPa) | 101.300 | 101.000 | 104.000 | 103.200 | 102.000 | 101.400 | Outlet Particle Loading (g/m3) | 0.002 |
| Dry-bulb Temperature (°C) | 20.000 | 20.000 | 22.466 | 110.000 | 43.730 | 43.731 | Particle Collection Rate (kg/h) | 8.331 |
| Wet-bulb Temperature (°C) | 15.383 | 15.353 | 16.542 | 36.866 | 35.628 | 35.538 | Particle Loss to Gas Outlet (kg/h) | 0.017 |
| Dew Point Temperature (°C) | 12.458 | 12.413 | 12.859 | 12.741 | 33.923 | 33.817 | Filtration Velocity (m/s) | 2.500 |
| Absolute Humidity (kg/kg) | 0.009 | 0.009 | 0.009 | 0.009 | 0.034 | 0.034 | Total Filtering Area (m2) | 5.797 |
| Relative Humidity | 0.618 | 0.616 | 0.546 | 0.010 | 0.590 | 0.587 | Bag Filters: BagFilter 1 | |
| Specific Enthalpy (kJ/kg) | 42.377 | 42.377 | 44.866 | 133.368 | 127.287 | 127.287 | Gas Pressure Drop (kPa) | 0.600 |
| Humid Heat (kJ/kg.°C) | 1.018 | 1.018 | 1.018 | 1.024 | 1.066 | 1.066 | Collection Efficiency | 0.990 |
| Density (kg/m3) | 1.198 | 1.194 | 1.220 | 0.934 | 1.100 | 1.093 | Inlet Particle Loading (g/m3) | 0.161 |
| Material Streams: | Mat 1 | Mat 2 | Mat 3 | Mat 4 | Mat 5 | Mat 6 | Outlet Particle Loading (g/m3) | 0.002 |
| Mass Flow Rate Wet Basis (kg/h) | 1000.000 | 1750.000 | 1500.002 | 750.001 | 750.001 | 750.000 | Particle Collection Rate (kg/h) | 1.486 |
| Mass Flow Rate Dry Basis (kg/h) | 750.000 | 1498.500 | 1497.002 | 748.501 | 748.501 | 748.500 | Particle Loss to Gas Outlet (kg/h) | 0.015 |
| Volume Flow Rate (m3/h) | | | | | | | Filtration Velocity (m/s) | 2.500 |
| Pressure (kPa) | | | | | | | Total Filtering Area (m2) | 6.471 |
| Temperature (°C) | 20.000 | 37.775 | 75.000 | 75.000 | 75.000 | 75.000 | Bag Diameter (m) | 0.300 |
| Vapor Fraction | | | | | | | Bag Length (m) | 2.000 |
| Moisture Content Wet Basis (kg/kg) | 0.250 | 0.144 | 0.002 | 0.002 | 0.002 | 0.002 | Number of Bags | 9.648 |
| Moisture Content Dry Basis (kg/kg) | 0.333 | 0.168 | 0.002 | 0.002 | 0.002 | 0.002 | Dryers: Dryer 1 | |
| Mass Concentration (kg/kg) | | | | | | | Gas Pressure Drop (kPa) | 1.200 |
| Specific Enthalpy (kJ/kg) | 39.889 | 63.482 | 94.939 | 94.939 | 94.939 | 94.939 | Heat Loss (kW) | 0.000 |
| Specific Heat (kJ/kg.°C) | 1.992 | 1.681 | 1.266 | 1.266 | 1.266 | 1.266 | Heat Input (kW) | 0.000 |
| Specific Heat Dry Basis (kJ/kg.°C) | 2.857 | 1.963 | 1.268 | 1.268 | 1.268 | 1.268 | Work Input (kW) | 0.000 |
| Density (kg/m3) | | | | | | | 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 |

Figure 4 Simulation Results for Example 2

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 introduced into the dryer material inlet. The established flowsheet is displayed in Figure 3. The simulated result is shown in Figure 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 in stead 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 50000 kg/hr 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/m³ 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 following Durhing lines expressed in Table 2

Table 2. Durhing Lines

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

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 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 °C. Then part of the thermally compressed secondary vapor from the first effect is used to further heat the material to nearly the bubble point of the material. It then goes to the first falling film evaporator operating at a pressure of 106 kPa. Water vapor of 265 kPa is used as the heating steam for this evaporator. Vapor and liquid mixture coming out of the first evaporator goes to a liquid-vapor separator to separate the concentrated liquid with the vapor. Secondary vapor coming out of the separator is compressed with a fresh steam of 350 kPa using a steam jet ejector. A very small portion of the compressed secondary vapor is used to preheat the feeding material from 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 Figure 5. The results of the calculation are shown in Figure 6. Note that not all results are shown in the table due to space limitation in Figure 6. Interested readers may visit www.simprotek.com to download a trail version of Simprosys 1.01 and load Example 11 in the Tutorial to fully study this example.

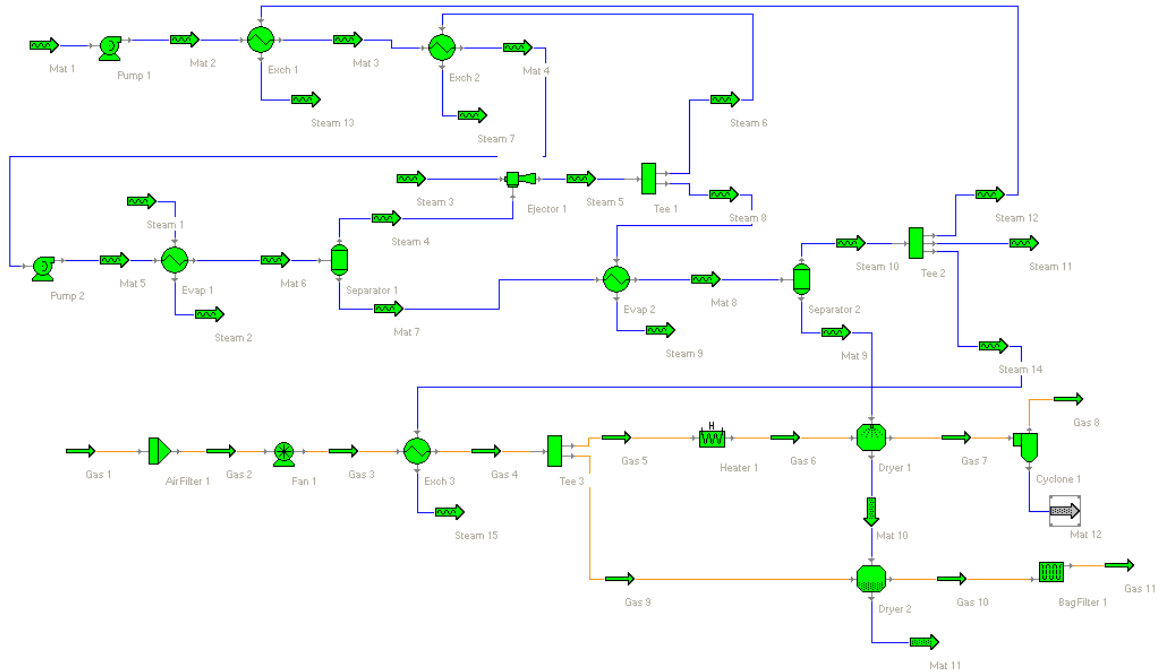


Figure 5 Combined Evaporation and Drying Flowsheet

| 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 | | | | | Air Filters: AirFilter 1 | |
| 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 | | | | | Gas Pressure Drop (kPa) | 0.300 |
| 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 | | | | | Collection Efficiency | 0.995 |
| Volume Flow Rate (m3/h) | 127921.082 | 128301.120 | 123454.332 | 152520.870 | 117181.506 | 139962.623 | 119849.773 | 120551.678 | 35339.364 | 32986.127 | 33179.855 | | | | | Inlet Particle Loading (g/m3) | 0.100 |
| Pressure (kPa) | 101.300 | 101.000 | 105.000 | 103.800 | 103.800 | 103.200 | 102.200 | 101.600 | 103.800 | 102.800 | 102.200 | | | | | Outlet Particle Loading (g/m3) | 0.000 |
| 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 | | | | | Particle Collection Rate (kg/h) | 12.728 |
| 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 | | | | | Particle Loss to Gas Outlet (kg/h) | 0.064 |
| 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 | | | | | Filtration Velocity (m/s) | 2.500 |
| 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 | | | | | Total Filtering Area (m2) | 88.834 |
| Relative Humidity | 0.618 | 0.616 | 0.637 | 0.026 | 0.026 | 0.004 | 0.242 | 0.241 | 0.026 | 0.316 | 0.314 | | | | | Bag Filters: BagFilter 1 | |
| 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 | | | | | Gas Pressure Drop (kPa) | 0.600 |
| Humid Heat (kJ/kg °C) | 1.018 | 1.018 | 1.018 | 1.022 | 1.022 | 1.088 | 1.088 | 1.088 | 1.022 | 1.048 | 1.048 | | | | | Collection Efficiency | 0.995 |
| 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 | | | | | Inlet Particle Loading (g/m3) | 0.197 |
| 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 | Cyclones: Cyclone 1 | | |
| 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 | Outlet Particle Loading (g/m3) | 0.001 | |
| Mass Flow Rate Dry Basis (kg/h) | 6500.000 | 6500.000 | 6500.000 | 6500.000 | 6500.000 | 6500.000 | 6500.000 | 6500.000 | 6493.500 | 6487.007 | | | | | Particle Collection Rate (kg/h) | 6.480 | |
| Volume Flow Rate (m3/h) | 69.444 | 69.444 | | 69.444 | 69.444 | | | | | 13213.564 | 20.760 | 2200.818 | 32078.255 | 37474.805 | Particle Loss to Gas Outlet (kg/h) | 0.033 | |
| 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 | Filtration Velocity (m/s) | 2.500 | |
| 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 | Total Filtering Area (m2) | 22.907 | |
| 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 | Bag Diameter (m) | 0.400 | |
| 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 | Bag Length (m) | 2.000 | |
| Moisture Content Dry Basis (kg/kg) | 6.692 | 6.692 | 6.692 | 6.692 | 6.692 | 6.692 | 3.860 | 0.087 | 0.003 | | | | | | Number of Bags | 24.747 | |
| 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 | Cyclones: Cyclone 1 | | |
| 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 | Gas Pressure Drop (kPa) | 0.600 | |
| 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 | Collection Efficiency | 0.950 | |
| Specific Heat Dry Basis (kJ/kg °C) | 29.499 | 29.299 | 29.347 | 29.498 | 29.299 | | | 1.623 | 1.273 | | | | | | Inlet Particle Loading (g/m3) | 0.059 | |
| Density (kg/m3) | 720.000 | 720.000 | | 720.000 | 720.000 | | | | | 1.470 | 935.637 | 1.908 | 0.574 | 0.542 | Outlet Particle Loading (g/m3) | 0.003 | |

Figure 6 Simulation Results of Example 3

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 plant and optimize their operations; R&D engineers can do cost-effective simulations for better design, optimization and control; researchers can develop innovative concepts and ideas;

Simpros 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, the drying community must be able to nourish and sustain properly designed drying software. Software such as Sympros can be widely used by academia for teaching and by industry. With concerns over global warming, the possible implementation of carbon tax and depleting energy resources, Sympros can make an effective contribution to alleviating these problems.

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