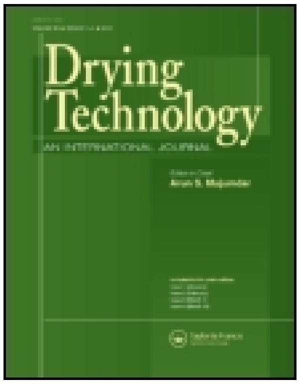

Drying Technology: An International Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ldrt20

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Published online: 12 Feb 2014.

To cite this article: Zhen-Xiang Gong & Arun S. Mujumdar (2014) Process Simulation of Combustion Drying with Simprosys Software, Drying Technology: An International Journal, 32:4, 447-454, DOI: 10.1080/07373937.2013.835319

To link to this article: http://dx.doi.org/10.1080/07373937.2013.835319

Drying Technology, 32: 447–454, 2014

ISSN: 0737-3937 print/1532-2300 online
DOI: 10.1080/07373937.2013.835319

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Process Simulation of Combustion Drying with Simprosys Software

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This article presents a software tool, Simprosys, and its newly added burner unit operation model for process modeling and simulation of drying. Combustion generation using the burner unit operation is described briefly. Humid gas properties of combustion are compared and found to be different from those of air. The effects of pressure on both air and combustion humid gas properties are investigated. It is found that both combustion and air could be significantly different in their moisture carrying capability when the operating pressure is different from standard atmospheric pressure, especially for some vacuum drying cases where the operating pressure is well below atmospheric pressure. A model combustion drying flowsheet is simulated with Simprosys 3.0 and simulation results are presented and discussed.

Keywords Burner design; Combustion; Combustion drying; Dryer calculations; Dryer design; Drying software; Psychrometrics

INTRODUCTION

Combustion drying has been gaining popularity in industry in the last few decades due to new developments in pulse combustion drying technologies. However, due to a lack of suitable calculation tools, engineers continue to use the psychrometrics of air for the calculation of combustion drying. Such a practice is inappropriate because the humid gas properties of combustion are different from those of air due to the differences in their compositions. Combustion gases resulting from different fossil fuels also have different humid gas properties for the same reason.

In addition, traditional air–water vapor psychrometric charts are in general computed at standard atmospheric pressure. In reality, most dryers do not operate exactly at atmospheric pressure. Some dryers such as vacuum dryers operate well below atmospheric pressure. Some other dryers may operate above atmospheric pressure, although very few operate at significantly elevated pressure. It is inaccurate to use traditional psychrometric charts for drying calculations. Although quite a few air psychrometric calculators are available online, there is no one available for combustion. In addition, such standalone calculators are of limited value for practical drying calculations such as drying process simulations because drying problems are much more than only humidity and psychrometric calculations.

With Simprosys, a Windows-based software package developed by Simprotek Corporation, the inaccuracy and inconvenience of detailed computation can be averted. Simprosys 3.0 provides a comprehensive and integrated but simple and easy tool not only for the calculation of humid gas properties of 14 solvent–gas systems (including combustion gases from any specified fossil fuel) but also for process modeling and simulation of drying systems.

Simprosys version 3.0 includes a burner unit operation along with 19 unit operations available in version 2.2. This newly added burner unit operation can not only be combined with the dryer and other unit operations to simulate combustion drying systems but can also be used for design of new burners and evaluation of existing burners.

As energy costs have been escalating and greenhouse gas has become a major issue for global warming, it is important for industry to reduce energy consumption and the carbon footprint in the energy-intensive operation of thermal drying. Simprosys 3.0 is a convenient and user-friendly software tool to improve energy efficiency in the design of new drying systems and in evaluation and optimization of existing drying systems. It can be also used for troubleshooting of existing dryers and drying plants. Design engineers as well as process engineers can use Simprosys 3.0 to determine the thermal efficiency and specific energy consumption of any convective drying processes.

In the following sections, a brief introduction is provided for the reader to understand the basic principles and application of this software for combustion drying.

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PRINCIPLES OF SIMPROSYS 3.0

Simprosys 3.0 can model and simulate not only the most commonly encountered water–air system but also the following 13 solvent–gas systems:

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

The dryer model of Simprosys is based on extensive studies of the most authoritative handbooks by Mujumdar,[1] Masters,[2] and Genskow et al.[3] The drying gas models, such as relative humidity, wet bulb temperature, dew point temperature, etc., are based on Pakowski and Mujumdar.[4]

The thermal–physical properties of water were calculated according to the 1967 ASME Steam Tables. The properties of dry air and nitrogen are based on Liley et al.[5] The properties of the organic liquids and each component (such as carbon dioxide) of air and combustion are based on Liley et al.,[5] Yaws,[6] and Yaws and Gabbula.[7]

For air–carbon tetrachloride, air–benzene, and air–toluene systems, the psychrometric ratios come from Moyers and Baldwin.[8]

The psychrometric ratio model for ethanol–air, ethanol–nitrogen, acetic acid–air, acetic acid–nitrogen, acetone–nitrogen, methanol–nitrogen, N-propanol–nitrogen, isopropanol–nitrogen, N-butanol–nitrogen, and isobutanol–nitrogen is based on Keey[9] and Pakowski and Mujumdar.[4] Please refer to Gong and Mujumdar[10] for details about the calculations of the psychrometric ratio of the above-mentioned systems.

For details about the material property model and other unit operation models in Simprosys please refer to Gong and Mujumdar.[11]

BURNER UNIT OPERATION MODEL

Combustion is a chemical reaction between a fossil fuel and the oxygen in air, which requires stoichiometric calculations to determine the compositions of the generated flue gas. It also requires the enthalpy of formation of each component involved in the chemical reaction to determine the final combustion gas temperature.

The stoichiometric relationships used to determine the compositions of combustion in Simprosys 3.0 are based on Gary.[12] The enthalpy of formation of chemical compounds is based on Yaws and Gabbula.[7]

The calculation of theoretical flame temperature is based on the assumption that combustion is an adiabatic constant volume process. Because the temperature of the combustion in drying is in general not very high (it is rare to see cases over 450°C), dissociations are not taken into consideration in the calculation of flame temperature in the burner model of Simprosys 3.0.

The specific heat of each component of the air and combustion is temperature dependent and based on Liley et al.,[5] Yaws,[6] and Yaws and Gabbula.[7] The specific heat of combustion for the calculation of flame temperature is calculated as an integral average in the temperature range of the combustion from the starting to end temperatures.

Figure 1 shows the interface of the burner unit operation. It should be noted that the values in the white cells are specified by the user and the values in the gray cells are calculated by Simprosys.

From Fig. 1 one can see that the user can choose a predefined fuel from a list of predefined fuels (the fuel is defined in the Fuel Catalog of Simprosys). Then the user can specify the mass flow rate, pressure, and temperature of the drying fuel; the pressure, temperature, and relative humidity of air; the pressure of the flue gas; and the excess air percentage and heat loss percentage of the burner. Simprosys calculates the flow rates of the required air and the temperature, moisture contents, and flow rates of the flue gas, etc.

It should be noted that the "Total Heat Generation" of the burner does not include the condensation heat of water generated during combustion process because the water is in a vapor state in a drying system and dryers. The states of air from the environment are assumed to be known. Therefore, the user is always required to specify the states of the air inlet stream first when the burner unit operation is used. Then the user can specify some major process variables such as fuel inlet mass flow rate, excess air percentage, and heat loss percentage of the burner. Simprosys monitors each user's specification and automatically solves the unit operation and calculates the other process variables when the solving condition is met.

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

Table 1 lists all possible use cases that Simprosys supports for the burner unit operation. Each row in Table 1 represents a use case. In each of the cases in Table 1, the "Specified" columns are major process variables user can specify and the "Calculated" colums are major process variables calculated by Simprosys with user-specified values.

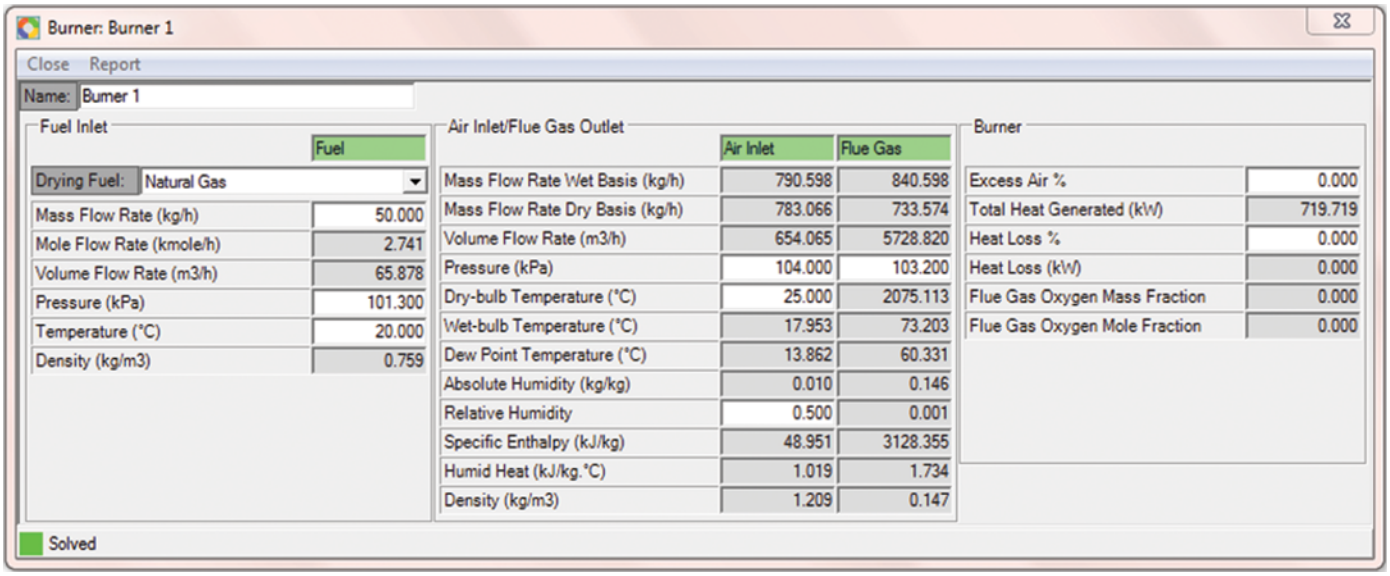


FIG. 1. Burner model.

TABLE 1
Use cases of burner unit operation

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

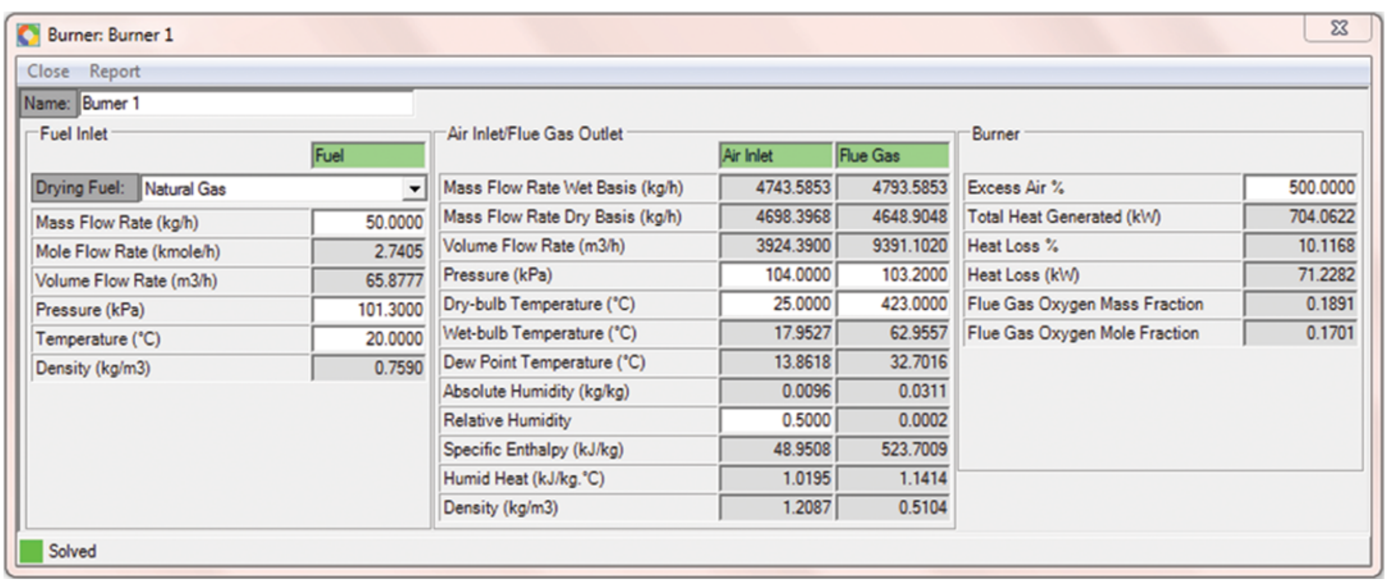


FIG. 2. Heat loss evaluation of burner.

Take case 2 in Table 1, for example. One can evaluate the heat loss of a burner by measuring the actual flue gas temperature and excess air percentage and then input these measured values into the unit operation model to get the heat loss percentage of the burner calculated as displayed in Fig. 2.

PROPERTIES OF COMBUSTION PRODUCTS

In order to investigate the effects of combustion product composition and pressure of a combustion stream on humid gas properties, a typical natural gas (see Table 2) is used to generate combustion with 0% excess air using the burner unit operation of Simprosys 3.0. Table 3 shows the calculated combustion compositions.

With the generated combustion stream and a reference air stream, simulations were carried out and the simulation results are shown in Figs. 3–6.

Figure 3 shows the humid gas properties of a reference air stream at 1 atm (101.3 kPa), 65°C, and 75% relative humidity. Figure 4 shows the humid gas properties of the combustion stream under the same conditions.

It can be seen from Figs. 3 and 4 that under the same conditions the absolute moisture content of the combustion stream was 0.136 kg/kg compared to 0.1414 kg/kg for the air stream. This indicates that at this specific condition (1 atm, 65°C, and 75% relative humidity) the combustion stream carried about 4.0% less moisture compared to the air stream.

Figures 5 and 6 display the humid gas properties of the combustion stream at the same dry bulb temperature and relative humidity as in Fig. 3 but at different pressures. Figure 5 is below atmospheric pressure at 95 kPa. Figure 6 is above atmospheric pressure at 106 kPa.

From Figs. 3 and 5 one can see that the absolute moisture content of the combustion stream was 0.1472 kg/kg at 95 kPa compared to 0.1414 kg/kg of the air stream at 1 atm. This

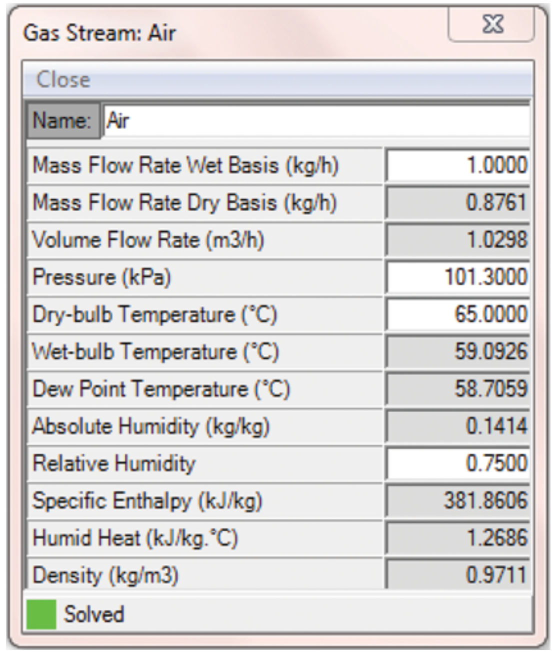


FIG. 3. Humid gas properties of air at 1 atm.

TABLE 2
Natural gas compositions

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

TABLE 3
Combustion compositions

Component	Mass fraction
Carbon dioxide	0.1749
Nitrogen	0.8082
Sulfide dioxide	0.0031
Argon	0.0138

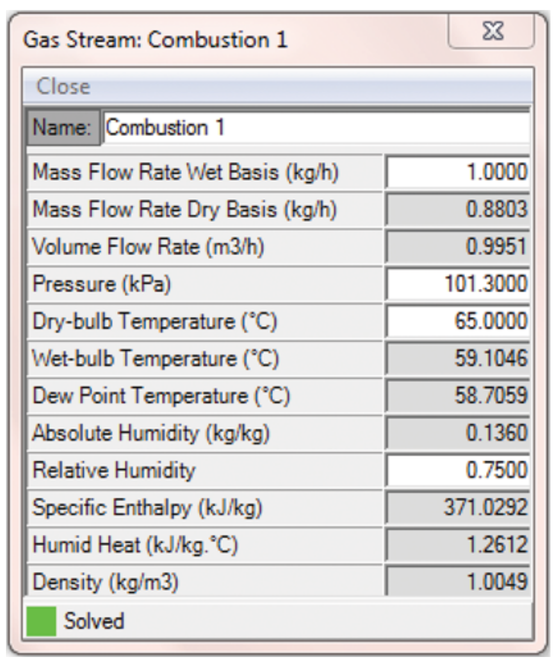
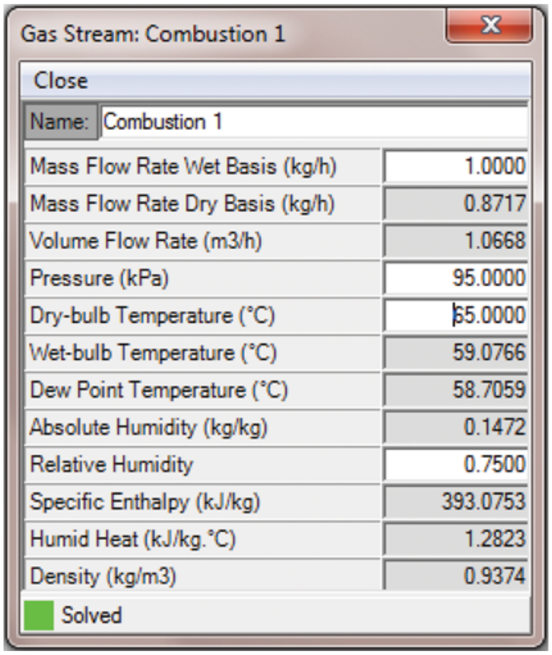


FIG. 4. Humid gas properties of combustion at 1 atm.



Gas Stream: Combustion 1

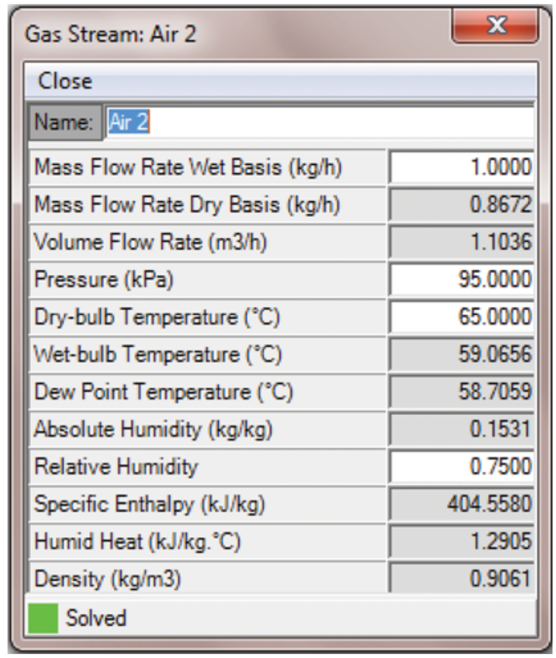
Close

Name: Combustion 1

Mass Flow Rate Wet Basis (kg/h)	1.0000
Mass Flow Rate Dry Basis (kg/h)	0.8717
Volume Flow Rate (m3/h)	1.0668
Pressure (kPa)	95.0000
Dry-bulb Temperature (°C)	65.0000
Wet-bulb Temperature (°C)	59.0766
Dew Point Temperature (°C)	58.7059
Absolute Humidity (kg/kg)	0.1472
Relative Humidity	0.7500
Specific Enthalpy (kJ/kg)	393.0753
Humid Heat (kJ/kg.°C)	1.2823
Density (kg/m3)	0.9374

Solved

FIG. 5. Humid gas properties of combustion at 95 kPa.



Gas Stream: Air 2

Close

Name: Air 2

Mass Flow Rate Wet Basis (kg/h)	1.0000
Mass Flow Rate Dry Basis (kg/h)	0.8672
Volume Flow Rate (m3/h)	1.1036
Pressure (kPa)	95.0000
Dry-bulb Temperature (°C)	65.0000
Wet-bulb Temperature (°C)	59.0656
Dew Point Temperature (°C)	58.7059
Absolute Humidity (kg/kg)	0.1531
Relative Humidity	0.7500
Specific Enthalpy (kJ/kg)	404.5580
Humid Heat (kJ/kg.°C)	1.2905
Density (kg/m3)	0.9061

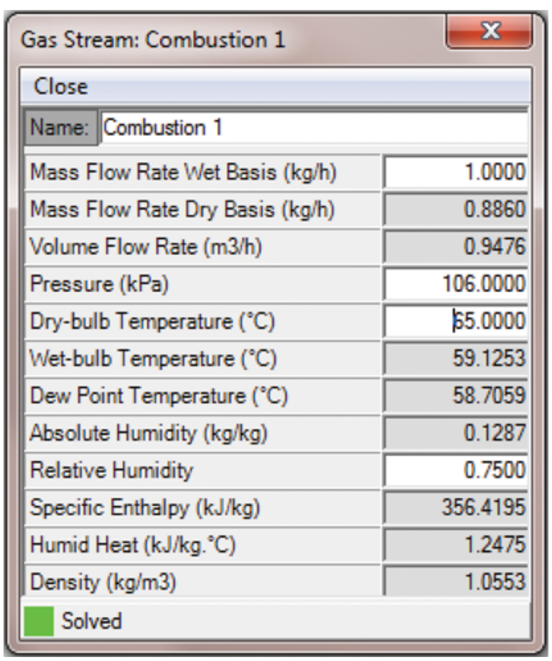
Solved

FIG. 7. Humid gas properties of air at 95 kPa.

indicates that the combustion stream carried about 4.1% more moisture at 95 kPa than the air stream at 1 atm.

From Figs. 3 and 6 one can see that the absolute moisture content of the combustion stream was 0.1287 kg/kg at 106 kPa compared to 0.1414 kg/kg for the air stream. This indicates that the combustion stream carried about 9.0% less moisture at 106 kPa compared to the air stream at 1 atm.

To see similar effects of pressure on the humid gas properties of an air stream, simulations were carried out and the simulation results are shown in Figs. 7 and 8. From Figs. 3 and 7 one can see that the absolute moisture content of the air



Gas Stream: Combustion 1

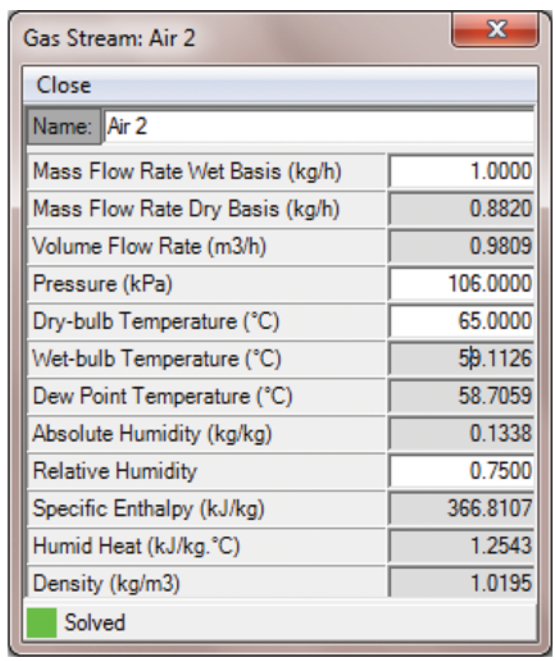
Close

Name: Combustion 1

Mass Flow Rate Wet Basis (kg/h)	1.0000
Mass Flow Rate Dry Basis (kg/h)	0.8860
Volume Flow Rate (m3/h)	0.9476
Pressure (kPa)	106.0000
Dry-bulb Temperature (°C)	65.0000
Wet-bulb Temperature (°C)	59.1253
Dew Point Temperature (°C)	58.7059
Absolute Humidity (kg/kg)	0.1287
Relative Humidity	0.7500
Specific Enthalpy (kJ/kg)	356.4195
Humid Heat (kJ/kg.°C)	1.2475
Density (kg/m3)	1.0553

Solved

FIG. 6. Humid gas properties of combustion gases at 106 kPa.



Gas Stream: Air 2

Close

Name: Air 2

Mass Flow Rate Wet Basis (kg/h)	1.0000
Mass Flow Rate Dry Basis (kg/h)	0.8820
Volume Flow Rate (m3/h)	0.9809
Pressure (kPa)	106.0000
Dry-bulb Temperature (°C)	65.0000
Wet-bulb Temperature (°C)	59.1126
Dew Point Temperature (°C)	58.7059
Absolute Humidity (kg/kg)	0.1338
Relative Humidity	0.7500
Specific Enthalpy (kJ/kg)	366.8107
Humid Heat (kJ/kg.°C)	1.2543
Density (kg/m3)	1.0195

Solved

FIG. 8. Humid gas properties of air at 106 kPa.

stream was 0.1531 kg/kg at 95 kPa compared to 0.1414 kg/kg at 1 atm. This indicates that the same air stream carried about 8.3% more moisture at 95 kPa than at 1 atm.

From Figs. 3 and 8 one can see that the absolute moisture content of the air stream was 0.1338 kg/kg at 106 kPa compared to 0.1414 kg/kg at 1 atm. This indicates that the same air stream carried about 5.4% less moisture at 106 kPa than at 1 atm.

In addition, one can see from above analysis that it is inaccurate to calculate humid gas properties of combustion using standard air psychrometrics, especially for combustion streams that deviate from atmospheric pressure. When the drying gas pressure is below or above atmospheric pressure, the difference between humid gas properties can be large, depending on how far the pressure of the combustion stream is from atmospheric pressure.

SIMULATION OF A COMBUSTION DRYING SYSTEM

Using the burner unit operation and other unit operations in Simprosys 3.0, one can conveniently lay out any drying systems one wants to design or analyze all possible arrangements of unit operations and simulate different operating conditions to optimize one's designs and operations.

One example is presented here to demonstrate how to use Simprosys to model and simulate combustion drying. For more examples, readers can refer to Gong and Mujumdar,[10,11] Gong et al.,[13] Gong,[14] and the tutorials in Simprosys 3.0.

The drying material is wet solid particles:

- Feed moisture content = 0.22 kg/kg wb
- Feed temperature = 20°C
- Product temperature = 50°C
- Product moisture content = 0.002 kg/kg wb
- Specific heat of the absolute dry material = 1.26 kJ/kg · °C
- Mass flow rate (wb) = 2, 000 kg/h

Air has the following conditions:

- Initial pressure = 101.3 kPa
- Initial temperature (dry bulb) = 20°C
- Initial absolute humidity = 0.009 kg/kg

The natural gas compositions are listed in Table 1:

- Pressure = 101.3 kPa
- Temperature = 20°C
- Mass flow rate = 34 kg/h

Air to the burner needs to go through an air filter first. The pressure drop in the air filter is 0.3 kPa. Assume a dust volume concentration of 0.1 g/m^3, collection efficiency of the air filter of 99.8%, and filtration velocity of 2.5 m/s. Air then goes through a fan (the efficiency of the fan is 0.7) to gain 3 kPa static pressure and then enters a burner to generate the needed combustion for the dryer. Excess air percentage of the burner is 500%. Heat loss of the burner is 10%. The flue gas outlet pressure is 103.2 kPa. Pressure drop of the air in the dryer is 1.2 kPa. The exhaust air entrains 0.1% of the total material. It needs to go through a cyclone to collect the entrained dust material. The collection efficiency of the cyclone is 95%. The pressure drop of the cyclone is 0.6 kPa.

The established flowsheet using Simprosys is displayed in Fig. 9. The simulated results are shown in Fig. 10.

From Fig. 10 one can see that the calculated combustion temperature, mass flow rate, and absolute moisture content are 421.7°C, 3,257.7 kg/h, and 0.031 kg/kg, respectively. The needed air mass flow rate for combustion generation is 32,213.7 kg/h. Total heat generation and heat loss of the burner are 478.8 and 47.9 kW, respectively.

With the same flowsheet shown in Fig. 9, diferent process variables can be specified to simulate different cases. For example, one can specify the mass flow rate of the gas inlet stream (Gas 4) of the dryer to compute the mass flow rate of the fuel stream of the burner. One can also specify the dry bulb temperature of the gas inlet stream (Gas 4) of the dryer to get the heat loss percentage of the burner. Such "what-if" computations can provide a better feel of the process and lead to better design and operation as well.

CLOSING REMARKS

Both the combustion product composition and pressure of a combustion stream have appreciable effects on humid gas properties and therefore affect the moisture-carrying capacity

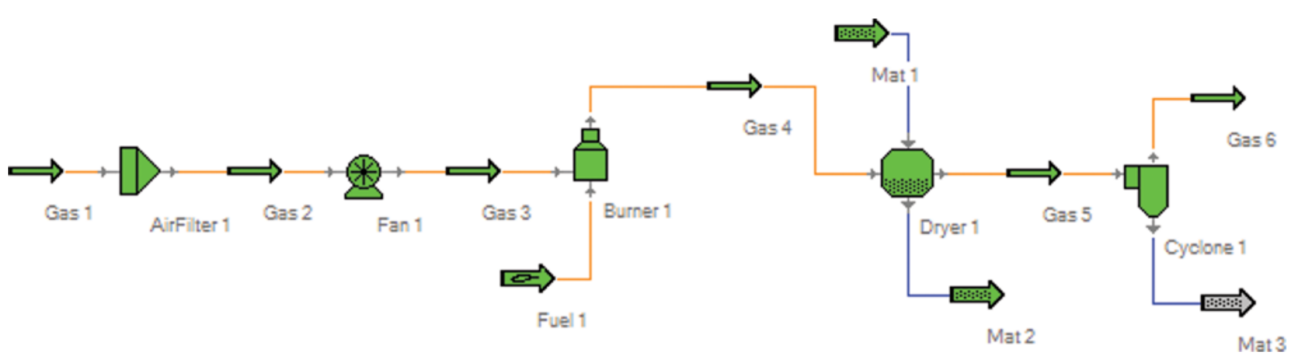
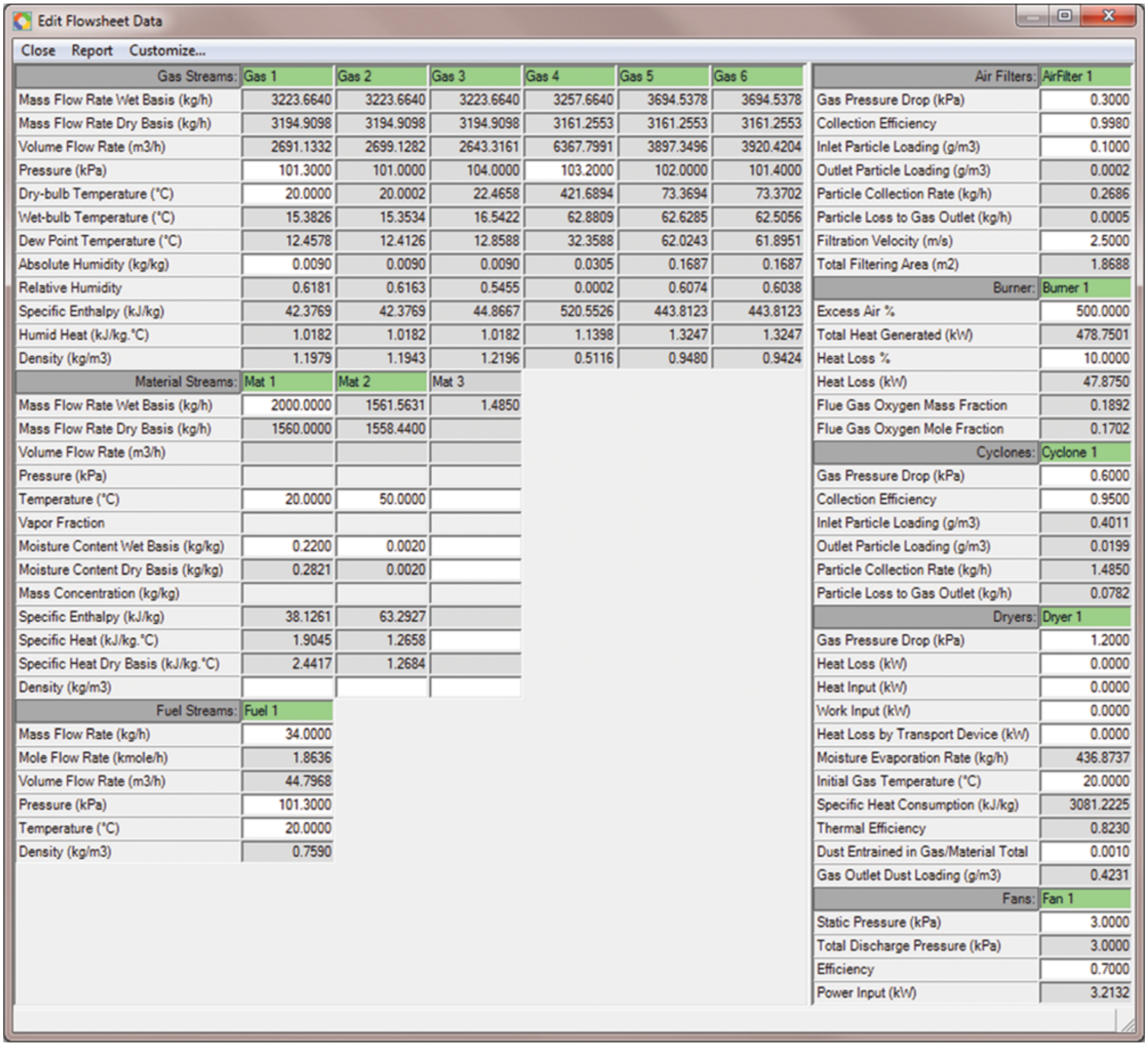


FIG. 9. Flowsheet of a combustion drying system.



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

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

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

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

FIG. 10. Simulation results of combustion drying system.

of the combustion stream. It is not only inappropriate but also inconvenient to use standard psychrometric charts for drying calculations when drying is not operated at atmospheric pressure and when combustion is used. Simprosys is a simple and convenient tool to address these problems.

The burner unit operation in Simprosys 3.0 can be used not only for simulation and optimization of combustion drying systems but also for design and troubleshooting of burners. The smart spreadsheet-like interactive interfaces of Simprosys make it not only user-friendly but also very easy to learn.

Interested readers may download a free trial version of Simprosys 3.0 from http://www.simprotek.com to explore the capabilities of Simprosys for their own applications.

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