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Wade A. Amos
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A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
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EXECUTIVE SUMMARY

Using dry fuel provides significant benefits to combustion boilers, mainly increased boiler efficiency, lower air emissions, and improved boiler operation. The three main choices for drying biomass are rotary dryers, flash dryers, and superheated steam dryers. Rotary dryers are least sensitive to material size and are the most common, but also have the greatest fire hazard. Flash dryers are more compact and easier to control, but require a small particle size. Superheated steam dryers are less common, but provide significant energy savings.

Environmental controls and safety are important considerations in the dryer design. Superheated steam dryers have zero air emissions, but a medium-strength wastewater may need to be processed. The fire risk is much lower with superheated steam dryers because all drying occurs in an inert steam atmosphere.

Which dryer is chosen for a particular application depends very much on the material characteristics of the biomass, the opportunities for integrating the process and dryer, and the environmental controls needed or already available. Heat recovery can improve the efficiency of some drying options, but at an added capital cost.

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ABBREVIATIONS AND ACRONYMS

BOD	Biological oxygen demand
Btu	British thermal unit
°C	Degrees Celsius
CD$	Canadian dollars
CO	Carbon monoxide
ESP	Electrostatic precipitator
°F	Degrees Fahrenheit
FD	Forced draft (fan)
h	Hour
HCHO	Formaldehyde
ID	Induced draft (fan)
IVO	Imatran Voima Oy (dryer manufacturer)
kg	Kilogram
kJ	Kilojoule
kW	Kilowatt
lb	Pound
MMBtu	One million Btu’s
MoDo	MoDo-Chemetics (dryer manufacturer)
MW	Megawatt
MW_{th}	Megawatt–thermal power
NO_x	Nitrous oxide
ppm	Parts per million
RTO	Regenerative thermal oxidizer
SO_2	Sulfur dioxide
SO_3	Sulfur trioxide
SSD	Superheated steam dryer
ton	English ton (2,000 pounds)
tonne	Metric ton (1,000 kilograms)
USD	U.S. dollars
VOC	Volatile organic compound
WESP	Wet electrostatic precipitator

1.0 INTRODUCTION

There are several established methods, plus some promising technology, for drying biomass fuels for use in combustion boilers and gasifiers. Drying biomass fuel provides significant benefits to boiler operation, but they must be balanced against increased capital and operating costs. A general discussion of some benefits of drying biomass materials, descriptions of the most common types of dryers for biomass drying, the associated capital costs, heat requirements, and comments on safety and environmental issues follow.

Most of the discussion is based on information for drying woody biomass, but the information would generally apply to bagasse, grasses, straw, agricultural residues, and other biomass materials. Most of the discussions and descriptions are related to using biomass in combustion boilers, but applying the same technology to gasifiers would be similar.

1.1 Benefits of Drying Fuel for Combustion Boilers

Using dry fuel in a direct combustion boiler results in improved efficiency, increased steam production, reduced ancillary power requirements, reduced fuel use, lower emissions, and improved boiler operation (Frea 1984; FBT, Inc. 1994; Fredrikson 1984; Hulkkonen et al. 1995; Intercontinental Engineering, Ltd. 1980; Linderoth 1992; MacCallum et al. 1981; Technology Applications Laboratory 1984; Wardrop Engineering, Inc. 1990).

One of the main reasons for these benefits is an increased flame temperature. With wet fuel, some heat of combustion is used to evaporate the water in the fuel. With dry fuel, all the heat of combustion goes into heating the air and products of combustion. As a result, dry fuels have a flame temperature of about 2,300°-2,500°F (1,260°-1,370°C), while green wood has a combustion temperature of about 1,800°F (982°C) (FBT, Inc. 1994; Technology Applications Laboratory 1984). In cold climates, the heat of fusion of any ice that may be mixed with the fuel will also have a significant effect on the flame temperature (MacCallum et al. 1981).

This increased flame temperature is beneficial in a number of ways. First, the higher flame temperature means there is a larger temperature gradient in the boiler for radiant heat transfer. More heat transfer takes place for the same boiler tube area, increasing steam production (MacCallum et al. 1981; Intercontinental Engineering, Ltd. 1980). In new boilers designed for dried fuel, the boiler can be smaller because less heat transfer area is needed.

With the higher flame temperature there will be more complete combustion of the fuel, resulting in lower carbon monoxide (CO) levels and less fly ash leaving the boiler. More complete combustion also means more heat is released from the fuel. In a new boiler, the fire box can be smaller and the downstream ash handling system can be smaller (MacCallum et al. 1981; Technology Application Laboratory 1984).

With better combustion, the excess air can be reduced and acceptable opacity and CO levels maintained. For moist fuels, approximately 80% excess air is required to prevent smoke formation, but for dry fuels, only 30% excess air is required (MacCallum et al. 1981). This reduction in excess air means less heat of combustion goes into heating air. Using less excess air also reduces sensible heat losses with the flue gases, increasing boiler efficiency. Less air flow through the boiler increases the residence time in the boiler and lowers the gas velocities, aiding in more complete combustion and reducing the amount of light fuel blown out of the fire box before it completely burns (MacCallum et al. 1981; Frea 1984; Intercontinental Engineering, Ltd. 1980).

The forced draft (FD) fan, which provides the combustion air for the boiler, will consume less power with less excess air. Likewise, the induced draft (ID) fan, which draws the flue gas out of the boiler and through the pollution control equipment, will require less power because of the lower air flow and the reduced water vapor from the fuel. For boilers that are limited by the ID fan, this can result in increased capacity. For new boilers, using drier fuel allows the FD fan, ID fan, and downstream pollution control equipment to be smaller (MacCallum et al. 1981; Frea 1984; Technology Application Laboratory 1984).

Another reason for a higher overall boiler efficiency is the lower flue gas temperature to the stack. In a boiler without fuel drying, the flue gas temperature might be 350°F (177°C) or higher, but with a dryer this temperature will be closer to 220°F (104°C) coming out of a dryer (FBT, Inc. 1994). This heat that would otherwise be lost goes instead into drying the fuel.

Overall thermal efficiency increases can amount to 5%-15%, with steam production increases of 50%-60% (Technology Application Laboratory 1984; Linderoth 1992).

1.2 Drawbacks of Using Dried Fuel

Although economic factors may discourage the use of dried fuel, only three major operational concerns were identified.

As mentioned before, burning dried fuel results in higher combustion temperatures in the boiler, which for the most part provides overall benefits to the boiler. However, as the flame temperature increases, it approaches the fusion temperature of the ash. If the ash starts to flow and form slag, this can be very detrimental to boiler operation. Usually the flowing temperature of the ash is safely above the flame temperature, but when contaminants from construction debris or salts are mixed with the fuel, the flowing temperature can be lower (MacCallum et al. 1981).

A second concern is what to do if a boiler is designed to use dry fuel and there is a problem with the dryer, because the boiler will be undersized for burning wet fuel. One solution is to use a fossil fuel backup to allow the boiler to operate at full capacity until the dryer can be repaired (Linderoth 1992.)

The final concern is the materials of construction. When the hot flue gases from the boiler are cooled below the dew point of the flue gas, sulfur trioxide (SO_3) can condense, resulting in sulfuric acid formation. This can seriously corrode downstream equipment and duct work. Depending on the configuration of the dryer and boiler, and whether the dryer is a new installation or a retrofit, this may require expensive materials of construction or result in higher maintenance costs.

Nitrous oxide (NO_x) emissions may increase or decrease depending on the boiler design. Lower excess air tends to decrease NO_x emissions, but high flame temperatures can increase NO_x formation (Cooper and Alley 1994).

2.0 DRYER PRINCIPLES

There are three requirements for drying (Lipták 1998a):

1) A source of heat,
2) A method of removing the water evaporated,
3) Some form of agitation to expose new material for drying.

How this is done in each dryer is what makes them different.

2.1 Types of Dryers

Dryers can be broadly divided into two categories based on how heat is provided for drying. In direct dryers, the material gets heat from direct contact with a fluid providing the heat--either hot air or hot steam. With indirect drying, the material being dried is separated from the heat source by a heat exchange surface. One important consequence of indirect drying is that it is possible to recover the latent heat of evaporated water because the water vapor is not diluted by air. This can be done by drawing a vacuum on the material as it is drying and condensing the water vapor before a vacuum pump, or if the dryer is operated at a sufficiently high temperature, the water evaporates at an elevated pressure.

Directly heated dryers can be further divided into two more categories: air and superheated steam dryers (SSDs). In air dryers, hot air is contacted with the material to be dried. The air loses its sensible heat and provides the latent heat of evaporation to dry the material. The air also removes the water vapor that is evaporated. The material can be agitated by some mechanical means or by the flowing air.

In SSDs, the heating fluid is steam rather than air, but the concept is the same. The superheated steam is contacted with the biomass material and loses some of its sensible heat to provide the latent heat of evaporation to dry the fuel. The steam, however, remains above its saturation temperature, so it doesn't condense. The water vapor leaving the biomass is heated by the superheated steam so the net result is a larger amount of steam at a lower temperature than when the steam entered the dryer. The excess steam is removed, and the remainder is reheated and recycled back to the dryer.

In the case of the indirectly heated dryer operated under a vacuum, or with an SSD, the latent heat of evaporation of the water vapor is easy to recover because it is not diluted by air. With vacuum drying, this heat is available only at a low temperature, but with superheated steam drying, the dryer can be designed to produce steam at practically any pressure for use in other parts of the plant.

2.2 Stages of Drying

There are several steps to drying. First, the material must be heated from the temperature at which it entered the dryer, up to the wet bulb temperature, to produce a driving force for water to leave the wet material. Next, any surface moisture on the material is evaporated--this occurs fairly quickly. Once all the surface moisture is removed, the material must be heated to drive water from the inside of the biomass to the surface so it can evaporate. This occurs during the "falling rate period" when the rate of drying drops as the material becomes drier. During the falling rate period, the surface temperature of the material remains close to the wet bulb temperature. Once the material is completely dry, it begins to heat up to the surrounding temperature, because water is no longer present to keep its temperature low.

These steps are important when drying a combustible material. On the one hand, high temperature is desired to encourage heat transfer and minimize equipment size, but at the same time there is a constant concern that the fuel may ignite. By understanding the steps in drying, the fast drying provided by high temperatures can be exploited with minimal fire risk.

There are two points in the drying process when there is a significant fire risk. The first occurs after the surface moisture has evaporated, but before an appreciable amount of water has been driven out from inside the biomass. During this very brief period, there is no water vapor near the surface to keep the fuel particle cool, and the surface can quickly heat up while the inside remains cool. If the surface remains hot for a long enough time, the material can ignite even if it is not completely dry. However, once the inside of the particle starts to drive water to the surface, a constant supply of moisture moving to the surface will keep it cool until it is completely dry (Intercontinental Engineering, Ltd. 1980).

The other time when fire is a concern is when material is overdried. If the material loses all its moisture, it will begin to warm and can ignite when it reaches its combustion temperature, or when any gases evolved reach their flash point. Because the drying rate drops as biomass material gets drier, most dryers are not designed to completely dry material. Overdrying would be expected to occur only during upset conditions or when processing a material with better drying properties than what the dryer was designed for.

As noted earlier, when a material still has moisture associated with it, its temperature will be very close to the wet bulb temperature of the air as evaporation occurs, regardless of the air temperature. This means that a very hot air stream can be used to dry biomass in a co-current flow process because the hot air is introduced to the dryer along with the wet biomass. Because the wet material will have a surface temperature close to the wet bulb temperature it will not ignite. By the time the material does dry out, the air will have lost enough sensible heat that it will be below the ignition temperature of the biomass (Intercontinental Engineering, Ltd. 1980).

In SSDs there is no wet-bulb temperature because only steam is present. The water in the fuel must instead be heated to its saturation temperature before it evaporates from the biomass, but once it turns to vapor, it does not need to diffuse through air to get out of the biomass or have saturated air removed from the surface to promote evaporation. As long as the temperature of the material is higher than the saturation temperature, the vapor pressure of the water will cause the moisture to flow out of the material. This also means the material will stay at its saturation temperature until it is completely dry, then the temperature will start to increase, just as in the air-dried case.

Because no oxygen is present in superheated steam drying, the fuel cannot burn, even at elevated temperatures. However, there is one potential for fire: if the material is allowed to dry completely and heats up above the ignition temperature of about 500°F (260°C) due to the high temperature of the superheated steam, it may spontaneously ignite if exposed to air (Ceckler 1994).

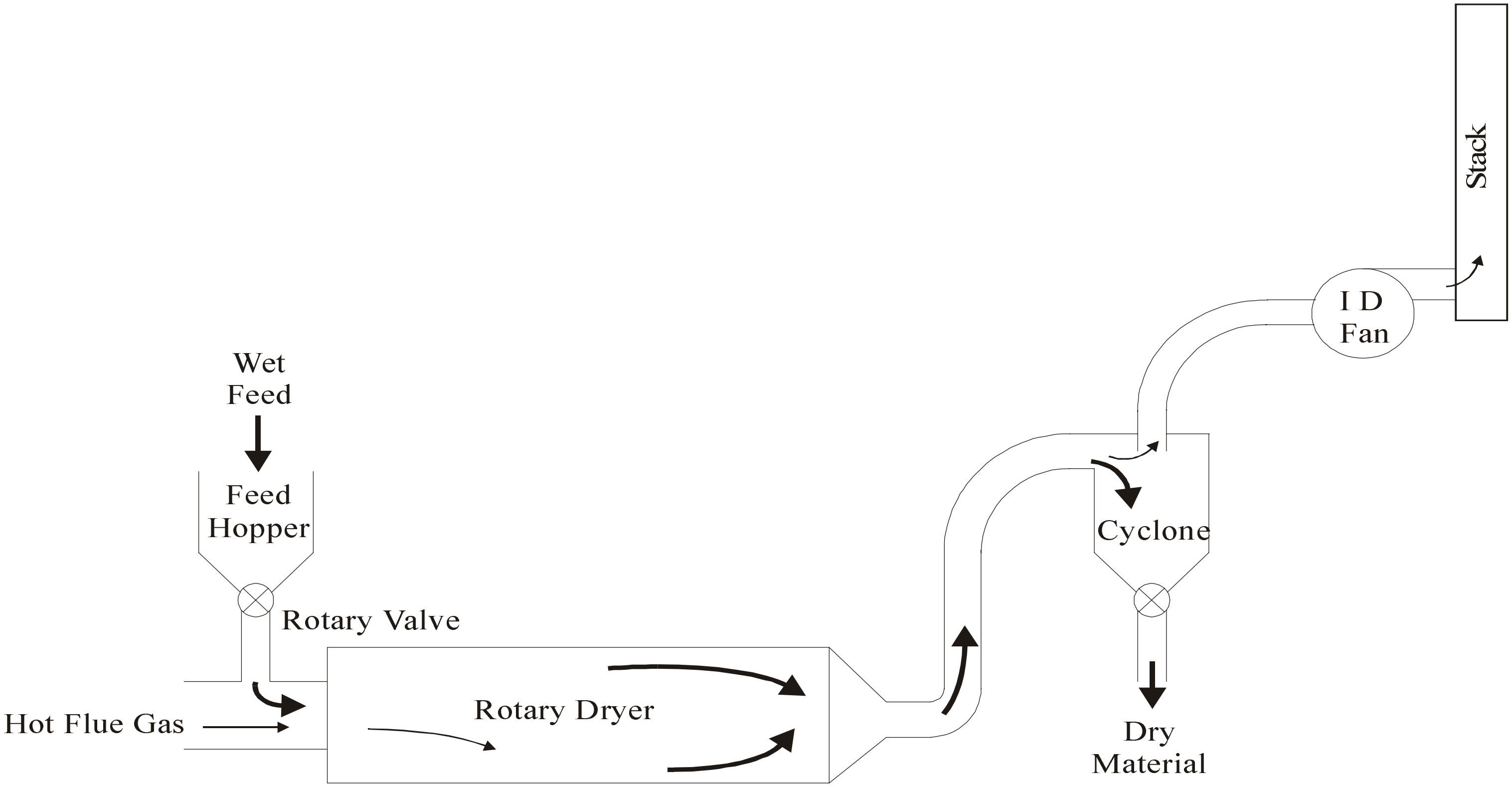
3.0 DRYER DESCRIPTIONS

3.1 Rotary Dryers

Rotary dryers are the most common type for biomass. There are several variations of rotary dryers, but the most widely-used is the directly heated single-pass rotary dryer (see Figure 1). In this type of dryer, hot gases are contacted with biomass material inside a rotating drum. The rotation of the drum, with the aid of flights, lifts the solids in the dryer so they tumble through the hot gas, promoting better heat and mass transfer. If contamination is not a concern, hot flue gas can be fed directly into the dryer. Other options include using a burner or a steam heater to raise the temperature of incoming air.

The biomass and hot air normally flow co-currently through the dryer so the hottest gases come in contact with the wettest material, but for materials where temperature is not a concern, the flue gas and solids flow in opposite directions, so the driest solids are exposed to the hottest gases with the lowest humidity. This latter configuration produces the lowest moisture leaving the dryer, but for biomass this exposes essentially dry material to a high flue gas temperature, which would increase the fire risk.

Figure 1 - Single-Pass Rotary Dryer



The exhaust gases leaving the dryer may pass through a cyclone, multicyclone, baghouse filter, scrubber or electrostatic precipitator (ESP) to remove any fine material entrained in the air. An ID fan may or may not be required depending on the dryer configuration. If one is needed, it is usually placed after the emissions control equipment to reduce erosion of the fan, but may also be placed before the first cyclone to provide the pressure drop through downstream equipment.

The basic single-pass rotary dryer design can be modified to allow three passes of the air and material through the dryer. The material first enters an inner cylinder with the hot air. Smaller or drier material is quickly blown through the cylinder into a larger concentric cylinder for the second pass. Larger material is moved and tumbled with the aid of flights. After the second pass, the air and material pass back up the outermost cylinder of the dryer and out. The triple-pass design works best with material smaller than one inch because larger material can cause plugging. Single-pass dryers can take larger material.

Indirectly heated rotary dryers use a heat source--steam or hot air--passing through the outer wall of the dryer or through an inner central shaft to heat the dryer by conduction. This is more common with materials that would be contaminated by direct contact with flue gases or with materials that react with air. A hybrid direct/indirect rotary dryer also exists where very hot flue gases enter the dryer through a central shaft and initially provide heat indirectly by conduction, then the same gases pass through the dryer coming into direct contact with the wet material. During the second pass, the indirect heating warms the flue gas and solids. In this way, a high flue gas or burner temperature can be used for heating while reducing the fire risk by limiting the temperature of the gas in direct contact with the biomass.

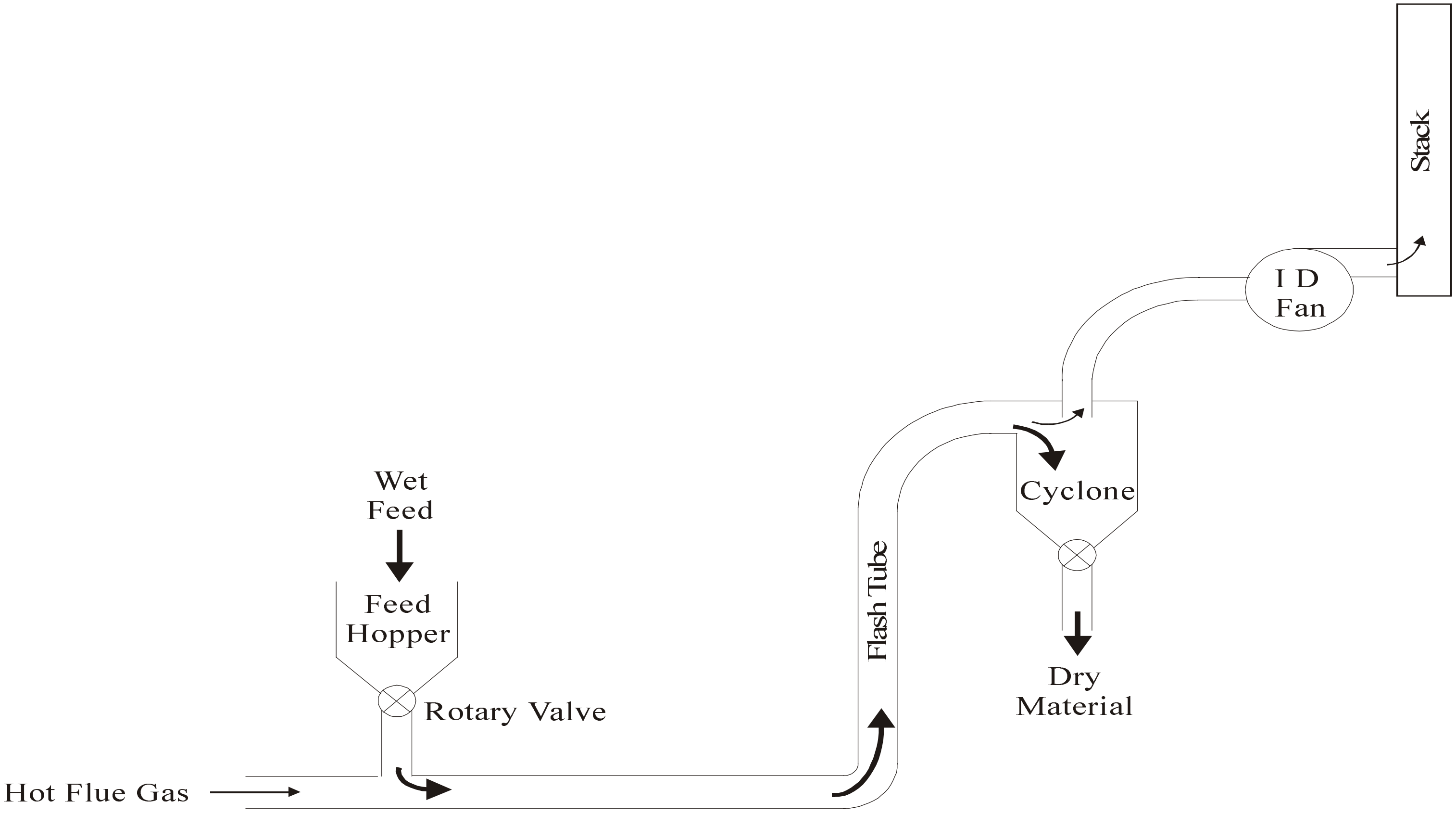
The inlet gas temperature to rotary biomass dryers can vary from 450°-2,000°F (232°-1,093°C). Outlet temperatures from rotary dryers vary from 160° to 230°F (71°-110°C), with most of the dryers having outlet temperatures higher than 220°F (104°C) to prevent condensation of acids and resins. Retention times in the dryer can be less than a minute for small particles and 10-30 minutes for larger material (Haapanen et al. 1983; Intercontinental Engineering, Ltd. 1980; MacCallum et al. 1981; Wardrop Engineering, Inc. 1990).

3.2 Flash Dryers

In a flash or pneumatic dryer, the solids are mixed with a high-velocity hot air stream. The intimate contact of the solids with the air results in very rapid drying. The solids and air are separated using a cyclone, and the gases continue through a scrubber to remove any entrained particulate material. A simple flash dryer (without a scrubber) is shown in Figure 2.

Because of the short drying time in a flash dryer, the equipment is more compact than for a rotary dryer. However, the electricity consumption is higher because of the faster air flows through the unit, and because biomass must pass through a shredder or grinder to reduce its size so it can be suspended in the air stream. For wet or sticky materials, such as sludge, some of the dry material can be recycled back and mixed with the incoming wet material to improve material handling.

Figure 2 - Typical Flash Dryer Configuration



Flash dryers have been used successfully for drying most biomass materials, including wood, sludge, and bagasse (Wang et al. 1990).

Gas temperatures are slightly lower for flash dryers than for rotary dryers, but they still operate at temperatures above the combustion point. The solids retention time in a flash dryer is typically less than 30 seconds, minimizing the fire hazard.

3.3 Disk Dryers

For smaller flows of material, a disk dryer or "porcupine" dryer (Figure 3) is an option. In a disk dryer, solids are heated by condensing steam inside of a central shaft with many hollow disks that increase the area for heat transfer. Fingers or "breaker bars" mix the material and act to keep the heat transfer surfaces free of buildup. The disk dryer can be operated under a vacuum or under pressure, and the condensate from inside the heating shaft can be recovered and returned to the boiler.

3.4 Cascade Dryers

Cascade or spouted dryers (Figure 4) are commonly used for drying grain, but they can be used for other types of biomass. Material is introduced to a flowing stream of hot air as it enters an enclosed chamber. The material is thrown into the air, then falls, or cascades, back to the bottom to be lifted again. Some of the material is drawn out through openings in the side of the chamber that control the residence time and amount of drying. The typical residence time for a cascade dryer is a couple of minutes (MacCallum et al. 1981).

3.5 Superheated Steam Dryers

Most SSDs are similar to flash dryers, except that the fluid suspending the solids and providing heat is steam instead of air. Under normal operation, the wet material is mixed with enough superheated steam to dry the material and still end up with superheated steam. Typically 90% of the steam leaving the dryer is recirculated while 10% of the steam, representing the amount of water evaporated from the biomass, is removed and either condensed or used directly in other parts of the plant (Hulkkonen et al. 1994; Hulkkonen et al. 1991).

Several SSD designs are in development or in limited operation. The first is the basic IVO dryer made by Imatran Voima Oy (IVO) where biomass material is mixed with a recirculating superheated steam stream. The superheated steam and biomass pass through a flash tube and the solids are separated from the steam using a cyclone, just as in a flash dryer. Most of the steam is recycled through a fan to provide the motive force to suspend the solid material and then the steam passes through a heat exchanger to increase its temperature. The excess steam can be condensed to recapture the latent heat, compressed to a higher temperature, or with high pressure operation, the steam can be injected into a gas turbine to increase the power output (Mercer 1994; Hulkkonen et al. 1991). Figure 5 illustrates a basic SSD.

A second IVO SSD design called a bed mixing dryer (Figure 6) can be used with a fluidized bed gasifier or boiler. Some of the hot bed material from the combustion chamber is mixed with the incoming wet biomass in a steam atmosphere. The sensible heat from the bed material evaporates the water from the fuel. The fuel can then be fed, along with the bed material back into the process, while the steam can be recycled, with the excess steam being used for other process heating (Hulkkonen et al. 1995).

Another SSD design is the MoDo dryer from MoDo-Chemetics. Like the basic IVO dryer, the biomass is introduced into a superheated steam stream, but in this case, the walls of the flash tube are heated with high-temperature steam, providing the heat to evaporate the water in the biomass. Like the other superheated steam processes, the MoDo dryer can be operated at low or high pressure depending on the process needs, and the excess steam can be recaptured for other uses (MacCallum et al. 1981). This process is shown in Figure 7.

4.0 HEAT RECOVERY

Drying tends to be energy intensive because, in addition to the heat of vaporization of the water removed, energy goes into heating the biomass solids and into heating the air or steam used for drying. Recovery of some of this heat improves the overall efficiency of the drying process and boiler, but usually requires a significant capital investment.

4.1 Heat Recovery in Air Drying

Energy efficiency in air drying can be improved by:

1) Using heat exchangers,
2) Recirculating exhaust gases,
3) Using exhaust gases for burner air,
4) Using multistage drying,
5) Using a run-around coil,
6) Using a heat pump.

(Mercer 1994; Wilson 1990; Kitan and Hall 1989)

Two types of heat exchangers are possible: recuperative, where the heat is transferred directly from the exhaust gas through the wall of a heat exchanger to the inlet gas; or regenerative, where an intermediate material is heated by the exhaust gases, then exposed to the cold inlet gas.

The air leaving a directly heated air dryer is usually not saturated, so some of the hot exhaust gas can be recirculated to the inlet of the dryer. Because it is still warm, energy is not needed to heat it, increasing the drying efficiency. This exhaust gas, if high enough in oxygen can also be used as preheated burner air to incinerate some of the volatile organic compounds in the exhaust gas (Mercer 1994). The amount of recycle depends on the specific dryer configuration.

Figure 3 - Side View of a Disk Dryer

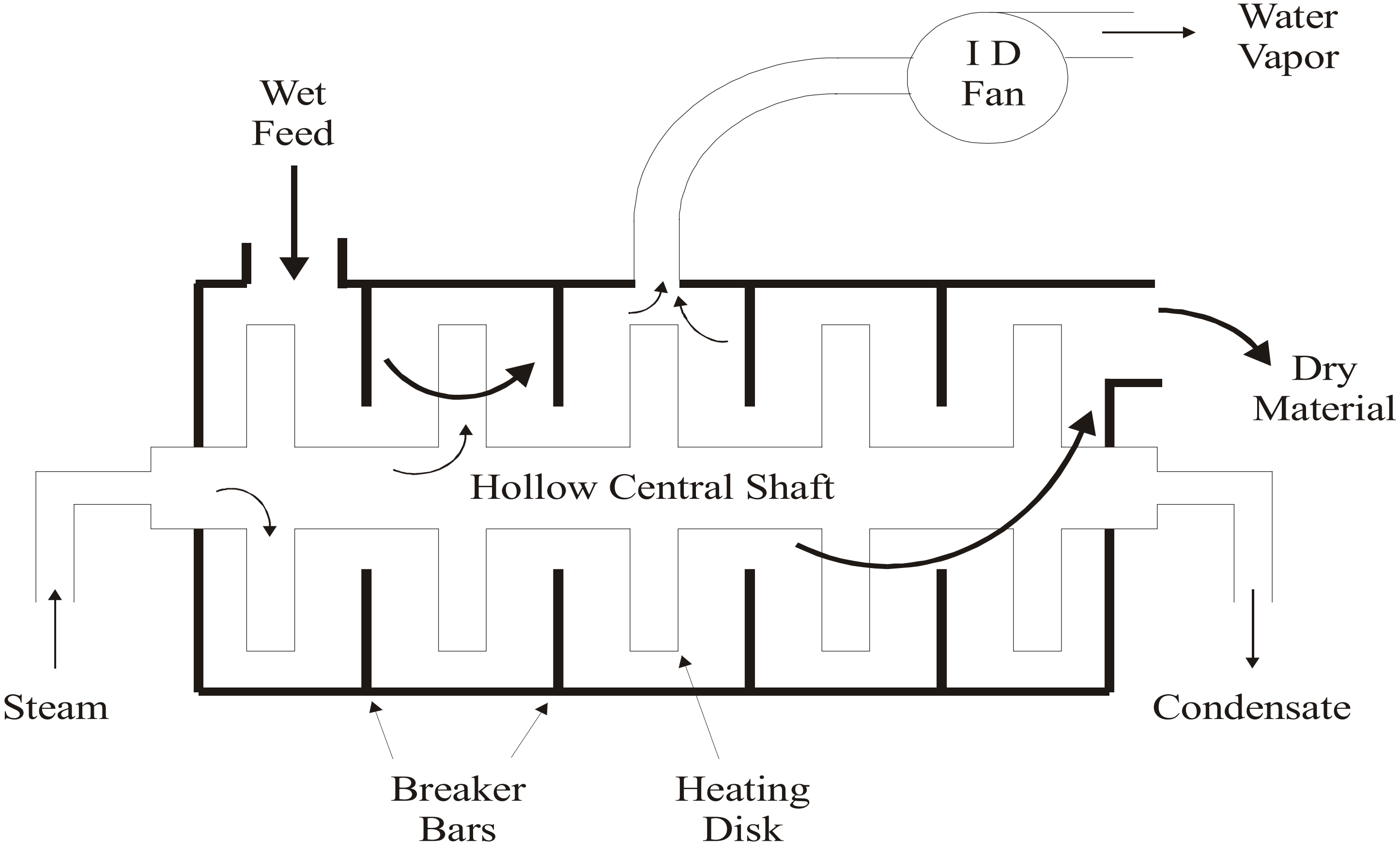


Figure 4 - Side View of a Cascade Dryer

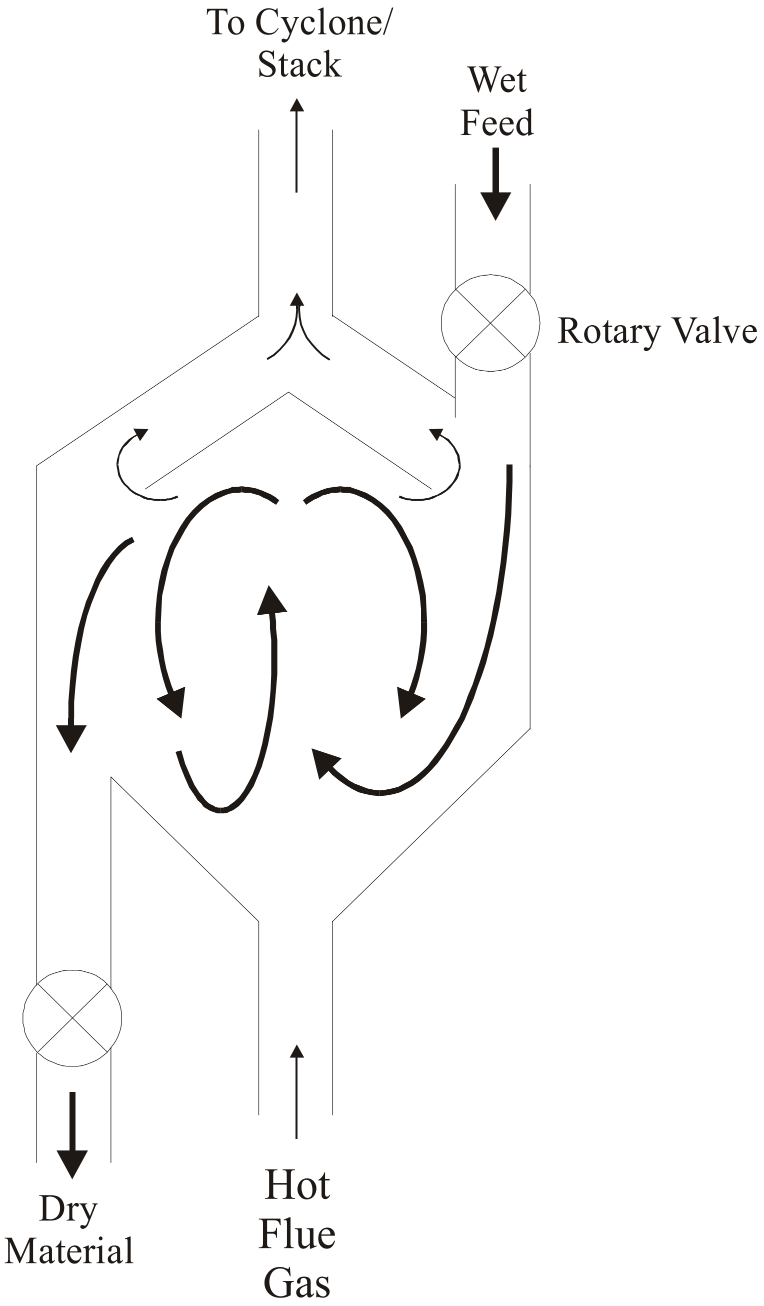


Figure 5 - Basic Superheated Steam Dryer Design

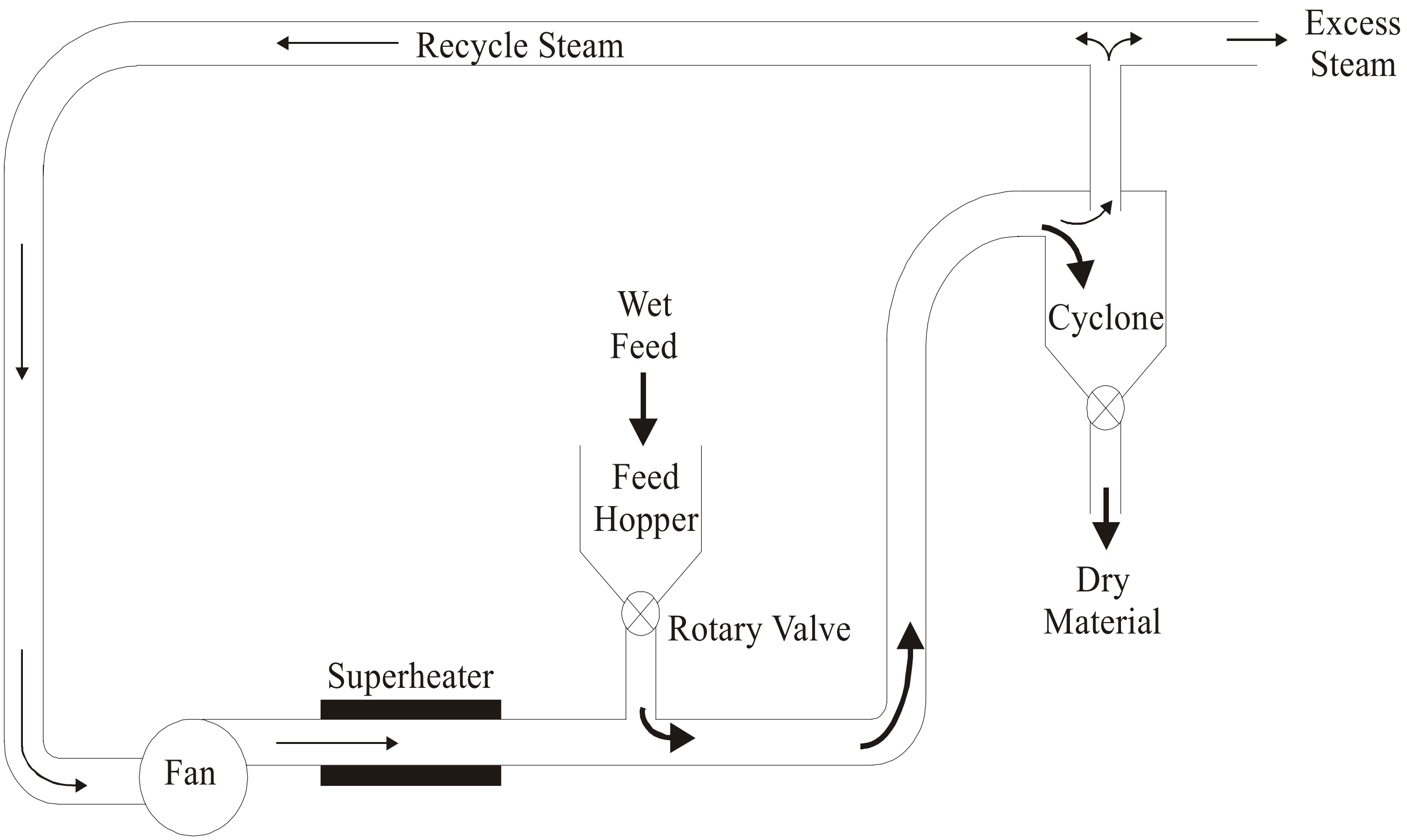


Figure 6 - Bed Mixing Superheated Steam Dryer

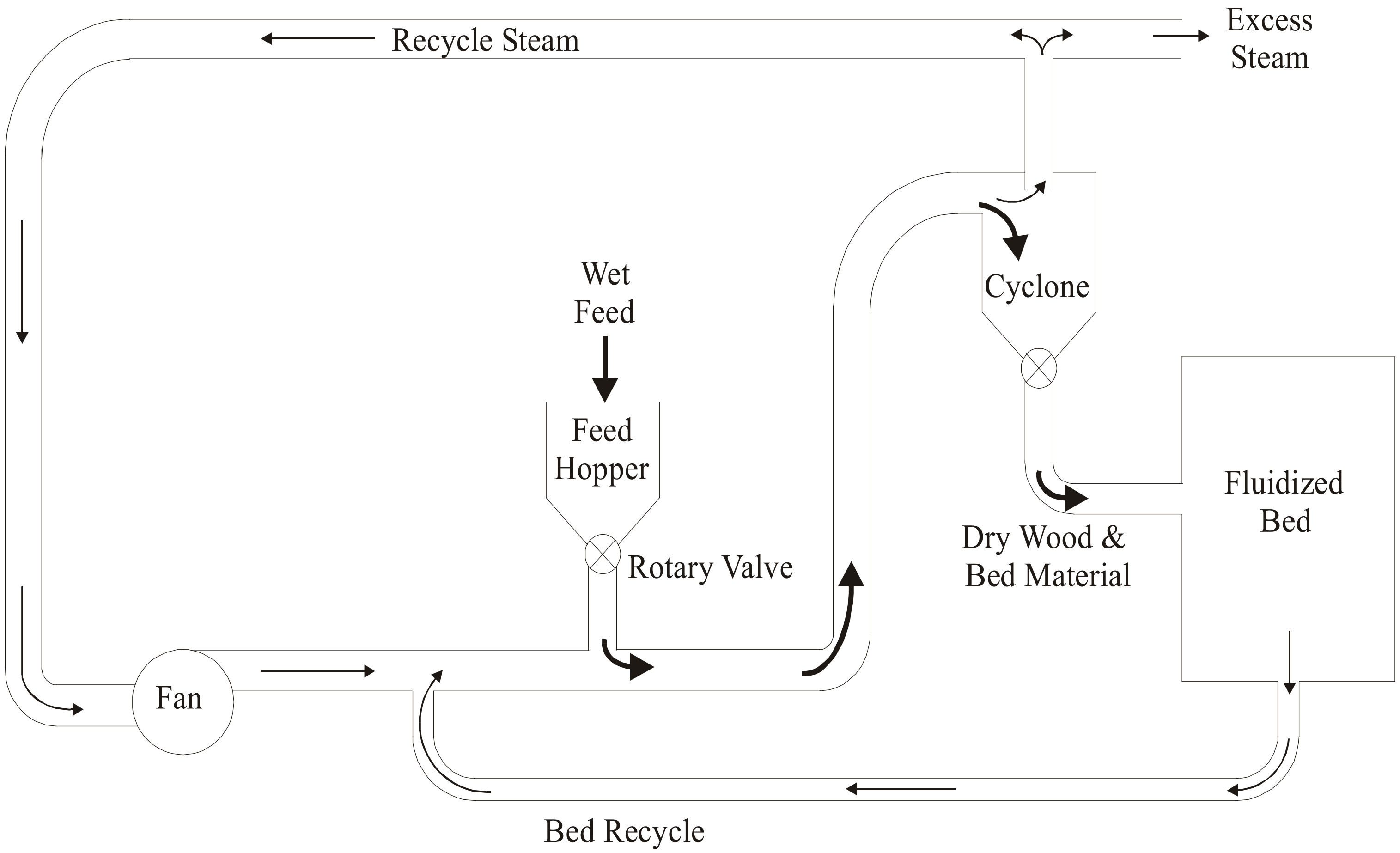
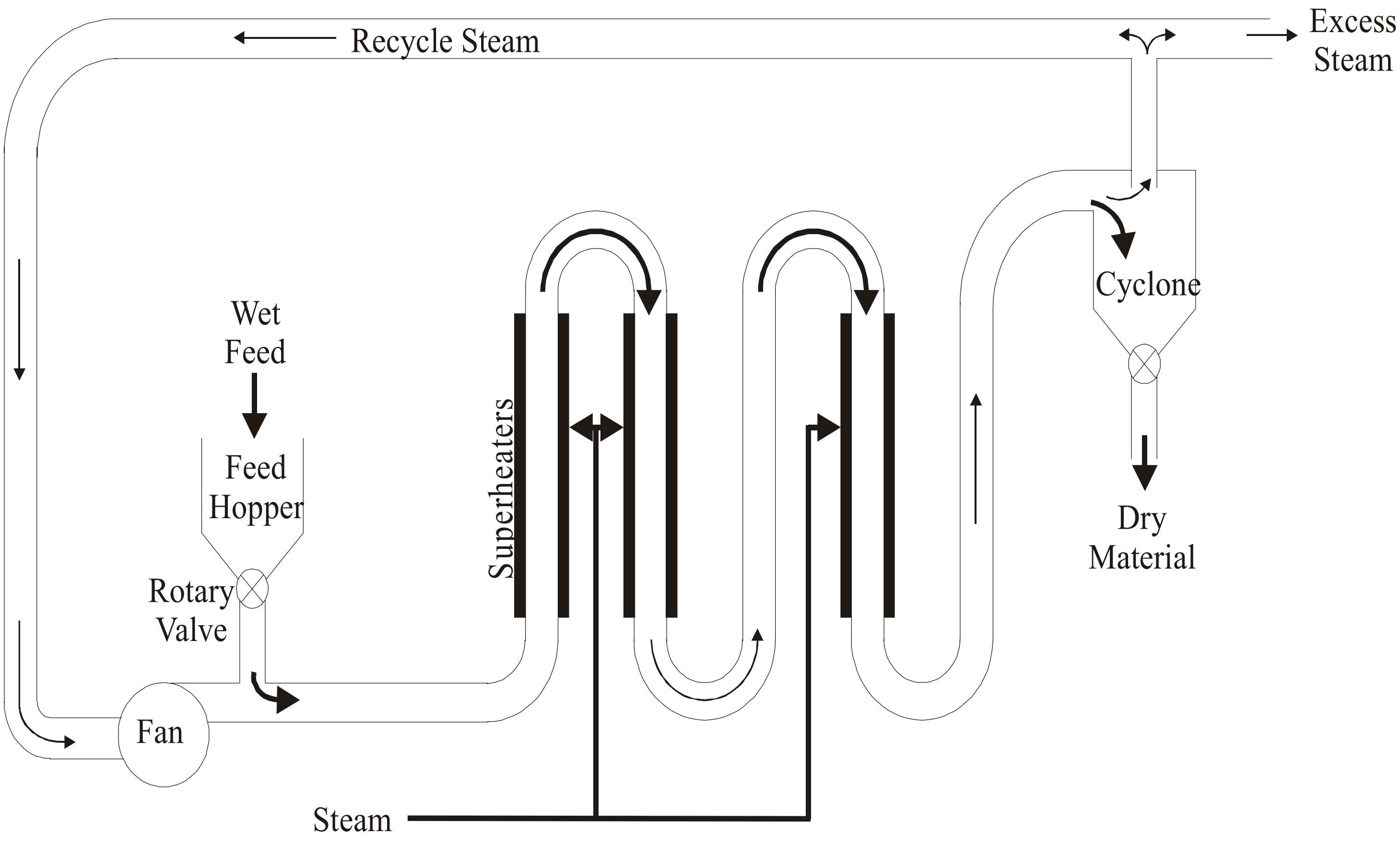


Figure 7 - MoDo Superheated Steam Dryer



Multistage drying can be used when high inlet temperatures are a concern. Instead of diluting the entire hot gas stream with cool air to reduce the temperature, some of the hot gas can be introduced to later stages of the dryer to boost the air temperature. In this way, less dilution air is required.

A run-around coil can be used where the physical layout of the dryer doesn't allow the exhaust gas to be close to the inlet gas. An intermediate heat carrier, such as antifreeze, oil, or a commercial heating fluid is first pumped through a heat exchanger coil in the exhaust gas duct, then through a heat exchanger in the inlet air duct to give up its heat to the colder inlet air. The disadvantage of this method is that two heat exchangers are needed instead of one recuperative heat exchanger, but this is sometimes cheaper than running extra duct work (Mercer 1994).

A heat pump is similar to a run-around coil, but because it uses a refrigerant and compressor, it can recover part of the latent heat of vaporization by condensing or dehumidifying the exhaust gas and can then provide this heat to the inlet air at a higher temperature. Although energy efficient, the capital costs for the compressor can be very high with significant compressor energy requirements. Heat pumps are also generally limited to providing heat at no more than 140°-150°F (60°-66°C) (Wilson 1990).

4.2 Superheated Steam Heat Recovery

In the case of superheated steam drying and vacuum drying, the latent heat of vaporization is easier to recover because the water vapor that leaves the fuel is not diluted by air, so it can be condensed directly to recover the heat.

Depending on the dryer and plant configuration, there are several possibilities for heat recovery. In cases where the power plant also provides hot water for heating, the SSD can be operated at atmospheric pressure and still produce hot water at a reasonable temperature. However, if process steam is required, the dryer must either be operated at a higher pressure, or the steam from the dryer must be compressed to increase the temperature it condenses at. The steam from the dryer can then be used directly, or it can be condensed on the outside of boiler tubes to produce clean steam without any impurities.

Another option for integrating an SSD with a combined-cycle gasifier is to inject high-pressure dryer steam into the fuel to the gas turbine. The steam will provide a boost in output by passing a greater volume of gas through the turbine without requiring compression of the dryer steam.

5.0 DRYER CHOICES

The choice of dryers will depend on the characteristics of the material being dried, the source of heat for the dryer, and integration options available.

An important consideration is the size of the material to be dried. For flash dryers and most SSDs, a small particle size is needed to suspend the material in a moving air or steam stream. Triple-pass rotary dryers will accept larger material, but may experience plugging with very large material. Cascade dryers need a very uniform particle size. For large or variable material, a single-pass rotary dryer might be best. For some materials, reducing the size of the material may be an option, but often this is an energy-intensive operation.

The heat source and temperature for drying are important considerations. Flue gas is an efficient source of heat, but the temperature may be too low to provide enough heat for complete drying. Using a process stream for heating may be energy efficient, but will require the capital investment in a heat exchanger and the interactions between the dryer and process must be considered. SSDs typically require a high-temperature heat source. If saturated steam is available, the disk dryer or MoDo dryer would be an option. The goal should be to determine what excess heat is available in the system, then design the drying system to take advantage of it. If all else fails, a burner can be installed with an auxiliary fuel source to provide the heat for drying.

High-pressure operation can improve material handling in many cases when dealing with gasifiers. In those cases, the superheated IVO dryer or MoDo dryer would be favored. Again, SSDs have advantages when used for combined heat and power plants or combined cycle plants.

6.0 BENEFITS AND DISADVANTAGES OF EACH DRYER

As mentioned in Section 5.0, the choice of dryers depends on many factors. A brief summary of the benefits and disadvantages of each type of dryer follows. The particular type of dryer, its configuration, and operating conditions should be determined case-by-case.

6.1 Benefits and Disadvantages of Rotary Dryers

Rotary dryers are less sensitive to particle size and can accept the hottest flue gases of any type of dryer. They have low maintenance costs and the greatest capacity of any type of dryer (Intercontinental Engineering, Ltd. 1980). However, material moisture is hard to control in rotary dryers because of the long lag time for material in the dryer (Fredrikson 1984). Rotary dryers also present the greatest fire hazard and require the most space (Intercontinental Engineering, Ltd. 1980). Compared to single-pass dryers, triple-pass dryers have higher capital costs, higher maintenance costs, higher blower costs and pose more of a fire hazard (Intercontinental Engineering, Ltd. 1980).

6.2 Benefits and Disadvantages of Flash Dryers

Flash dryers are much more compact than rotary dryers, but have higher installation costs (Fredrikson 1984). They can be used on most types of biomass, but have high blower power costs in addition to the heat requirements for drying. The particles being dried must be small to be suspended in the air stream. With the short retention time in the dryer, the hydrocarbon emissions may be slightly lower than for a rotary dryer (MacCallum et al. 1981). Like the rotary dryer, heat recovery can be difficult because of the air mixed with the water vapor. Flash dryers, because of their shorter retention time and lower operating temperature, have a lower fire risk than rotary dryers.

6.3 Benefits and Disadvantages of Disk Dryers

The main advantage of disk dryers is that saturated steam can be used for heating. Because they are indirectly heated, condensing the vapor from the dryer is possible to recover some of the latent heat of vaporization. Operation is fairly straightforward and maintenance costs are reasonable. The main disadvantage is the limited capacity because of the relatively low operating temperature compared to other dryers.

6.4 Benefits and Disadvantages of Cascade Dryers

Cascade dryers are similar to flash dryers, except they can handle slightly larger particles. However, for a good cascading effect in the dryer, the particle size must be fairly uniform. Like other air-heated dryers, heat recovery is difficult and expensive.

6.5 Benefits and Disadvantages of Superheated Steam Dryers

The main benefit of all SSDs is that the latent heat of vaporization from drying can be recovered and no heat losses occur from heating air for the dryer (Wardrop Engineering, Inc. 1990; Svensk Exergiteknik AB 1984). There are normally no air emissions from a SSD; all the vapor, including organics, is condensed. This does, however, mean the condensate from the process will require wastewater treatment (Svensk Exergiteknik AB 1984). The mixed bed SSD design has the advantage of requiring no heat exchangers for drying (Hulkkonen et al. 1995). A high-pressure IVO dryer integrated with a gas turbine eliminates the wastewater stream by combusting the organics in the turbine.

Superheated steam dryers have higher heat transfer and faster drying, and because of the inert steam atmosphere presents no fire hazard (Svensk Exergiteknik AB 1984; Wardrop Engineering, Inc. 1990). Some disadvantages are the need for small particle size to allow mixing of the steam and particles, high capital costs for a stainless steel pressure vessel, and in the case of the MoDo design, the need to consume process steam for drying (Svensk Exergiteknik AB 1984).

Table 1 summarizes the main considerations in choosing among the dryer types.

Table 1 - Summary of the Advantages and Disadvantages of Each Dryer

Dryer Type	Requires Small Material?	Requires Uniform Size?	Ease of Heat Recovery	Fire Hazard	Steam Use
Rotary Dryer	No	No	Difficult	High	Can use steam
Flash Dryer	Yes	No	Difficult	Medium	None
Disk Dryer	No	No	Easy	Low	Saturated steam
Cascade Dryer	No	Yes	Difficult	Medium	None
Superheated Steam Dryer	Yes	No	Easy	Low	Excess steam produced

7.0 CAPITAL AND OPERATING COSTS

Costs of various dryers were taken from several studies. Often the costs were for a specific material or specific plant, so for clarity, each quote is given in its “raw” form. A summary of the costs, adjusted to 1998 dollars, is also presented.

Rather than putting a dollar value on the operating costs, the estimated heat required for each dryer is given. Power costs for the blowers and fans were not included because many details would need to be known to calculate these loads.

7.1 Rotary Dryer Costs

The following is a list of costs for rotary dryers from various sources and some details of the estimates:

Single-pass rotary dryer: $9.00/lb/h ($20/kg/h) water removed (includes primary cyclone and drives, installation not included, 1981 USD-Fredrikson 1984).
Triple-pass rotary dryer: $8.00/lb/h ($18/kg/h) water removed (includes primary cyclone and drives, installation not included, 1981 USD-Fredrikson 1984).
Rotary dryer cost for 16,700 lb/h (7,600 kg/h) wet wood chips: $323,000 (installed cost, 1984 USD-Frea 1984.)
Stearns & Roger rotary single-pass dryer: $11.99-$21.42/lb/h ($26-$47/kg/h) water removed (complete unit, 1980 USD-Intercontinental Engineering, Ltd. 1980).
MEC rotary dryer: $11.11-$29.33/lb/h ($24-$65/kg/h) water removed (complete unit, 1980 USD-Intercontinental Engineering, Ltd. 1980.)
Aeroglide rotary dryer: $7.68-$13.94/lb/h ($17-$31/kg/h) water removed (complete unit, 1980 USD-Intercontinental Engineering, Ltd. 1980).

Heil rotary dryer: $14.31-$40.00/lb/h ($32-$88/kg/h) water removed (complete unit, 1980 USD-Intercontinental Engineering, Ltd. 1980).
Biomass dryer: $38,000/ton/h ($42/kg/h) of wet fuel (installed cost, 1984 USD-Technology Application Laboratory 1984).
Biomass flue gas dryer for 55 tonne/h (120,000 lb/h) boiler: $5.4 million (complete unit, installed, 1989 CD$-Wardrop Engineering, Inc. 1990).
Rotary dryer for 15-130 MW_{th} (50-450 MMBtu/h) boiler: $1.6-$5.3 million (complete unit, installed, 1981 CD$-MacCallum et al. 1981)

Table 2 lists the approximate costs for each of these cases in $/lb and $/kg water removed in 1998 dollars.

The heat requirements were 1,300-3,500 Btu/lb (3,000-8,100 kJ/kg) of water removed, with most estimates in the 1,500-2,000 Btu/lb (3,500-4,700 kJ/kg) range (Intercontinental Engineering, Ltd. 1980; Mercer 1994).

Table 2 - Rotary Dryer Capital Costs, Current Dollars

Dryer Type	Capital cost per lb/h of water evaporated	Capital cost per kg/h of water evaporated	Source
Single-Pass	$12/lb/h	$26/kg/h	Fredrikson 1984
Triple-Pass	$10/lb/h	$22/kg/h	Fredrikson 1984
Stearns and Roger, Single-Pass	$18-$32/lb/h	$40-$71/kg/h	Intercontinental Engineering, Ltd. 1980
Aeroglide	$11-$21/lb/h	$24-$46/ kg/h	Intercontinental Engineering, Ltd. 1980
Heil	$17-$48/lb/h	$37-$106/kg/h	Intercontinental Engineering, Ltd. 1980
*Rotary	* $102/lb/h	* $224/kg/h	Frea 1984
*Rotary	* $80/lb/h	* $176/kg/h	Technology Application Laboratory 1984
*Flue Gas Dryer	* $346/lb/h	* $761/kg/h	Wardrop Engineering, Inc. 1990
*Rotary Dryer	* $136-362/lb/h	* $300-796/kg/h	MacCallum et al. 1981

*Installed cost. Note: Installed costs tend to be very site-specific (Technology Applications Laboratory 1984).

7.2 Flash Dryer Costs

Below are some capital cost estimates for flash dryers:

Flash dryer: $7.00/lb/h ($15/kg/h) water removed (complete unit, installation not included, 1980 USD-Fredrikson 1984).
Flash dryer for 400,000 lb/h (180 tonne/h) boiler burning bark: $7.5 million (15% outlet moisture, 1983 USD-Haapanen et al. 1983).
Williams Hot Hog dryer: $16.22-$49.33/lb/h ($36-$109 kg/h) water removed (complete unit, 1980 USD-Intercontinental Engineering, Ltd. 1980).
Flash dryer for 15-130 MW_{th} (40-450 MMBtu/h) boiler: $3.5-$10.6 million (complete unit, 1981 CD$-MacCallum et al. 1981).

Table 3 lists these costs in current dollars. The estimated energy requirement for flash drying was around 1,600 Btu/lb (3,700 kJ/kg) water removed (Intercontinental Engineering, Ltd. 1980).

Table3 - Flash Dryer Capital Costs

Dryer Type	Capital cost per lb/h of water evaporated	Capital cost per kg/h of water evaporated	Source
Flash Dryer	$8-$16/lb/h	$18-$35/kg/h	Fredrikson 1984
Williams Hot Hog	$24-$73/lb/h	$53-$160/kg/h	Intercontinental Engineering, Ltd. 1980
*Bark Dryer	* $170/lb/h	* $335/kg/h	Haapanen et al. 1983
*Flash Dryer	* $250-$726/lb/h	* $550-$1,600/kg/h	MacCallum et al. 1981

*Installed cost.

7.3 Disk Dryer Costs

The only cost found for a disk dryer was for superheated steam applications. In that case, the total cost for the unit and associated steam equipment was CD$ 5.4 million for a 55 tonne/hour (120,000 lb/h) steam boiler (Wardrop Engineering, Inc. 1990). This results in an installed cost of $181/lb/h ($400/kg/h) of water removed in 1998 U.S. dollars (USD).

7.4 Cascade Dryer Costs

Cascade dryer costs ranged from CD$ 3.5-$10.6 million for 15-130 MW_{th} (40-450 MMBtu/h) boiler sizes (MacCallum et al. 1981). This amounts to an installed cost of $166-$316/lb/h ($365-$695/kg/h) of water removed in 1998 USD. The heating requirements were the same as those of rotary dryers: 1,500-3,500 Btu/lb (3,500-8,100 kJ/kg) (Mercer 1994).

7.5 Superheated Steam Dryer Costs

Costs of SSDs were given in one study for three dryer configurations. In all cases, the dryers were sized for a 55 tonne/h (120,000 lb/h) boiler drying material from 60% to 40% moisture. For a MoDo type SSD, the capital cost was CD$ 4.5 million. For an SSD with a heat exchanger, the cost was CD$ 7.0 million, and for a disk/porcupine dryer, the cost was estimated at CD$ 5.4 million. All costs are in 1990 Canadian dollars (Wardrop Engineering, Inc. 1990). This equates to $150, $235, and $181/lb/h in 1998 USD ($330, $157, and $362/kg/h).

With efficient heat recovery, SSDs have net heating requirements as low as 20% of that of conventional air drying (Mercer 1994; Wardrop Engineering, Inc. 1990).

7.6 Other Capital Costs

Retrofits of heat recovery equipment for dryer exhaust gases were estimated at $150-$750/kW ($0.04-$0.22/Btu/h) of heat duty, depending on the configuration (Mercer 1994). Another consideration is the capital cost of pollution control equipment to reduce hydrocarbon emissions from air dryers. These costs will be presented in Section 9.0 where the various control options are described.

8.0 DRYER SAFETY

The combustion temperature of wood and organic vapors released during drying is 400°-500°F (204°-260°C), with an autoignition temperature of 500°-550°F (260°-288°C) (MacCallum et al, 1981). However, most dryers can operate at much higher temperatures because the evaporating water vapor keeps the biomass surface temperature lower than the air temperature. This increases the drying rate, but also increases the fire risk in the dryer, especially during upsets. For this reason, all dryers are designed to minimize fire risk and are equipped with fire suppression systems.

One precaution used in most air or flue gas dryers is to maintain a low oxygen concentration in the dryer. This can be done by limiting the amount of excess air or by recirculating exhaust gases to the dryer inlet. Recirculation also increases the thermal efficiency of the dryer. Flue gas dryers typically operate at higher temperatures than indirectly heated air dryers, partly because of the lower oxygen content of the gas (Intercontinental Engineering, Ltd. 1980).

The longer a material is exposed to high temperature air and the lower the moisture content, the greater the fire risk. Rotary dryers have the highest fire risk because they have the longest retention times. Equipment to control fires includes fire detection equipment, fuel and air shut-offs, deluge showers, steam or water sprays, and fire dumps to prevent smoldering material from reaching fuel stockpiles (Intercontinental Engineering, Ltd. 1980).

One other cause of fires in biomass dryers is the condensation of resins that are released from the wood during drying. If the dryer exhaust gases cool, or come in contact with cold surfaces, the resin vapors may condense and then attract dust. This dust and resin mixture is very flammable and may build up and ignite at some later time (Mercer 1994; Lamb 1994).

With SSDs the fire risk is minimal. The biggest risk is when the dry material leaving the dryer is still hot and comes in contact with air. Because of the low moisture and high temperature leaving the dryer, it can ignite (Haapanen 1983; Wardrop Engineering, Inc. 1990; Ceckler 1994).

9.0 ENVIRONMENTAL CONTROLS

The exhaust gas from a biomass dryer may require several types of treatment. If flue gas is used, it may contain sulfur dioxide (SO_2), NO_x, CO, particulate matter, and unburned hydrocarbons in addition to the dust and organic substances from the wood. Even with a SSD that has no air emissions, if the excess steam is condensed, the resulting wastewater will need to be treated to reduce the biological oxygen demand (BOD).

9.1 Air Emissions

The most common problem with biomass dryers is what is called "blue haze." It is caused by the condensing of resins and organic acids after leaving the dryer stack. The condensed acid and resins form aerosols 0.1-0.5 microns in diameter that reflect blue light due to their size (Lamb 1994). These condensible organics can result in opacities of 40%-60%, which is much higher than the regulated 20% opacity limit (Wastney 1994). These condensible organics may also be counted as particulate matter in some situations (Fredrikson 1984).

Blue haze is most common with dryers operated at temperatures higher than 500°-700°F (260°-371°C), but some volatilization of monoterpenes will also occur at lower temperatures (Fredrikson 1984; Intercontinental Engineering, Ltd. 1980; Wastney 1994). Hardwoods have relatively low resin contents of less than 1%, but softwood may have over 10% resins that can be released (Lamb 1994). Of these organic compounds released, 30%-90% are monoterpenes (Wastney 1994).

Table 4 contains emissions data from after the secondary cyclones of a softwood dryer.

Table 4 - Softwood Dryer Emissions Data (Lamb 1994).

Pollutant	Emissions Level
Particulate Matter (PM)	350 ppm
Condensed Particulate Matter	1,700 ppm
Carbon Monoxide (CO)	1,200 ppm
Nitrous Oxides (NO_x)	30 ppm
Formaldehyde (HCHO)	28 ppm

9.2 Pollution Control Equipment

The first piece of equipment after a rotary dryer or flash dryer systems is a cyclone to separate the biomass from the air stream. Usually the first, or primary cyclone, is meant to recover the fuel and not to remove small particulate matter. A smaller, more efficiency secondary cyclone or set of multicyclones can follow the primary cyclone. Cyclones, however, are not very effective for very small particles, so a baghouse, ESP or wet scrubber may be needed (Technology Application Laboratory 1984; Wardrop Engineering, Inc. 1990; Lamb 1994; Fredrikson 1984; Haapanen 1983; Intercontinental Engineering, Ltd. 1980).

Unluckily, although this equipment can effectively remove particulate matter, it is ineffective at removing volatile organic compounds (VOC's) or controlling the opacity problems associated with blue haze. Part of the reason for this is because baghouse filters and dry ESPs must operate above the dew point of the exhaust gases, or the resins will deposit on the equipment. This isn’t a concern with wet scrubbers, but wet scrubbers do not effectively remove the aerosols that form blue haze–they can reduce the opacity problem, but they cannot eliminate it (Wastney 1994; Lamb 1994).

The technology currently accepted as the Best Available Control Technology for dryers is a wet ESP (WESP). The WESP uses water on the collector plates to continually wash the surfaces and prevent the buildup of resins. All particulate matter (condensibles, fly ash, and dust) can be removed with the WESP. The WESP, however, requires a wastewater treatment system to reduce the BOD of the organics captured and to concentrate the solids in the wastewater stream (Lamb 1994).

For further control of non-condensible organics, a regenerative thermal oxidizer (RTO), chemical scrubber, or a biofilter is required. An RTO can remove as much as 98% of the VOCs and 100% of the CO, with up to 95% heat recovery, but the technology is very sensitive to solids in the gas being treated. For this reason, a WESP or some other form of wet particulate scrubber is needed before the RTO. RTOs have been required at several dryer installations (Lamb 1994).

Packed column chemical scrubbers can achieve 90% VOC removal efficiencies with 30% CO removal. Biofilters are another alternative for 90% VOC removal and 50% CO removal. Biofilters additionally provide some odor control. Again, packed columns and biofilters require pretreatment of the gas stream to remove particulate matter (Lamb 1994).

The capital cost of a WESP, RTO, and the associated wastewater treatment for a dryer processing 25,000 lb/h (11,000 kg/h) of dry wood was estimated at $2.65 million in 1994 USD, with an annual fuel cost of $40,000. A packed bed scrubber for the same dryer was estimated at a capital cost of $1.0 million. The biofilter alternative was $1.75 million with an operating cost of $150,000/ yr (Lamb 1994). On the basis of the amount of water removed in 1998 USDs going from 50% to 30% moisture content, an RTO/WESP system has a capital cost of $193/lb/h ($425/kg/h), the packed bed scrubber costs $73/lb/h ($161/kg/h) and the biofilter costs $128/lb/h ($282/kg/h) of water removed.

10.0 CONCLUSIONS

Using dry fuel provides significant benefits to combustion boilers, mainly increased boiler efficiency, lower air emissions, and improved boiler operation. The three main choices for drying biomass are rotary dryers, flash dryers, and SSDs. Rotary dryers are least sensitive to material size and are the most common, but also present the greatest fire hazard. Flash dryers are more compact and easier to control, but require a small particle size. SSDs are less common than the others, but provide significant energy savings.

Environmental controls and safety are important considerations in the dryer design. SSDs produce no air emissions, but a medium-strength wastewater may need to be processed. The fire risk is much lower with SSDs because all drying occurs in an inert steam atmosphere.

Which dryer is chosen for a particular application depends very much on the material characteristics of the biomass, the opportunities for integrating the process and dryer, and the environmental controls needed or already available. Heat recovery can improve the efficiency of some of the drying options, but at an added capital cost.

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