Heat transfer dynamics

Thomas M. Smith

ABSTRACT: As heat transfer technology increases in complexity, it becomes more difficult for those without thermal dynamics engineering training to choose between competitive heat transfer systems offered to meet their drying requirements. A step back to the basics of heat transfer can help professional managers and papermakers make informed decisions on alternative equipment and methods. The primary forms of heat and mass transfer are reviewed with emphasis on the basics, so a practical understanding of each is gained. Finally, the principles and benefits of generating infrared energy by combusting a gaseous hydrocarbon fuel are explained.

KEYWORDS: Drying, heat transfer, infrared radiation, mass transfer.

Dewatering and drying are capital intensive and high-operating-cost processes in any equipment producing wet-formed, woven, and nonwoven webs. Management personnel need to evaluate the total design and operating performance of a system if they are to make the best purchasing decision. A decision based only on low capital investment may result in a long-term high unit cost, as energy costs will certainly continue to increase. Hence, decision-makers must know basic heat and mass transfer engineering principles, so alternative proposals can be critically evaluated and ranked.

Tradition is not necessarily the best teacher. It is well known that cellulosic fibers and man-made polymeric filaments are relatively poor thermal conductors, yet the majority of drying systems in the paper industry continue to operate on the principle of conduction. Heat transfer can be augmented by hot-gas impingement, through-drying, and radiant heating. These methods should be reviewed and evaluated for existing and proposed systems.

A knowledge of a substrate's structure and formation is just as important as an understanding of the heating system. For example, the effective heat conduction from a hot metal surface to a fabric or paper substrate depends not only on the heated surface area but also on the effective physical contact area, and therefore sheet formation and smoothness. For tissue and products with a more open structure, additional energy transfer by hot-gas impingement is mandatory for fast machines. Even though the sheet grammage (basis weight) is low, the machine speed is high, and the heat contact residence time is very short. Air-laid and nonwoven webs are candidates for through-drying, but these systems require large blower motors to drive large volumes of air at moderate to high pressures to and through the web. Microwave and radio frequency drying systems are still too capital intensive for most continuous large-scale installations. However, infrared radiant drying systems are rapidly becoming more acceptable, because they dry more than ten times faster than conductive units; Infrared systems transmit heat into the web rather than relying solely on heat conduction from the outer surface. As drying equipment and subsequent building size to house the dryer affect the total cost, a fresh look at the overall principles of heat transfer and engineering strategy is well worthwhile.

Discussion

Heat transfer modes

Heat transfer is defined as energy transferred by temperature difference or gradient. In a vectorial sense, heat flows from higher-temperature regions to those of lower temperature. There are four basic heat transfer mechanisms: conduction, convection, radiation, and internal generation. The method(s) selected depend on the application and operating conditions.

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Conduction is the mechanism in which energy is transferred by atomic or molecular excitation from a solid's higher-energy zone to its lower-temperature zone. Most metals are good conductors because their atoms are more readily set in a vibration mode by thermal excitation. Most inorganic compounds and organic molecules, such as polymers, plastic, and cellulose, are more difficult to set in a vibration mode and are poor conductors.

A second heat transfer mechanism is convection. For engineering purposes, this is a subclass of conduction in a fluid where bulk motion or flow of the thermally excited molecules is the mechanism for transferring heated fluid to a colder region. The hot fluid must still transfer energy to a solid surface by molecular collision and then transfer it into the solid by conduction. Convection may be augmented by forced flow to increase the rate of molecular collisions. The power to do this must be added to the system's total energy load. Note, however, that liquid molecules naturally collide with a solid surface at over 1000 times the rate of a gas at the same temperature and pressure. This clearly shows that hot-air/gas drying systems are inherently inefficient unless the hot gas is either recycled or the molecular collision frequency with the substrate is increased significantly by forced convection and directed jet impingement.

A third mechanism is thermal radiation. Externally generated radiation from a hot body travels at the speed of light to the object and is absorbed by both the liquid and the solid substrate. The wavelength (or frequency) of the radiant energy must match the product's absorptivity for the best energy coupling and maximum heating and drying rate. Some substrates act as a window to radiant energy at specific electromagnetic wavelengths, and in many cases, hotter radiant heaters do not produce better drying rates.

Heat can also be transferred by internal thermal generation caused by radio frequency and microwave energy produced outside the substrate. These electromagnetic wavelengths only heat dielectric products; hence, the method is often called dielectric drying. The thermal excitation is selective to small dipole molecules such as water, and therefore temperature and moisture profiles are uniform. This capital-intensive method is most efficient when the moisture content is low, and it is frequently added to conventional drying processes.

Modes of mass transfer in drying processes

Simultaneous heat and mass transfer occur in all drying systems. Some dryers or sections of a dryer are mass-transfer limited and are therefore constrained by the transfer rate of water to the web surface and into the dryer environment. Mass transfer requires a concentration gradient to effect a net transfer of liquid, just as heat transfer requires a temperature differential. In a liquid, molecular diffusion and turbulent mixing are the two basic mechanisms. In a porous web structure, additional mechanisms of capillary action, surface tension forces, wicking (movement along a fiber), and vaporization are very significant. At the interface, the rate of water removal into the gas boundary layer depends on the shear mechanism (laminar or turbulent motion) as well as the concentration gradient (actually the difference between the vapor pressure at the surface and the partial vapor pressure in the boundary layer). These water transfer mechanisms exist to some extent in all drying processes (conduction, convection, or radiation).

Radiant energy methods are the most effective in drying nonwoven webs, because the internal heat transfer resistance in the web structure is low. Mass transfer rates are low because conductive and convective processes must get thermal energy from the surface into the web while the water is being transferred out. Radiation methods thermally excite the water molecules throughout the web structure, allowing more rapid transfer of water to the web surface.

A key barrier limiting the rate of overall water removal is the stagnant gas boundary layer adhering to the moving web. Boundary layer scavenging by gas impingement (hot or cold) lowers the water vapor concentration at the surface and increases the local concentration gradient and hence the mass transfer rate. Consequently, the water molecules travel faster from the web into the boundary layer. During a phase change, a large quantity of thermal energy is required to separate water molecules as a liquid into those in the vapor state (latent heat of vaporization). This energy comes from the surface layers, and therefore the surface temperature decreases. The effect, called evaporative cooling, occurs in all drying operations.

Conductive drying systems

Steam-heated drum dryers are used to conduct heat into the web while holding it in tension to limit shrinkage. Heating effectiveness is governed not by the heated surface area but by the web-metal contact area. After warmup, the water in the web structure travels to the surface and evaporates at a constant rate. Farther down the dryer section, however, there is insufficient water to keep the pores or capillaries filled, so the drying rate decreases. The web structure remains wet inside, while the outer layers are below liquid saturation. As a result, approximately two-thirds of a paper machine's drying cylinders are required in the falling-drying-rate section, because heat must be conducted through the insulating fiber structure and water must be transported to the outer surface by different mechanisms. The heat and mass transfer limitations are intensified in low-density, bulky webs. Conductive drying systems for these products are inefficient as stand-alone systems and must be supplemented by hot-gas/air impingement or radiant energy heaters.

Gas impingement and through-drying systems

It is well known that a boundary layer of essentially stagnant air adheres to the free surface of a substrate moving through a dryer. The boundary layer is in laminar shear (sliding fluid layers), and the only heat transfer mechanism is conduction. The thermal conductivity of air is extremely low (0.042 W/m·°K), and the layer acts as an insulating blanket. Increasing the speed of the web increases the shear rate, but a thin insulating boundary layer still exists. In addition, the only mechanism for transporting the water vapor from the substrate surface to the atmosphere is by diffusion, which is several orders of magnitude lower than by turbulent mixing. Hence, for effective heating and drying, the boundary layer must be sheared and disturbed to minimize the high mass and energy transport resistance.

Because gaseous molecules are much farther apart than those in the liquid state, very few hot-gas molecules strike the solid surface to give up their energy. The heat content (specific heat) of air is also low, and large quantities of air must be heated and constantly brought to the work area to give hot gas dryers reasonable efficiency. Consequently, high-pressure, high-volume hot-gas flows are essential for reasonable drying rates and removal of water vapor from the substrate surface. Even with hot-gas circulation, a large proportion of the energy simply heats the environment, as many of the highly energized molecules never collide with the moving substrate. When curing nonwovens, there is a long period of time before the binder or additive can be concentrated and heated to its critical curing temperature. The net result is that hot-gas/air dryers are large, require numerous fans to sustain turbulence and hot-gas/substrate interaction, and need recirculation to reach reasonable efficiencies. These large dryers are usually expensive, and the operating cost is high.

High-impingement hot gas can disturb a binder or coating or physically dewater porous substrates, removing valuable additives *(1)*. High-pressure hot-gas jets can also disrupt the web structure and remove valuable fiber or binder. Some of these materials can be recirculated and trapped by the web, thereby reducing product quality. Therefore, there are operating limitations, and some systems must be downrated to balance energy efficiency with product quality requirements.

The process realities of hot-air curing, and binder and coating drying, as they relate to required quality and economics, dictate upper limits to both air temperature and air velocity. It has been reported that high air dryer nozzle velocities alone can cause binder migration, even with room temperature air *(2)*. High air dryer temperatures adversely affect quality and fuel efficiency, increasing web structure warping and cross-machine nonuniformity.

Through-drying of porous webs greatly increases drying rate, but it can only be used when the fiber-to-fiber bonds are set and the web structure is dimensionally stable. The high-speed hot-gas flows can remove (dewater) pigments, binders, and additives without drying, and produce a product with a nonuniform *z*-direction distribution of material (two-sidedness). Also, the porous web acts as a filter, and any particulate solids, fibers, or debris returned with the recycled gas are forced into the substrate and trapped. Through-dryers are usually added to another web-drying process to achieve better overall system performance.

Intense hot-air turbulence, high local velocities, and multiple molecular collision opportunities are essential for effective air drying systems. Consequently, these dryers require considerable space, numerous fans or blowers, and specially designed nozzles for each type of application. Web transport mechanisms using the hot air also deserve special consideration.

Thermal radiation drying systems

Electromagnetic energy (ultraviolet, visible, infrared, radio frequency, microwave, and X-ray) is transmitted either through a vacuum or through most solid and fluid media to various extents. This form of energy can be reflected, absorbed, absorbed and reradiated, or transmitted through an object *(3)*. Thermal radiation, or simply infrared radiation (IR), is most commonly used in heating and drying processes. All bodies above absolute zero temperature emit radiant energy at different frequencies (or wavelengths), but the net energy transfer is from the hotter to the colder body. In conduction, the heat flux through a solid depends on the type of material and the temperature difference (temperature to the first power). The mechanism is one of atomic or molecular excitation. In contrast, the overall driving force in radiation is proportional to the fourth power of temperature; therefore, far greater energy fluxes can be realized, subsequently resulting in far higher drying rates.

The IR heat flux between two gray bodies is calculated according to the following equation *(4)*:

$$q_r = \sigma\,(T_e^4 - T_a^4)\,F_e F_a F_g \qquad (1)$$

where

q_r = heat flux

σ = Stefan-Boltzmann constant

T_e, T_a = temperatures of the gray bodies

F_e, F_a = emittances of the gray bodies

F_g = view factor.

I. Radiation data for gas-fired infrared burners *(6)*

Burner	Type	Material	Surface temp., °C	Radiant energy output, W/m²	GIR (Eq. 2)
A	Atmospheric	Ceramic tile	771	58,042	0.85
			816	70,660	0.87
			913	94,382	0.84
A_1	Atmospheric	Ceramic tile	760	44,163	0.76
			810	56,213	0.71
B	Atmospheric	Inconel	760	59,052	0.90
			838	88,956	1.02
			868	102,836	1.06
C	Catalytic	Glass wool	316	2,523	0.37
			371	3,533	0.36
			454	10,409	0.65
D	Powered	Cordurite	816	70,187	0.87
			982	103,152	0.73
			1,093	140,059	0.69
E	Powered	Low-density refractory	816	55,834	0.79
			907	74,130	0.66
			938	91,795	0.74
F	Powered	Refractory brick	982	122,394	0.86
			1,093	162,456	0.81
			1,260	198,102	0.63
G	Powered	Refractory brick	871	68,294	0.69
			982	109,145	0.77
			1,093	182,961	0.91
H	Powered	Inconel	904	80,912	0.69
			977	115,770	0.83
			1,038	146,999	0.85
I	Atmospheric	Ceramic tile	771	56,150	0.83
			816	67,664	0.84
			866	87,221	0.94
J	Atmospheric	Inconel	804	59,935	0.77
			843	75,708	0.85
K	Powered	Silicon carbide	788	77,442	1.06
			829	97,474	1.16
			877	117,189	1.17
L	Atmospheric	"Cercor" glass	843	45,361	0.51
			932	73,184	0.60

An ideal or perfect radiator is termed a "black body," and all other materials are rated by comparison. A black body has an emissivity (ε) of unity, and the emissivity values of other materials are less than one. Hence, emissivity is the ability of a material to emit radiant energy relative to an ideal radiator.

Because emissivity is an absolute material property, a further term, emittance (F_e), is used to incorporate the effects of the material state as well as its surface roughness or topography. When the geometrical shapes of the emitting and receiving materials are different from a flat surface, a view factor (F_g) is required to determine the heat flux.

The American Gas Association Laboratories *(6)* developed the gross infrared radiation (GIR) factor. This factor, similar to emittance, is the ratio of the measured output (as determined by a spectrophotometer) to the total possible infrared output per unit area. The GIR factor is calculated as follows:

$$GIR = q/\sigma T^4 = (Q/A)/\sigma T^4 \qquad (2)$$

where

q = heat flux

Q = heat transferred

A = area of the emitter

σ = Stefan-Boltzmann constant

T = red brightness temperature of the emitting surface.

A radiant gas emitter with a high natural emissivity can have an effective GIR emittance greater than unity *(6)*. GIR values for a selection of gas-fired infrared emitters are presented in **Table I**. It is noteworthy that powered silicon carbide emitters have GIR ratings as high as 1.17. The total emittance is the sum of the radiation coming from the emitting material, the surface effects caused by the form or state of the material, and the radiation coming from the flame.

In the early stages of IR drying, the absorption and conversion to heat in the wet binder or coating are very high. Water has a total spectral emittance (absorption) greater than 0.92 *(4)*. Therefore, the IR absorption by the water can be as high as 87.4% [1.00 (IR output) x 0.95 (Transmission) x 0.92 (Emittance)]. In most cases, the average IR coupling efficiency is often less because water vapor evaporating from the coating continues to absorb radiant energy. Well-designed and properly positioned IR systems convert more than 80% of the emitted power to heat energy in a nonwoven substrate.

Calculations using Eq. 1 indicate that very high heat outputs are possible with IR drying. An IR emitter operating at 980°C, with a GIR emittance of 1.17, emits 163.2 kW/m^2 into a 20°C environment. That amount of power, if transmitted at 80% efficiency to one side of a water-base-coated or nonwoven sheet would evaporate 186.5 kg/m^2·h (water evaporation load is 0.7 kW/kg). Since the IR heat transfer mechanism is independent of the mass transfer mechanism, both can be optimized.

For porous nonwoven substrates, radiant energy provides a nondisruptive, noninvasive energy transport method for curing or drying. The intensity and duration of the energy can be controlled, and water is evaporated from the binder solution, so the maximum amount of binder or coating is retained by the substrate. Regarding dewatering, Hagen *(1)* indicates, "Dewatering should not be confused with drying. Water from the coating moves to the base sheet; it doesn't leave the web. To reach an objective web dryness, this water must still be removed by drying. Its significance to mottle and binder migration lies in the path it takes and the type of binder. After coating consolidation, obeying the idea of small pore preference, this water becomes the capillary reservoir. Its removal will result from flow to the coating surface combined with evaporation through the back side of the substrate." This demonstrates the importance of drying the inside of the web in addition to its surface.

Another benefit of radiant drying over conductive drying for nonwoven and paper substrates is the duration of the constant-rate drying period. In conduction systems, the drying rate usually decreases when the web moisture content drops to 30–35%. In radiant drying, the constant drying rate is not only an order of magnitude greater, but is also sustained until the web moisture level is 12–15%. This clearly shows that the controlling heat and mass transfer limitations in conduction are not transport limitations in radiant drying systems until very low web moisture contents are reached. Hence, infrared radiant systems can be used more effectively over the entire drying span for wet, porous-woven, or nonwoven webs. They also provide a faster and more effective means of curing polymeric additives, thereby reducing required machine space. The same benefits apply when bonding nonwoven structures with thermoplastic polymeric filaments.

The power output of certain modern IR emitters can be easily and instantly modulated for precise control of the heating operation and improved drying. Compact IR dryers, combined with mass transfer air jets, can provide the gentle heat transfer necessary to dry to moisture levels of less than 5%. High-performance IR dryers, mounted face to face (on opposite sides of the web) with mass transfer air bars, can produce water evaporation rates exceeding 300 kg/m^2·h. The difference in gross power between IR and other methods is important to managers trying to increase production beyond the abilities of conductive dryers. According to Lawton *(2)*, "The advantages of using infrared as compared with convection or flotation drying is the ability to transfer heat into the sheet at higher rates without surface-drying the coating, which results in an improvement in quality." Radiant heaters dry from inside the web structure outward, rather than from the outside inward.

Generating IR with gas

To produce usable industrial quantities of infrared radiation, an emitter surface is heated to incandescence. This can be accomplished by electrical resistance or gas combustion. Electric emitters operate at higher temperatures than gas emitters, and the very-short-wavelength IR radiation does not match the water and cellulose absorption spectra. Secondary reradiation of the electrically generated infrared energy is needed to reduce the radiation to the low-wavelength end of radiant spectrum and effect reasonable transfer efficiencies. Large air-moving blowers are required to cool the lamps and glass window. Electrically heated wires or rods also have a very small radiant surface area per unit area of heater; this is often overlooked in energy efficiency calculations. The high relative cost of electricity and the low overall effective energy transfer efficiency have caused managers to reassess the use of electric IR in the industry. High-intensity electric infrared units are candidates for replacement with gas-fired emitters simply based on economic considerations. Gas emitters use less energy and emit radiation at wavelengths that can be more effectively absorbed by the product.

Radiant output is dependent on emitter surface area, surface temperature, emittance, and the mode of heating the emitter material. A burner tile whose surface is 40–50% holes or a metal screen whose surface is 65% holes emits less energy per unit projected area at a given temperature than a continuous surface. To increase power density, a wire screen is often placed in front of the fragile ceramic porous plate, and the input gas flow is increased. The noise levels from the units are high (particularly on startup), and unit life is reported by the suppliers to be approximately two years *(7)*. The thermal mass is also large, and these emitters take considerable time to warm up and cool down (> 60 seconds). Automatic fire extinguishing systems are therefore mandatory.

Another method of infrared generation uses a multitude of flat metal inserts heated by hot-gas jet impingement on the back side. A wire reverberatory screen at the front is used to increase the power density. The all-metal units begin to deteriorate by oxidation from the moment of commissioning. The same fire safety problems apply when using these burners.

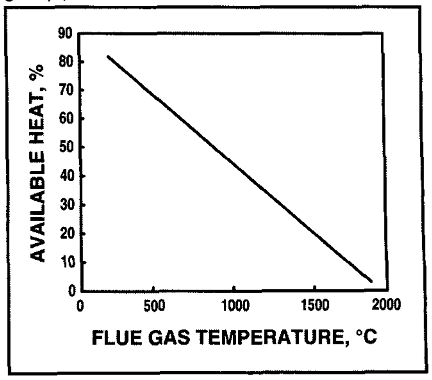
A recent development is the metal fiber emitter *(9)*, which features a coated alloy steel (Fecralloy steel). A porous metal plate made from bonded metal fibers allows gas to be burned on the surface. Although the radiant power output is acceptable, the gas usage (800 kW/m^2 gas supply at 950°C) is two to four times higher than ceramic-based emitters at the same radiant flux.

Based on previous calculations, the best practical radiant flux to an ambient environment from an emitter at 980°C is 163.2 kW/m^2. Neglecting the surface temperature difference for the metal fiber emitter, this would indicate only a 20.4% conversion efficiency to radiant energy. Furthermore, the lowest reported stable operating surface temperature of 600°C (gas input 150 kW/m^2) *(9)* could pose operating problems for variable-speed drying systems requiring a moderate turndown ratio. The gross conversion of gas energy to radiant energy at a given temperature is much lower than that for ceramic-type emitters; therefore, the metal fiber units are more costly to operate.

The metal fiber emitter reaches operating temperature in approximately 20 seconds and takes approximately the same time to cool to ambient conditions *(9)*. Some fire safety procedures are most likely necessary because of the thermal storage in the metal emitter.

The development of a metal fiber emitter material closely follows the successful, proven refractory composite fiber matrix emitters that have been commercially available for the last 15 years *(10)*. The pre-mixed gas/air passes through the bonded composite refractory fiber pad and burns just below the surface of the emitter. The inherent insulating properties of the composite fiber material prevent energy backflow and therefore backfire. The opacified refractory fibers have a much higher emissivity than metal fibers, and the residence time of the hot gas in the tortuous channels between the fibers improves energy transfer to the fibers and subsequent radiant generation. The hot combustion gas also augments the radiant output. The warmup time to full output radiation

1. Generalized available heat for natural gas *(4)*



is only 5 seconds, and the ceramic fiber surface is cool to the touch in less than 1 second (ambient temperature in 5 seconds). Consequently, fire safety procedures are not necessarily required.

Of all the current methods, the 5-μm-diam. composite refractory fiber matrix has the greatest radiant surface area per unit emitter area. The high-emissivity incandescent fibers immediately below the surface layer fibers are heated by the hot gas (conduction) as well as by radiation from the neighboring hot fibers. Sub-surface amplification of radiation results, and the emittance is higher than that from a continuous solid surface made from the same material.

In a porous composite refractory emitter, the hot exhaust gas flows through the emitter. A boundary layer of stagnant molecules does not exist. Without the boundary layer requiring removal by high velocity "scrubbing," more energy is therefore available for heat transfer. The temperature differential between the combustion gases and the emitter is minimized. Another benefit of controlled, lower-temperature combustion is the virtual elimination of NO_x emissions.

Efficiency can be increased by lowering the temperature of the flue gas exiting the emitter. If the flue gas exit temperature were at the theoretical maximum flame temperature of the fuel, the available heat would be zero, and no IR could be produced by the emitter. **Figure 1** graphs the percentage of available heat at various flue gas temperatures. A porous, composite refractory fiber emitter causes the combustion reaction to occur below the outer surface, in the presence of thousands of small fibers per unit area. Under such conditions, the fuel combusts at a much lower temperature than it would in free space. This is another reason that the composite refractory fiber emitter has the highest efficiency for converting hot gas to radiation.

To increase runnability and eliminate fires when the sheet breaks, an emitter material should have a low thermal mass to limit heat storage. Gas impingement metal emitters take several minutes to cool below the sheet's ignition point. Large volumes of air must often be injected onto the web, or the heaters must be retracted by mechanical devices that are subject to failure. Comparatively, the composite refractory fiber emitters take less than 1 second to cool below the paper ignition point and are inherently safer.

Radiant energy should spectrally target the water, since the purpose of thermal transfer in coating and binder drying is to evaporate water in the substrate. The absorption coefficient of water peaks at approximately 3 microns; it decreases above and below that level *(5)*. Radiation emitted by composite refractory fiber systems brackets that peak, thus effecting a more efficient energy coupling. Radiant energy targets the moisture through the web rather than just at the sheet surface. Where moisture variations occur in the web structure, radiant energy is preferentially absorbed by the water, resulting in a measure of self-regulating moisture-leveling control.

A low-thermal-mass, fast-modulating IR emitter provides greatly improved automatic modulation for machine speed changes. When combined with noncontact thermal sensors and PID controllers, these emitters can precisely control the substrate exit temperature. The modulation speed of the low-thermal-mass fiber emitter is as fast as that of electric emitters. This is a significant benefit when IR is used exclusively for coating, drying, and curing and for limiting temperature in a substrate or coating.

Summary

The principles of heat and mass transfer have been reviewed and applied in a critical evaluation of existing industrial drying systems. Thermal radiation systems are shown to transfer more energy than conduction and convection systems, in less space and without physical contact. Modern, composite refractory fiber, gas IR emitters overcome the runnability problems associated with older perforate tile and metal screen gas burners. TJ

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Silicone antifoams for nonwoven applications

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Unwanted foam in nonwoven manufacturing processes is a problem that can be controlled with foam-control agents that have been properly selected and screened. A number are commercially available, so several factors should be considered when selecting a foam-control product.

Before choosing an antifoam agent, it is important to understand the root of the problem. The authors provide an overview about the surface chemistry of foam, the causes of foam stability, and theories on how antifoams break foam bubbles. The key components of antifoams and factors that influence foam control also are discussed. For instance, silicone antifoams are considered more effective than other conventional antifoams because their highly efficient, long-lasting action, and inert properties make them a good match for many nonwoven processes and product formulations.

A simple questionnaire has been developed to help narrow the antifoam selection process to two or three top candidates for screening. Coupling selection criteria with appropriate screening methods eases the selection process for nonwoven manufacturers, allowing them to choose the antifoam agent best suited for their application.

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Heat transfer dynamics

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Papermakers today face a myriad of heat transfer systems. Choosing between these systems is difficult, and a critical evaluation of existing methods is helpful in properly selecting heat transfer systems. The methods used in this comparison are based on common physics equations and chemical tables. By breaking down the equations into their constituents, it is possible to isolate the variables that are important in real-world situations. Consequently, a comparison of the different drying systems becomes scientific.

As papermakers push their lines to higher speeds and quality, the role of heat transfer becomes increasingly important. Through a greater understanding of the underlying processes, choosing the proper heat transfer system becomes easier.

The author provides a review of the primary forms of heat and mass transfer and explains the principles and benefits of generating infrared energy by combusting a gaseous hydrocarbon fuel.

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