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AP-40

MEAT SMOKEHOUSES

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The smoking of food, especially meat and fish, has been practiced for thousands of years. The original purpose of smoking was to preserve food and add flavor to it. Modern smoking operations are very similar to the ancient methods, except for the level of technology used. Smoking is now used to impart flavor, color, aroma, and sensory appeal to food. Smoking food also provides antioxidant and antimicrobial properties. Refrigeration systems significantly reduce the need for smoking for preservation.

Pork and beef meat products are the primary smoked foods, although increasing amounts of turkey, chicken, and fish are also smoked as these products enjoy greater consumer popularity. Some vegetables and nuts are also smoked as gourmet or snack foods. Because meat is the prevalent food smoked, the remainder of this discussion is devoted to meat smokehouses.

PROCESS DESCRIPTION

Smokehouses

The meat production process in a smokehouse involves four individual operations: tempering or drying, smoking, cooking, and chilling. There are endless variations of these individual operations throughout the industry. One or more of the individual steps may be deleted for any given product. The process is varied by adjusting such parameters as time, temperature, humidity, smoke density, and product type, shape, and density.

Virtually all modern meat processing systems use either conventional batch-type smokehouses or continuous-processing ovens. Atmospheric, nonrecirculating smokehouses are no longer used commercially. In both the batch and continuous-meat-processing systems, heated air with controlled temperature, humidity, and smoke density (when used) is circulated uniformly over the surface of the meat. Figure 1 depicts a typical batch smokehouse in which meat is placed on racks or "trees," which remain stationary in the

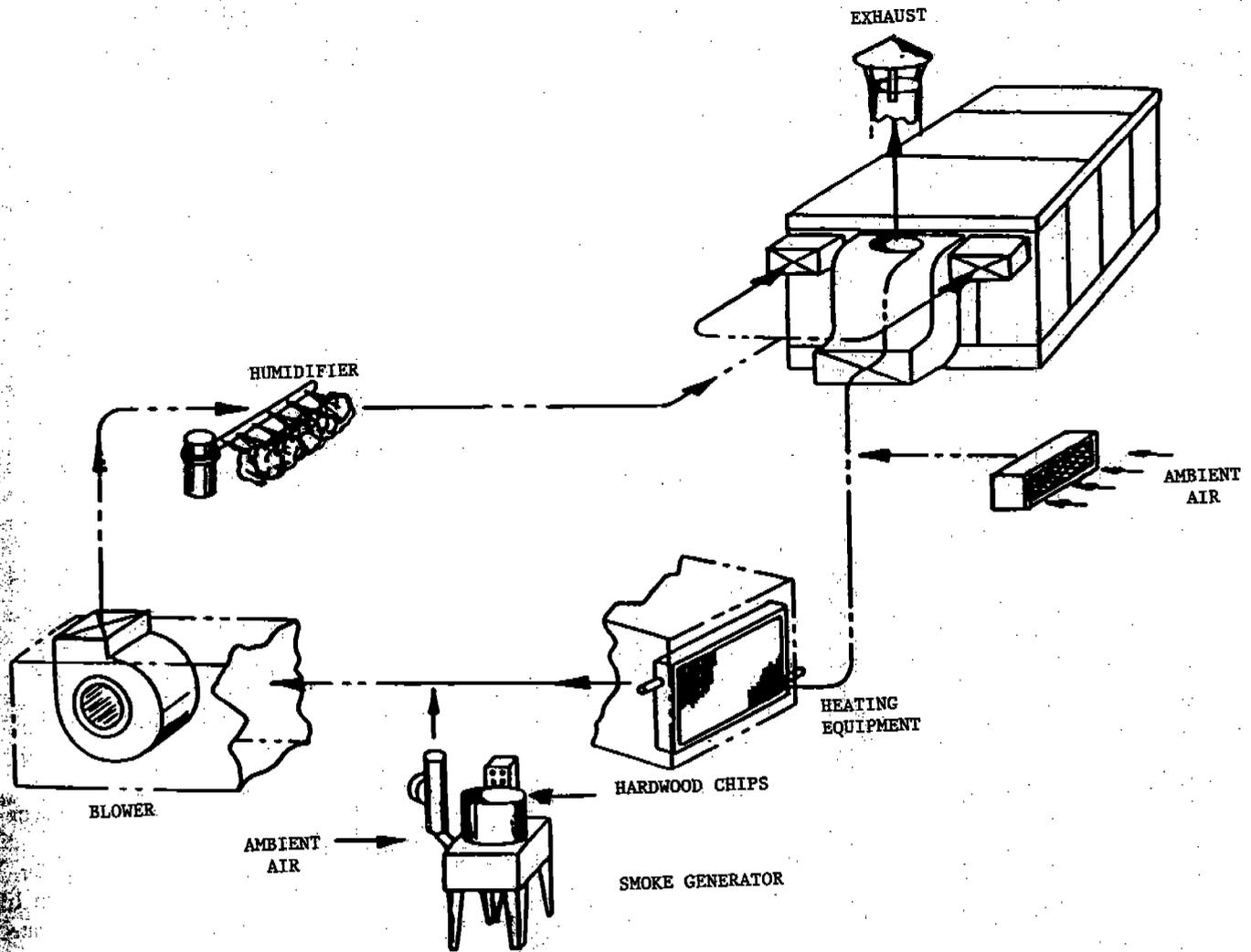


FIGURE 1. Conventional Smokehouse

smokehouse throughout the production cycle. Figure 2 is a schematic of a continuous system where meat is hung on sticks or hangers and is conveyed from zone to zone within the oven.

There are a variety of mechanisms for creating smoke, the most common of which is to pyrolyze hardwood chips (hickory, oak, maple, and beech are the most frequently used) in an external smoke generator. The chips are fed onto a gas-fired or electrically heated metal surface. Typically, this surface is heated to 350–400°C. Volatile components are carried away by a controlled air stream to a smoke tube leading into the air recirculation system. Smoke produced by this or similar methods is often referred to as natural smoke.

Another form of smoke flavor application that is increasingly popular in the industry is the use of liquid smoke, frequently called artificial smoke. Liquid smoke is produced from natural smoke through a smoke washing and concentration process. The concentrate is dissolved in water or oils and is sold commercially to meat processors. Liquid

smoke is atomized and dispersed into smokehouses through the air recirculation system as a fine aerosol.

Smoke Composition

Natural smoke consists of an extremely fine particulate phase and a gaseous phase in equilibrium. The smoke mixes in the smokehouse with moisture evaporated from the meat to form a diffused aerosol. The aerosol from sawdust smoke

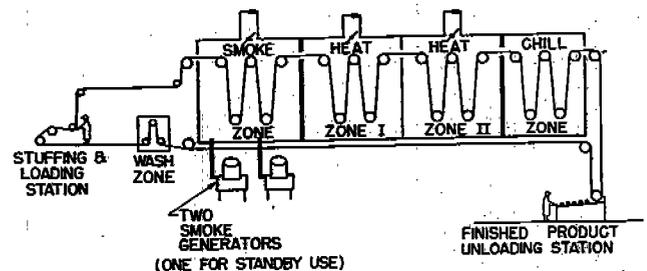


FIGURE 2. Continuous Meat Processing Oven

or liquid smoke is absorbed through the surface of the meat and reacts to give meats, or other smoked foods, their characteristic sensory properties.

Smoke research has generally focused on chemical groups rather than on individual compounds. Over 400 individual compounds have been identified qualitatively, and sometimes quantitatively, in smoke.¹ The quantitative data may be expressed as concentrations in pure smoke, as concentrations within a smokehouse or an exhaust stack (significantly diluted from pure smoke), as concentrations in smoke condensate (significantly higher than pure smoke because of the absence of air), or as fractions relative to the quantity of wood chips pyrolyzed.

The most important chemical components of smoke for sensory perception have been identified as phenols, carbonyls, and acids. These are present in both the solid and gaseous phases of smoke.²⁻⁴ Phenols are mainly responsible for aroma and contribute to flavor. Carbonyls are important for color and overall sensory properties. Acids act as surface sterilants and also contribute to flavor.⁵

AIR EMISSIONS CHARACTERIZATION

Just as smoke researchers have generally focused on chemical groups rather than individual compounds, the regulation of smokehouse emissions has generally focused on classes of pollutants. Most local and state air pollution regulations set limits for particulate matter opacity, concentration, and/or mass emission rate.⁶ Certain large urban areas also regulate smokehouses to control organics or odors. This generic regulation of smokehouses is reflected in emission factors published by the Environmental Protection Agency (EPA), that identify pollutants as particulate matter, carbon monoxide, hydrocarbons, aldehydes (all as formaldehyde), and organic acids (all as acetic acids).

Particulate Matter

The size of particulate matter within smoke aerosols is extremely fine. A particle-size determination conducted on the smoke zone exhaust of a continuous oven using sawdust smoke yielded a mass median diameter of 0.9 μm . Particles

smaller than 2.0 μm represented over 90% by weight of all particles.⁸ Particles this size have maximum light-scattering properties while having minimum mass. As a result, opacity limitations rather than concentration or mass emission limits have normally dictated the extent of emission control required.

Another factor contributing to generally low mass emission rates of pollutants from smokehouses is the small exhaust gas volumes during the smoking process. The minimum airflow rate is established by the volume of air entering the smokehouse through the smoke tube connection from the smoke generator. This volume is approximately 300 scfm. Actual exhaust gas volume is dependent on the humidity in the makeup air to the smokehouse and the desired humidity within the smokehouse. Typical airflow rates for conventional smokehouses range from 500 to 1500 scfm during the smoke cycle. Continuous oven smoke zones exhaust at a rate of 750 to 2000 scfm. The exhaust temperature is normally 35°C to 50°C.

Table 1 gives the long-standing emission factors from the EPA and the uncontrolled emission data from the previous edition of this manual.^{7,9} Concentration data correspond well with more recent published data⁶ and of industry experience.⁸ The only exception to this is found in certain high-product-volume, low-residence-time smoke zones in continuous ovens. Smoke concentration may be as high as 0.5 gr/scf for such systems since the product is exposed to smoke for only a few minutes. Opacity from such a system approaches 100%.

The uncontrolled emission factor of 0.3 pound of particulate matter per ton of meat (lb PM/ton) is based on 1 pound of wood chips consumed per 110 pounds of meat. Similar emission factors from recent industry experience give a range of 0.2 to 0.75 lb PM/ton for the lightest to the heaviest smoked meats. This is also corrected to 1 pound of wood chips per 110 pounds of meat. This range suggests that the emission factor from the EPA is perhaps low as an overall average.

One reason for this low factor may be that current emission tests often measure particulate matter in the front and back sections of the EPA Method 5 sampling equipment, whereas the original data are probably based on front-half

TABLE 1. Meat Smokehouse Emission Factors and Concentration Data

Pollutant	Uncontrolled Emission Factor (pounds/ton of meat)	Concentration
Particulate matter	0.3	0.14 gr/scf
Carbon monoxide	0.6	—
Hydrocarbons (CH _x)	0.07	—
Aldehydes (CHCO)	0.08	40 ppm
Organic acids (acetic)	0.2	87 ppm
Nitrogen oxides (NO _x)	—	3.9 ppm

Source: References 7 and 9.

results only. Recent industry tests show the back-half particulate matter (condensable gases and fine aerosols, identified before as present in smoke) account for 10–30% of all particulate matter measured.

Organics

Research on organics in smoke has focused primarily on identifying the ways in which different classes of compounds affect the many aspects of sensory perception. Until recently, when concern about the presence of air toxics such as formaldehyde and individual polycyclic aromatic hydrocarbons (PAHs) has increased, quantification of organics in smoke was directed at classes of compounds rather than individual substances.

Research in sensory perception has focused on phenols, carbonyls, and acids. For each 100 grams of dry wood used to generate smoke, phenols are expected to total 0.12 to 0.3 grams (as phenol), carbonyls 1.1 to 9.0 grams (as acetone), and acids 3.6 to 5.2 grams (as acetic acid).¹⁰ The amount of these groups present is a function of the temperature at which the wood is pyrolyzed, as seen in Table 2.¹¹ Note that both of these citations apparently refer to concentrations in pure smoke or in smoke condensate.

The amounts of organic acids and aldehydes have been measured in smokehouse exhausts by regulators in the Los Angeles area. In tests at a number of sources, organic acids ranged from 0.82 to 1.85 pounds per hour (pph), averaging 1.42 pph.¹² Aldehydes ranged from 0.13 to 0.83 pph, averaging 0.50 pph.¹² The ratio of aldehydes to acids in these tests is 0.35 to 1.0, which is very near the ratio of 0.4 to 1.0 in the EPA emission factors in Table 1.

The dominant compound within the organic acids group is acetic acid. Table 3 shows the contributions of formic, acetic, propionic, butyric, and higher acids to overall acid quantities present in smoke. Note that the formulation for liquid smoke is quite similar to the two wood smokes used in meat processing. The other wood smoke analysis is from seafood processing.

Formaldehyde is of special interest to present day regulators as an air toxin and possible carcinogen. While the EPA reports all smokehouse aldehydes as formaldehyde in smokehouse emission factors, formaldehyde is not the predominant aldehyde present. An early researcher reported formaldehyde in wood smoke at 20–40 ppm, whereas higher aldehydes were at 140–180 ppm (cited in the second edition of this publication).¹⁴ More recent data show formaldehyde and acetaldehyde composition in smoke from six different types of wood. Formaldehyde content averaged 17% and acetaldehyde averaged 83% for these two components. Higher aldehydes were not listed.^{15,1} A recent agency-witnessed emission test on a continuous-processing system gave these results: formaldehyde = 0.06 pph, acetaldehyde = 0.34 pph, and total particulate matter = 4.8 pph. The reported wood chips use was 90–120 pph.¹⁶ Note that formaldehyde is 15% of total aldehydes reported.

TABLE 2. Smoke Condensate Composition (mg/100 g Sawdust) as a Function of Temperature

Temperature°C	Total Phenols	Total Carbonyls	Total Acids
380	998	9996	2506
600	4858	14952	6370
760	2632	7574	2996

Source: Reference 11.

TABLE 3. Individual Organic Acids in Smoke (Percent of Total)

Acid	Meat Smoke A ²	Meat Smoke B ³	Seafood Smoke ¹³	Liquid Smoke ⁴
Formic	13.2	19.1	51.3	5.0
Acetic	74.5	69.3	7.0	75.6
Propionic	6.0	6.4	21.4	11.8
Butyric	1.8	1.3	3.4	1.3
Others	4.5	3.9	16.9	6.3

Extensive research has been conducted in recent years to determine the presence and effect of PAHs in meat and other food products. Many individual PAH compounds have been identified, but at extremely low concentrations. One study found 31 individual PAHs in mesquite smoke at a total concentration of 1280 $\mu\text{g}/\text{kg}$ of wood. The same study detected only 22 compounds in hickory smoke at a total concentration of 688 $\mu\text{g}/\text{kg}$ of wood.¹⁷ An earlier study found eight compounds in whole smoke and the vapor phase (particulate removed by electrostatic precipitation) from maple, but only at a total of less than 100 $\mu\text{g}/4.5$ kg of wood.¹⁸ Table 4 lists the compounds found in both studies. The data for hickory smoke PAHs were recently applied to a large meat processing facility in the Midwest (four continuous-processing ovens, 33 conventional smokehouses). The potential uncontrolled PAH emissions were predicted to be 10.5 lb/yr for all PAHs listed¹⁷ and 1.9 lb/yr for the PAHs regulated by the state environmental agency.¹⁹

As Table 2 shows, total phenols are a relatively minor constituent of smoke when compared with carbonyls and acids. Early research showed that phenols were present in smoke at 20 to 30 ppm compared with aldehydes at 150 to 200 ppm and acids at 550 to 625 ppm.¹⁴ More recent research identified "the four major phenols" as phenol, guaiacol, 4-methylguaiacol, and syringol. Their relative concentrations in whole-smoke condensate and the vapor phase are given in Table 5.²⁰

AIR POLLUTION CONTROL MEASURES

Smokehouse emissions have several characteristics that affect decisions concerning control equipment. Essentially all the emissions come from smoking rather than drying,

TABLE 4. PAH Composition of Different Wood Smokes

Compound	Smoke Mesquite ¹⁷	Hickory ¹⁷	Maple-Whole ¹⁸	Maple-Vapor ¹⁸
	($\mu\text{g}/\text{kg}$ wood)		($\mu\text{g}/4.5$ kg wood)	
Phenanthrene	204	114	51.5	28.4
Benzo(a)anthracene	60	38	7.0	4.3
Fluoranthene	162	94	5.7	4.2
Pyrene	155	104	5.5	4.1
Anthracene	47	31	3.8	1.9
Chrysene	72*	49*	2.6	0.3
Benzo(a)pyrene	74	41	1.2	0.4
Benzo(e)pyrene	36	20	0.9	Trace

*Chrysene and triphenylene

cooking, or chilling. All of the particulate matter is classified as "fine" with virtually no inorganics present. Smoke particles are hydrophobic, making water scrubbing difficult. Condensed wood smoke is viscous, sticky because of the tars and resins present, and mildly acidic. The major organic compound groups are present in both the gaseous and solid phases. In high concentrations, smoke is irritating to the eyes and is considered odorous. At low concentrations, smoke is generally considered pleasant.

A conventional smokehouse control device must be operated only during the smoke cycle and perhaps the first moments of the cook cycle as residual smoke is vented. The control device may be bypassed at other times, utilizing water dampers or mechanical dampers to direct exhaust gases appropriately. Damper operators are generally interlocked with smokehouse or smoke generator controls. Continuous-processing ovens may be designed to vent the individual zones together or separately. A combined exhaust may be considered if opacity is the only parameter of concern, provided the combined exhaust does not interfere with the recirculating air balance in each processing zone. If regulatory limits other than just opacity are applicable, the smoke zone should be separately vented and the control device sized accordingly.

Control devices that have proved acceptable for smokehouse control include high-pressure filters, certain scrubbers, modular electrostatic precipitators, and afterburners. Each of these devices has advantages and disadvantages. All are generally effective for controlling particulate matter when applied and operated appropriately. As the data in

TABLE 5. Major Phenol Concentrations in Smoke Concentrate and Vapor Phase

Compound	Whole Smoke (mg/l)	Vapor Phase (mg/l)
Phenol	59	5.9
Guaiacol	417	32.1
4-Methylguaiacol	333	13.6
Syringol	392	6.5

Source: Reference 20

Table 4 and 5 imply, all can be somewhat effective in removing organic compounds traditionally considered to be gaseous.

High-pressure filters utilize cleanable or disposable filter media at a cross-filter pressure drop of 20 inches to 30 inches water gauge. At this pressure differential, the fiberglass filaments composing the filter medium collapse together to promote particle growth and aerosol condensation. Particulate matter removal efficiencies in excess of 95% have been measured, yielding essentially clear stacks. High-pressure filters must be protected from adverse weather. Gas-contacting surfaces must be manufactured from stainless steel and must be cleaned periodically with smokehouse cleaners to prevent the buildup of smoke tars and resins. Because these filters function best when exhaust rates do not fluctuate much, they are more suitable for continuous ovens or groups of conventional smokehouses.

Next to afterburners, scrubbers have been utilized in the meat industry more than any other control device. Venturi scrubbers are the most common type used because they are more efficient for particulate matter removal. Scrubbers are more effective if a small amount of surfactant or wetting agent is used in the water sprays to offset the hydrophobic nature of smoke particles. A highly efficient mist separator is mandatory to prevent smoke-water-droplet carryover. The dilute smoke-water condensate can discolor building walls and roofs. The scrubber blow-down can be discharged into the plant process wastewater system as there is no known instance of adverse impacts of smoke condensate on biological treatment plants.

Modular electrostatic precipitators (ESPs) have been utilized on smokehouses in southern California since the 1950s. Multistage units are required to achieve desired particulate matter removal efficiencies. In combination with a wet centrifugal collector upstream, a two-stage ESP had a 65% particulate removal efficiency and 35-50% efficiency for aldehydes and organic acids.⁹ More recent tests show that a three-stage ESP can achieve over 95% particulate removal and a virtually clear stack. However, these units must have clean-in-place systems to remove smoke condensate and must have a heat source to keep ionizing ele-

TABLE 6. Smokehouse Afterburner Efficiency as Function of Temperature

Pollutant	800°F	1000°F	1200°F	1400°F
Particulate matter	70	90-93	96	97
Organic acids	60-80	75-90	90-98	95-100
Aldehydes	60-80	70-90	87-92	95
Total organics ^a	NA	68	88	77
Carbon monoxide	NA	99+	99+	99+
Nitrogen oxides ^b	NA	5	12	12

^aIncludes particulate matter and organic gases together. 1400°F cited as unexplained test anomaly.

^bReported as concentration (ppm) rather than removal efficiency.

Source: Reference 12.

ments dry. Otherwise, arcing will occur and efficiencies will suffer significantly.⁶ A promising technology for smokehouse emission control is the combination of a low-pressure-drop venturi scrubber with a modular wetted-wall ESP. Such a combination, properly developed, should offer high particulate matter efficiency, good control of organic gases, and continuous disposal of smoke condensate in a dilute wastewater stream.

Until the energy crises of the 1970s, afterburners had long been viewed as the preferred control device for smokehouses. Their low capital cost; high efficiencies for particulate matter, organic gas, and carbon monoxide control; low maintenance requirements; and high flexibility make afterburners attractive. For limited operating hours on conventional smokehouses, their cost of operation is reasonable when compared with amortized capital costs for other, more expensive technologies. Extensive studies in southern California document high afterburner efficiencies.¹² Table 6 lists efficiencies from several stack tests as a function of afterburner temperature. In consideration of such information, an afterburner temperature of 1200°F with a residence time of 0.5 second was accepted as best available control technology (BACT) for all pollutants of concern in southern California in 1989.

Another important factor for BACT is the temperature of the smoke generator, which should be minimized. Table 2 shows how organic gases increase as the smoke generator temperature increases. It has also been recommended that the smoke generator temperature be kept below 400°C to limit the formation of polycyclic aromatic hydrocarbons.²¹

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