

Introduction:

In order of presentation, this paper describes: batch coffee roasting in general; batch roasting systems used in the 1950's; conventional methods for controlling coffee roasting; new batch roasting systems introduced in the past 35 years; the development of fast-roasted, high-yield coffee; fluidized-bed roasters; continuous roasters; pollution control for roasting; new knowledge about roasting chemistry; and new roasting control methods..

Batch Roasters with Gas Recirculation

Fig.1 schematically depicts a typical industrial-scale, batch, coffee roasting system used in the 1940's. The same basic system is used today. It consists of: 1) a hopper containing a preweighed charge of green coffee beans; 2) a roasting chamber through which hot gas passes and into which, at the start of a roast, the green bean charge is dumped and where bean roasting and mixing occur; 3) a spray lance through which a metered volume of water is sprayed on the beans so as to quickly cool them to slightly more than 100°C and rapidly terminate the roast; 4) a normally-closed port that is opened to discharge beans after the end of a roast; 5) a damper that interrupts gas flow through the roasting chamber during bean quenching and unloading and that regulates pressure in the roasting chamber during roasting; 6) a furnace which heats roaster gas by admixing hot combustion products generated by burning a fuel gas or, less frequently, fuel oil; 7) a small blower that delivers air to the burner in the furnace; 8) effectively coupled valves that control the rate at which fuel and air flow into the burner and that set the air:fuel ratio used in the burner; 9) a cyclone for collecting the chaff released from coffee beans during roasting; 10) a larger blower that draws hot gas from the furnace through the roasting chamber and cyclone and then returns it to the furnace, after which most of the hot gas flows back into the roasting chamber and part leaves the system through a stack; 11) a perforated cooling tray on which quenched, roasted beans are dumped and then raked while room temperature air is drawn through them so as to cool them from the end-of-quench temperature to roughly 40°C.

To prevent out leakage of roaster gas and minimize in leakage of air during roasts, the roasting chamber is maintained at a slightly negative gage pressure (e.g. - 6 mm of water) The furnace is kept at slightly positive gage pressure to prevent air in leakage and minimize out leakage of furnace gas. Therefore, the gas entry to the discharge stack is located just downstream from the furnace.

The fuel and burner air control valves are effectively linked so as to provide a constant fuel:air ratio, roughly 11 to 12 volumes STP of air per volume STP of natural gas. 10% to 20% excess air is used to minimize formation of CO and NOX. For 10% excess the flame temperature is roughly 1710°C; for 20% excess air, roughly 1580°C.

Beans char (Backer et al. 1938) or even spall at their tips if roaster gas temperatures greater than 510°C are used. Inlet gas temperatures, T_{gi} , in batch roasting chambers vary during roasting (Schwartzberg, 2003), and at their peak can readily reach 500°C. To provide T_{gi} that beans can tolerate, recirculated roaster gas is mixed with the combustion products generated in the burner in the furnace. For most recycling roasters, the ratio of recycled gas to products of combustion should be more than 3.3:1 at the start of roasting and more than 6.2:1

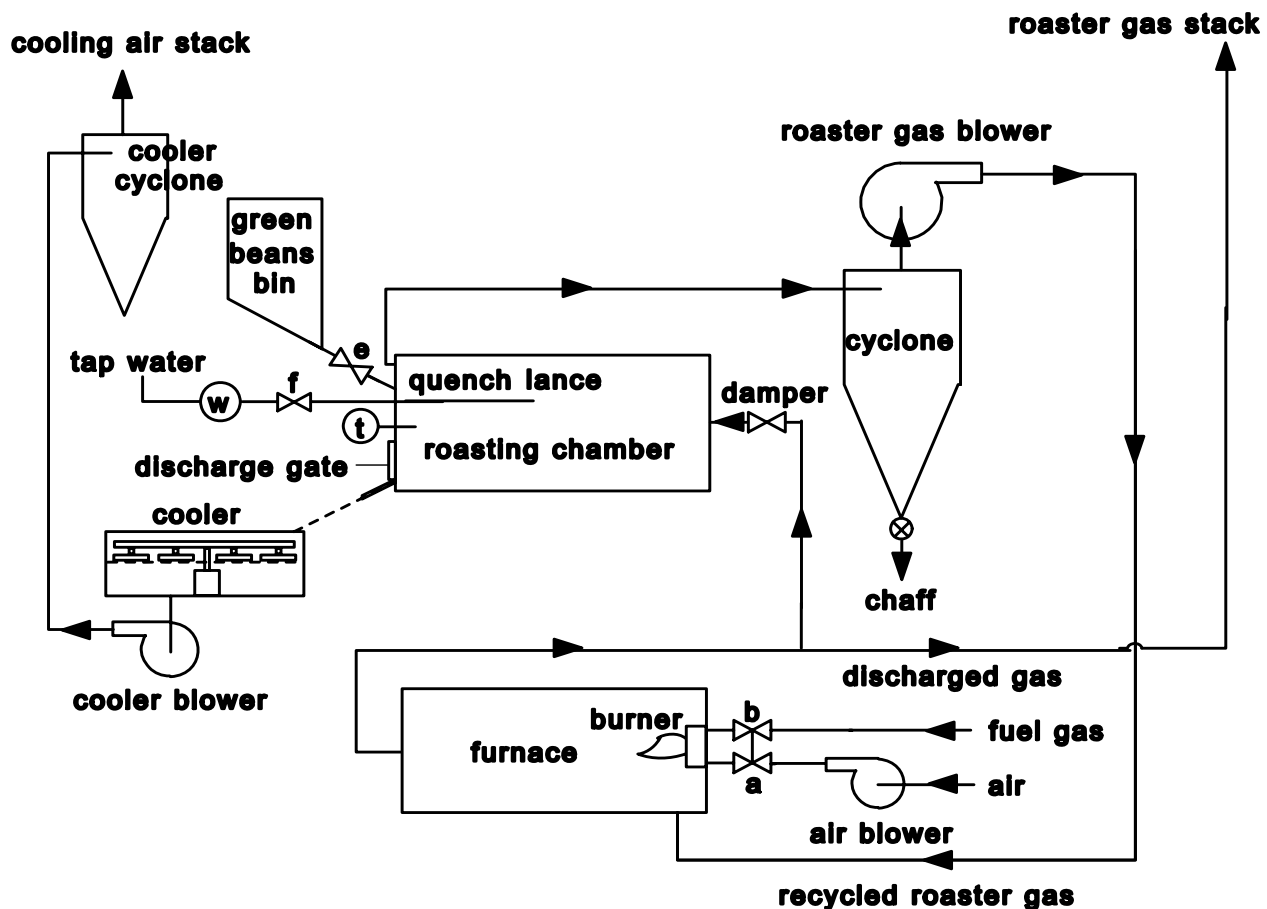


Figure 1 Schematic of coffee roasting system in which gas recirculation is used.. a and b respectively are the burner air and fuel gas control valves, e is the green bean feed damper, f the quench water valve, t the bean thermocouple and w the quench water volume meter.

at the end of roasting. Recycled gas is mixed with combustion products right after those products leave the burner so as to cool them rapidly and thereby minimize NOX production. If recirculating roaster gas contained only products of combustion, its weight % composition would be: 73.2% N₂, 10.2% H₂O, 12.8% CO₂ and 3.7% O₂ for a typical natural gas burned with 20% excess air. However beans emit CO₂, H₂O, CO and volatile organic compounds (VOC) during roasting. Therefore the average weight % composition of roaster gas in a recirculating batch roaster is roughly 50.6% N₂, 30.2% H₂O, 16.6% CO₂ and 2.6% O₂. These percentages vary during roasting, with the percentages of N₂ and O₂ approaching those in combustion gas at the start of roasting. The H₂O percentage peaks in the middle of roasting and those of CO₂, CO and VOC peak near the end of roasting. At the end of roasting, the VOC content of roaster stack gas can reach 0.2% by weight. Since VOC partly break down when roaster gas passes through the furnace, the % VOC for gas in the roasting chamber is probably even higher.

Horizontal, Rotating-Drum Roasters

Fig. 2 schematically depicts the roasting chamber for a Jabez Burns roaster, a widely used batch roaster. It consists of a motor-driven, horizontal, rotating drum with a perforated

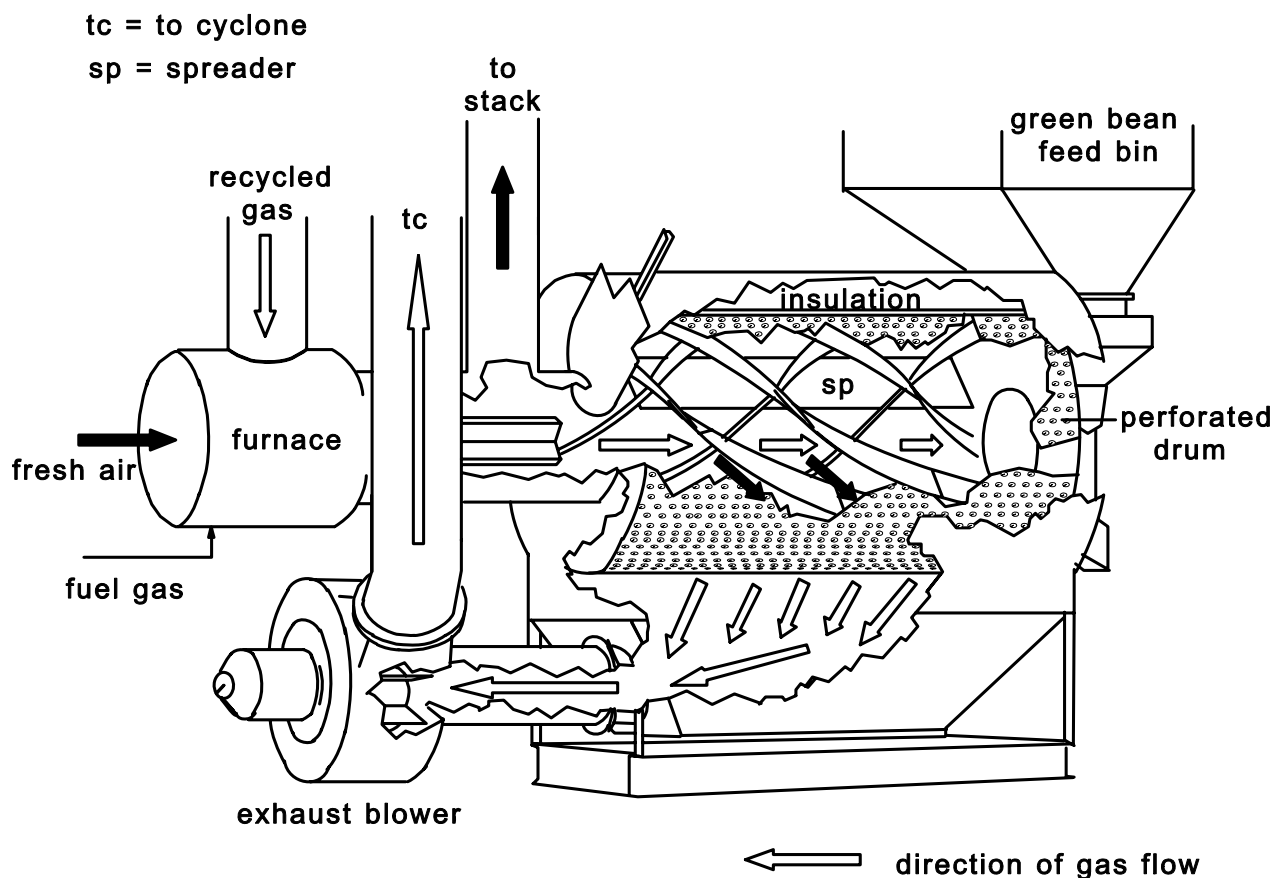


Figure 2. Roaster (Jabez Burns roaster) in which a horizontal, rotating drum with a perforated wall is used as a roasting chamber

wall. The perforations are small enough to retain coffee beans but large enough to pass chaff. Two oppositely-pitched sets of helical flights attached to the drum wall mix the beans and lift them. When the beans drop off flights they fall across the axially-flowing hot gas stream. The gas then turns and passes through the pile of beans at the drum's bottom and through the perforations on the bottom 1/3 of the drum wall, the only part of the drum wall not closely apposed by the insulation lining the roaster shell. While heat transfers to beans as they fall, much more heat transfers as the gas passes through the bean bed.

In other widely used horizontal, rotating-drum roasters, e.g. Probat type R roasters, the roasting chamber has solid walls.(see Fig. 3). Hot gas from the furnace first flows around the exterior of the drum wall and then enters the rear of the drum and flows through it parallel to the drum's axis. The drums contain oppositely pitched sets of segmented, helical flights that mix and lift the beans. The beans drop off the flights and fall across axially-flowing hot gas. Most heat transfer occurs as the beans fall through hot gas, but significant amounts of heat transfer to beans from the drum wall by conduction and radiation. To prevent excessive conduction heating and localized burning of beans, some roasting drums have double walls with an air gap between them. In the roaster shown in fig. 3, the whole front opens by moving forward to permit bean discharge. In other solid-walled drum roasters, a smaller, normally-closed discharge port opens for unloading.

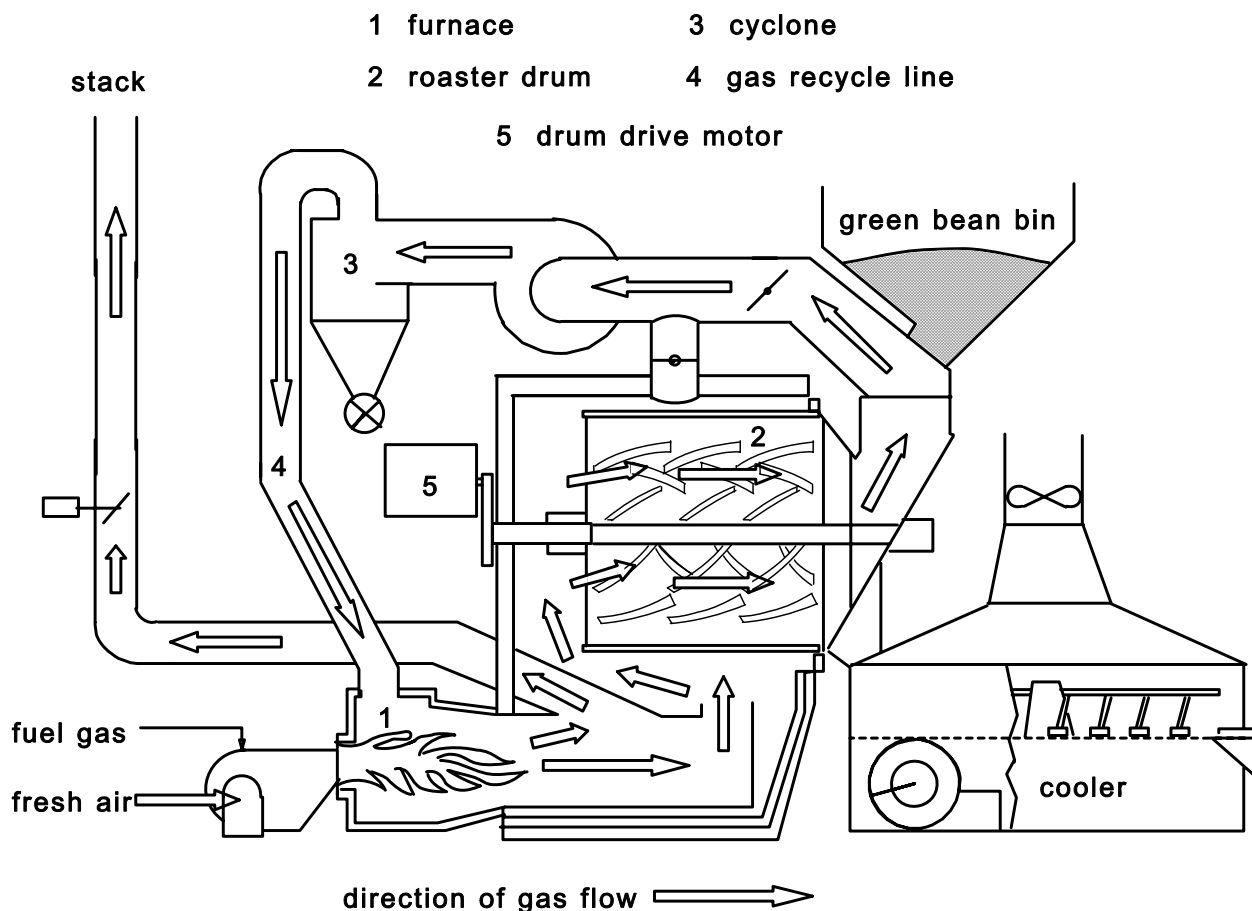


Figure 3 Roaster (Probat Type R roaster) in which horizontal rotating drum with a wall without perforations is used as a roasting chamber

To prevent centrifugal force from counterbalancing gravity and causing beans to stay at the drum wall without falling, horizontal-drum roasters have to rotate with an *RPM* smaller than $(30/\pi)(g/r)^{1/2}$, where g is the gravitational acceleration and r is the drum radius. The larger the radius of a horizontal-drum roaster is, the slower the drum must turn. Therefore, larger, horizontal-drum roasters provide poorer mixing than smaller roasters of the same type. This probably is a major reason why the maximum green bean batch capacity for commercial, horizontal, rotating-drum roasters is roughly 500 kg. As *RPM* increases, beans fall off flights at higher angles of rotation. The flights impart their velocity to beans falling off them. Thus beans fall in curved paths that rise slightly before descending. Bean exposure to flowing hot gas is maximized at an optimal *RPM* 10% to 25% less than $(30/\pi)(g/r)^{1/2}$.

Till the late 1950's, horizontal, rotating-drum roasters were they only types of industrial-scale, batch coffee roasters available and roast times ranged from 15 to 18 minutes. Similar roasters still are widely used and made today and now normally provide in 10 to 12 minute or 10 to 15 minute roasts, with the faster roasts being obtained with smaller bean loads.

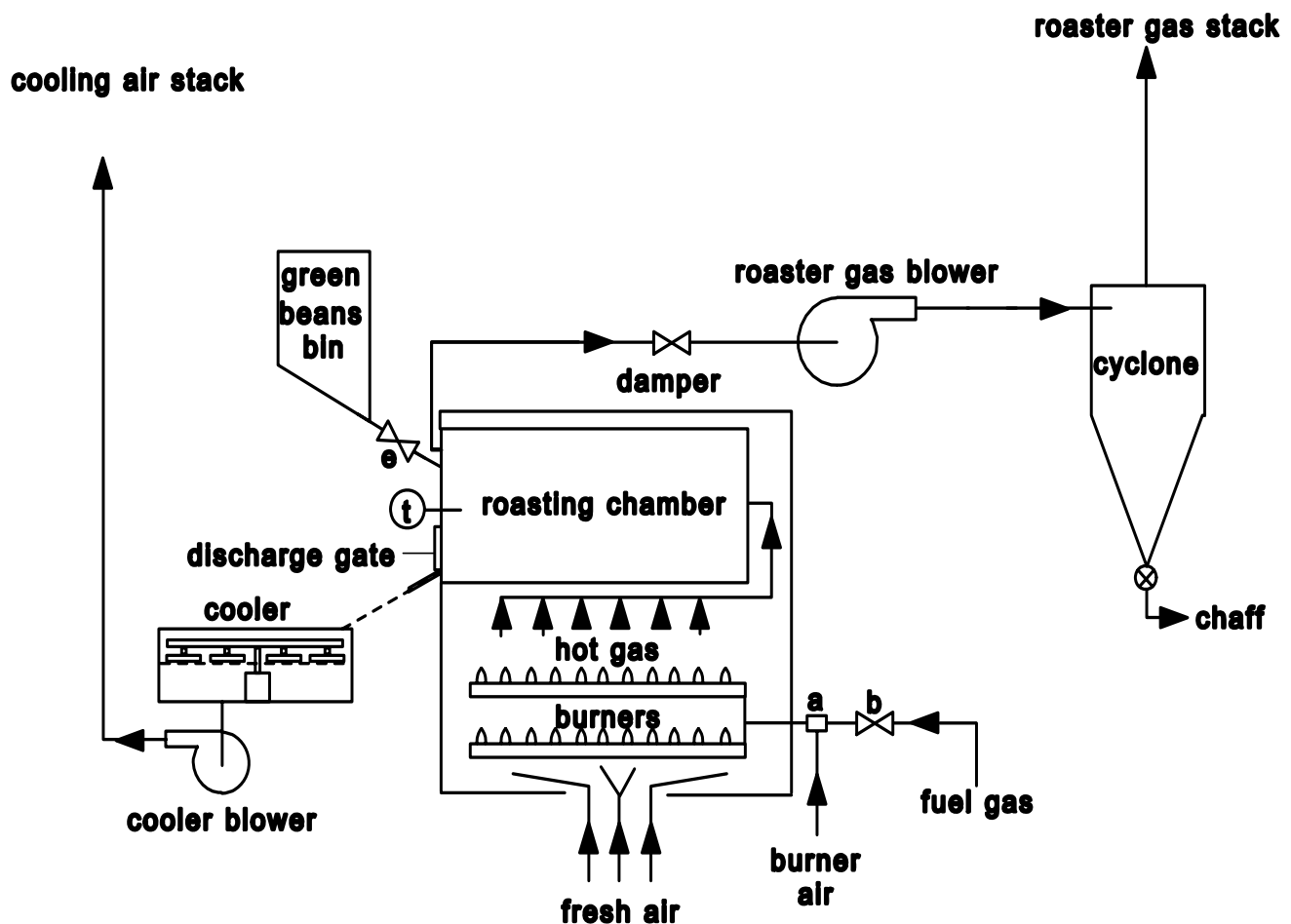


Figure 4 Roaster in which single-pass gas flow is used

Single-Pass Roasters

Small roasters usually are small, horizontal, solid-wall, rotating-drum roasters in which single-pass, hot-gas flow is utilized. Fig. 4 depicts a schematic of a typical roaster of this type. The figure shows only two lance-like burners in the roaster shell below the drum, but three burners are usually used. As roasting progresses, first one, then two of the burners are turned off. The damper in the gas discharge line from the drum can be used to adjust roaster gas flow, but is rarely adjusted after installation. Operators of small roasters usually do not use water quenching and rely solely on air cooling in the cooling tray to stop roasts.

Somewhat lower inlet gas temperatures are used in small, single-pass roasters than in recirculating roasters. Products of combustion in single-pass roasters are diluted with air instead of recirculated roaster gas to provide gas inlet temperatures suitable for roasting. On an average-weight-percent basis, gas passing through the roasting chamber of a single-pass roaster contains much more O_2 (22.8% in and 21.8% out), less H_2O (2.1% in and 5.2% out) and less CO_2 (2.7% in and 3.6% out) than gas in roasters employing gas recirculation. Thus, in single-pass roasters, there is a greater potential for oxidation at bean surfaces than in recirculating roasters but less exposure to tars that build up in recirculating roaster gas. The

flavor consequences of these differences in roasting environment do not appear to be known. Small single-pass roasters emit VOC in much more dilute form than recirculating roasters, but the amount of VOC emitted per unit mass of green beans is as great as and probably greater than in recirculating roasters

Conventional Roast Control Methods

Industrial-scale roasting was and is controlled primarily by stopping a roast when the measured bean temperature T_{bm} reaches a set value, $(T_{bm})_f$, that experience shows has provided roasted coffee with the desired flavor and color. Because of thermometric lags, T_{bm} differs the true bean temperature T_b . Thus $(T_{bm})_f$ are 10°C to 20°C lower the true final bean temperature, T_{bf} . While thermometric lags differ from roaster to roaster, $(T_{bm})_f$ for rotating-drum roasters are usually roughly 190°C for a very light roast and 260°C for a very dark roast.. $(T_{bm})_f$ depends on bean type, being roughly 4°C higher for Robustas and roughly 8°C higher for Columbians than for Brazilian Arabicas. During roasting, coffee beans lose weight due to evaporation of their water content (8% to 12% of the green bean weight) and destruction of dry matter, 1-5% for a light roast to > 12% for a very dark roast. The total percent weight loss and percent dry matter loss are used as after-the-fact measures of extents of roasting.

Operators of small custom roasters observe the color of bean samples periodically withdrawn from the roaster (every 15 seconds near the end of a roast) and stop the roaster when the beans reach the right color. After roasts, operators of large roasters measure the percent of light reflected from ground, roasted coffee at a standard wavelength, e.g. 595 nm for Photovolt roast color meters, (Stefanucci et al. 1982). Lighter roasts (50 to 60 on the Photovolt) are preferred in Northern Europe and the U.S. and darker roasts (32 to 36 on the Photovolt) in Southern Europe. The standard deviation in reflectance color of coffee roasted to the same $(T_{bm})_f$ in the same type and model of roaster is roughly two Photovolt units. The public can detect color and taste differences in roasts whose colors differ by four Photovolt units (Stefanucci et al. 1982). In conventionally operated batch roasters, increasing total roasting time, t_f , causes $(T_{bm})_f$ to increase, causes larger roasting losses and causes roast color to progressively decrease. Nevertheless, Mahlman (1986) and Schechter (2000) show that the same roast color can be obtained at both a lower and a higher $(T_{bm})_f$ by using roasting conditions providing a markedly longer t_f at the lower $(T_{bm})_f$.

Other reflectance colorimeters, Agtron, Neuhaus Neotec and Lange, are used by roasters today. Some of these meters employ infra-red or near infra-red light sources, e.g. 640 nm light is used in the Agtron meter. Colorimeters employing L (lightness), a (red-green) and b (yellow-blue) scales are used frequently in academic studies of roasting and have been used to a limited extent in industry. Though a and b values vary markedly during roasting (Severini et al 1991, Schechter 2000), L values alone usually are used to characterize degrees of roasting. Changes in roast color (including L changes) for the colorimeters cited appear to be linearly proportional to one another, but the zero of each color scale is shifted with respect to the others. Light roasts are 50 to 60 on the Photovolt, 48 to 68 on the Agtron and 36 to 38 on the L scale; dark roasts: 32 to 36 on the Photovolt, 25 to 33 on the Agtron and 16 to 18 on the L scale.

High pressures, developed due to CO₂ and water vapor generated inside coffee bean cells, cause beans to expand during roasting. Bean expansion is accompanied by cracking o

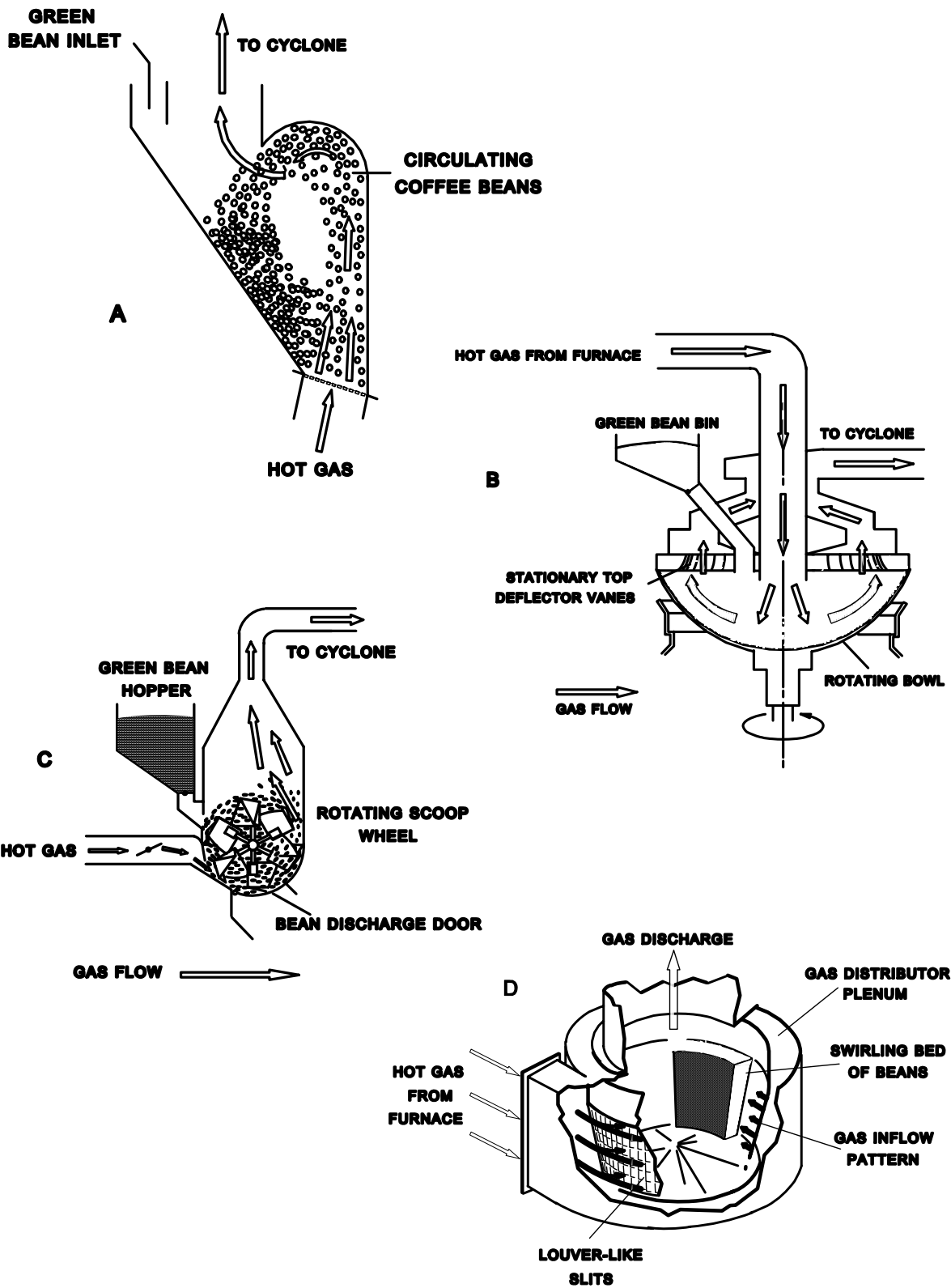


Figure 5 New types of roasting chambers: A) Asymmetric spouted bed; B) Rotating bowl; C) Chamber with rotating scoops; D) Swirling bed roaster

popping sounds. Some operators of small roasters and many amateur roasters base the stopping of roasts on these cracking sounds. Stopping a roast shortly after the “first crack” starts provides a light roast; stopping during the “second crack” a dark roast.

T_{go} , the temperature of gas flowing out of the roasting chamber, rises as roasting proceeds; and ρ_g , the density of the gas leaving the chamber and entering the blower, progressively decreases. Roaster system blowers tend to provide a nearly constant volumetric-flow rate, V_g , the mass-flow rate of roaster gas, $= V_g \rho_g$, and thus decreases as roasting proceeds (Schwartzberg, 2003). Unless Q_F , the heat-delivery rate of the furnace, is reduced, T_{gi} will rise excessively. Control systems in older roasters decrease Q_F in two steps. With the first step occurring when T_{bm} reaches a first set point, e.g. 170°C, and the second at a higher T_{bm} set point, e.g. 180°C. Reducing Q_F also permit greater control over the end of roasting.

New Types of Batch Roasters

New types of batch-roasting chambers came into use after 1971 and are depicted schematically in Fig. 5. Sivetz (1976) patented a roaster where the hot gas caused beans to circulate as an asymmetric spouted bed, often called a rotating fluidized bed, (Fig. 5A). He used gas temperature between 232°C and 277°C and roasted in 10 to 20 minutes. Neuhaus Neotec makes an industrial-scale version of that roaster (the RFB) in which higher gas temperatures, e.g. 360°C, are used and faster roasting is obtained, e.g. $t_f = 4$ minutes. High gas velocities and high gas pressure drops are needed to induce spouting. Therefore, unlike other roasters, roasting chambers in spouted-bed roasters operate at a positive gage pressure. In the Probat RZ (Fig. 5B), centrifugal force causes beans slide rapidly outward across the upper surface of a rotating bowl. The beans are then redirected inward across the flow of hot gas by stationary vanes. Arndt (1971) patented a stationary, solid walled roaster with a hemicylindrical bottom and rotating scoops, now the Gothot Rapido-Nova or Probat RT roaster (Fig. 5C). Wireman and Wireman (1991) patented a roaster, now the Burns System 90, in which gas injected through louvers on an inverted, vertical, truncated conical wall passes through a thin bed of coffee beans causing them to swirl around the wall's inside (Fig. 5D). The beans are held radially in place by centrifugal force. The systems shown in Figure 5 all utilize gas recirculation and can provide batch roasting as short as one to three minutes. Three to five minute roasts are commonly used. When fast roasts are used, most of these systems can roast up to 2,000 to 4,000 kg of green coffee per hour. If desired, they can provide eight minute roasts, albeit at reduced rates of throughput.

Fast-Roasted, Low-Density, High-Yield Coffee

MacAllister and Clifford (1964), at General Foods, roasted small batches of coffee (probably Robustas) with an earthy off-taste in a small fluidized bed. Using 316°C “air” the roast was completed in 2 minutes; and with 399°C “air” in 35 seconds. These roasts produced coffee that contained more residual moisture than normal, were more acidic, had a less earthy taste and which yielded significantly more solubles upon brewing. Other inventors also developed processes that also employed fast roasting and provided lower density roasted coffees that contained more solubles. Depending on the inventor: faster roasting was obtained by using much higher gas flow rates either in batch fluidized beds (Mahlman et al. 1985), continuous fluidized beds (Mahlman et al. 1985), (Brandtlein et al. 1988) or in continuous

Table 1. Comparison of roasting conditions used in normal roasts and in fast roasts and resulting roasted coffee bulk densities

Inventor	Roster type	T_{gi} (°C)	Roasting time (sec)	Bulk Density kg/m ³	SGR
Mahlman et al.#	BRD	560 640	600 300	389 350	approx. 1 approx. 0.85
MacAllister & Clifford	BFB	319 399	120 35	not reported	?
Hubbard et al.	CMJ	*1 238 *2 282	360 to 540	357	11.6-17.4
Hubbard	CMJ	293	180 to 240	365	8.4
Mahlman et al.#	BFB	200 220 232 240	450 195 165 120	404 358 332 330	150 65 55 40
Mahlman et al.#	CFB	238	150	333	50?
Brandlein et al #	CFB	*1 327 *2 271	60	310	14
Stefanuucci et al. #	BRD	649	420	340	approx. 0.7

BRD = batch rotary drum, BFD = batch fluidized bed, CFB = continuous fluidized bed, CMJ = continuous roaster where gas from multiplicity of jets impacts on moving bed of beans, *1 = T_{gi} in first stage of two-stage roaster, *2 = T_{gi} in second stage # bulk density data for Columbian beans, that for Brazilians is roughly 3% lower and that for Robustas roughly 8% higher.

roasters in which hot gas flowing out of an arrays of jets impinged on a vibrating bed of coffee (Hubbard et al. 1979), (Hubbard 1982), or by employing higher gas temperatures, moderately higher gas flow rates, lower bean charge weights and a $(T_{mb})_f$ 1.7°C higher than normal in a conventional drum roaster (Stefanuucci at al. 1982). Price et al. (1991) claim that when compared to coffee roasted for 840 seconds, coffee roasted in 60 seconds contains more low molecular weight solubles, more residual sucrose (0.8% versus 0.3%), provides 42% more head-space aroma and tastes less bitter both when freshly brewed and after the brewed coffee is held for an hour.

Table 1 lists fast-roasting conditions, conditions for conventional batch roasts yielding

product with a similar roast color, and the resulting bulk densities for the products obtained. As before, T_{gi} is the temperature of the gas entering the roasting chamber,

$$SGR = [\int Gdt] / R_o \quad (1)$$

G is the gas mass-flow rate, t the elapsed roasting time, R_o the initial weight of beans and the integral is evaluated from $t = 0$ to $t = t_f$ the total roasting time. The data in Table 1 show that SGR decreases as T_{gi} increases. By modifying an equation developed by Schwartzberg (1999), one can show that:

$$SGR = (1/E)(C_{bm}/C_{gm})\ln[(T_{gi} - T_{bo})/(T_{gi} - T_{bf})] \quad (2)$$

where C_{gm} and C_{bm} are the respective mean heat capacities of roaster gas and beans, E is the mean efficiency of heat transfer in the roaster and T_{bo} and T_{bf} respectively are the initial and final values of the true bean temperature. After taking into account cooling due to water evaporation, exothermic heat generation and effects of bean temperature change, $C_{bm} \approx 2.41$ kJ/(kg·°C); and after taking into account roaster gas composition and effects of gas temperature change, $C_{gm} \approx 1.31$ kJ/(kg·°C) for gas in rotating drum roasters.

One can use Eq (2) to roughly assess the heat transfer efficiency of the roasters, including those listed in Table 1. On this basis, E roughly equals: 0.058 for the fluid bed roaster used by Mahlman et al., 0.224 for the multi-jet roaster used by Hubbard, 0.61 for asymmetric spouted bed roasters and 0.72 for conventional horizontal, rotary-drum roasters.

$$E = [(T_{gi} - T_{go})/(T_{gi} - T_b)] \approx 1 - \exp[-(UA_{bg})/(GC_{gm})] \quad (3)$$

U is the overall gas-bean heat-transfer coefficient and A_{bg} the bean-gas heat transfer contact area. As G increases, U increases less rapidly than G does. Therefore E will be lower for roasters employing very high G . E should not be confused with thermal efficiency, i.e. (heat received by beans)/(heat input to the roasting system). The thermal efficiency of recirculating roasters can be high even when E is low.

Less time is available for CO₂ and water vapor to diffuse out of coffee beans during fast roasting. Therefore, during storage, considerably more CO₂ diffuses out of fast-roasted coffee than out of slow-roasted coffee (Schechter 2000). Fast-roasted coffee beans also have a higher water content than slow-roasted coffee (MacAllister and Clifford 1964). The extra retained CO₂ and water vapor cause higher pressures to develop inside coffee cells. Thus. the cells expand more, thereby providing lower bulk densities. The higher residual water content of fast-roasted coffee may also provide greater plasticity that facilitates greater expansion..

Green coffee solubles are partly destroyed or made insoluble during normal roasting (Schechter 2,000). Similar destruction occurs during fast roasting, but that loss is partly or sometimes slightly more than completely compensated for by the creation of more solubles (Fig. 6). Fast roasted coffees still contain roughly 4% water when bean temperature reaches 225°C (Geiger et al, 2005). At similarly high temperatures, the water activity of popcorn containing 4% water is 0.6 (Schwartzberg et al., 1994). If beans containing 4% water behave similarly at 225°C, the water vapor pressure inside their cells would be roughly 1.4 Mpa (14

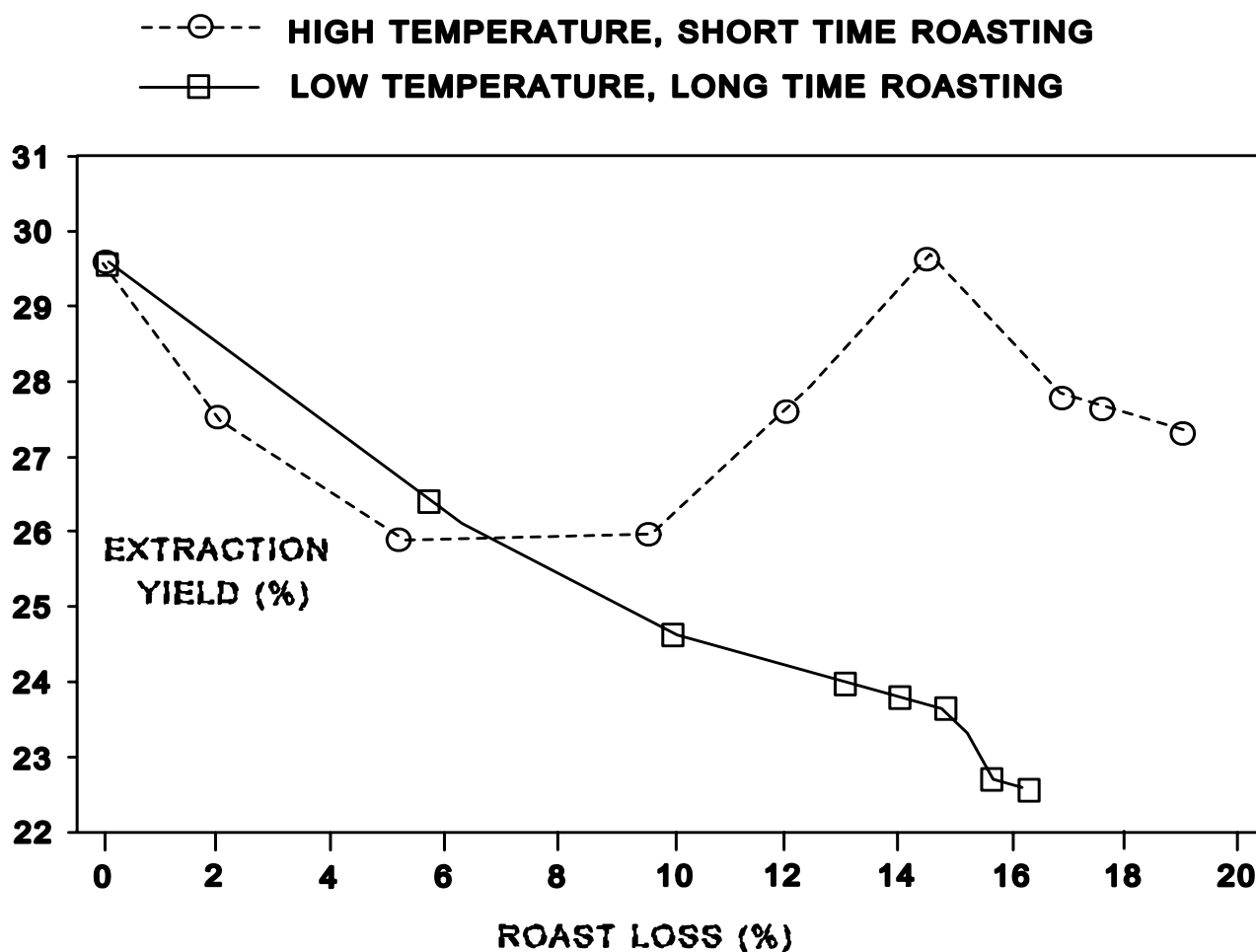


Figure 6 Extraction yield versus percent roasting loss for high-temperature, short-time roast and for low-temperature, long-time roast (Figure by Schecter 2000)

atm.). Thus, the created solubles might have been produced by hydrolysis of polysaccharides present in green coffee. Similar hydrolysis occurs in steam roasting of coffee and during high temperature extraction of coffee.

Low-density, high-yield roasting is now widely used by large-scale roasters. Therefore we now find 11.5 to 13 oz. of roasted ground coffee in 1,000 ml cans that used to hold 16 oz. Some manufacturers feel that ultra-fast roasts produce a dull, flat product and avoid roasting times shorter than four to six minutes (Schenker, 2000). Maier (1985) and Illy and Viani (1995) note that ultra-fast-roasted, high-yield espresso coffee contains more residual chlorogenic acid than conventionally roasted coffee and thus, when brewed, has an astringent sour taste. Custom and specialty roasters often avoid use of fast-roast, high-yield coffee.

Fluidized Bed Roasters

Several types of batch, fluidized-bed coffee roasters have been patented, e.g. Heimbs and Kangro (1953), Schytil (1954), Rios et al. (1980). Because of the large size of coffee beans, gas-induced fluidization of coffee beans normally is of the class D type. In class D fluidization, gas bubbles rise slowly through a bed which is otherwise relatively dense; and

bubble-induced bed mixing is poor. In class B fluidization, which occurs with much smaller particles, gas bubbles rise rapidly through the bed, more gas bypassing occurs, but bed mixing is good. Thus non-uniform roasting can occur when coffee is roasted in deep fluidized beds. Shallow beds, 6 to 50-mm deep in the unexpanded state, are used for fast roasting in continuous multi-jet roasters. The jets induce circulation due to local spouting. The Lurgi Aerotherm roaster, a roaster using a deep fluidized bed, was introduced in 1957, but is no longer marketed or used (Clarke and Macrae 1987). Numerous internet items show that swirling-bed popcorn poppers and other types of small, fluidized-bed roasters are used to roast coffee at home. Some small fluidized-bed roasters contain baffles that cause bean circulation, e.g. the small, fluidized-bed roaster described in a patent by Gell (1985).

Asymmetric-spouted-bed roasters (RFB roasters) provide good mixing and significantly higher E than conventional fluidized-bed roasters and are widely used for fast roasting and production of high yield coffee. The RZ, RT and System 90 roasters can also provide fast roasts and also are used often to produce low-density, high-yield coffee.

Continuous Roasters

Continuous roasters were first used commercially in the 1940's. Newer types of continuous roasters came into use in 1970's (Nutting et al. 1971, Bannar 1978) and 80's (Clarke and Macrae 1987). Continuous roasters can roast up to 5460 kg green coffee per hour. Many can provide roasting in as little as 60 seconds, and thus are suitable for producing high-yield coffee. Continuous roasters can also provide 8 minute roasts if desired. In batch roasters, bean temperatures change with time; in continuous roasters, bean temperatures change with axial position; and temperatures are more uniform from bean to bean as roasting progresses. In continuous roasters, beans are moved either by helical flights attached to a long, rotating, perforated, cylindrical shell, or by shafts in a rotating, impermeable, cylindrical shell (Probat Conti-Roaster) or by motion imparted by a vibrating impermeable plate (Wolverine Jet Zone Roaster). In continuous roasters where a perforated cylinder is used, hot gas passes through cylinder perforations both in entering and in leaving the cylinder. In some cases, the gas passes upward, fluidizing the beans (Brandtlein et al, 1988); in others, the gas flows diagonally downward (Burns continuous roaster). When an impermeable vibrating plate conveyor or an impermeable cylinder is used, hot gas flowing out of a multiplicity of tubular jets impacts on a moving bed of beans. Continuous roasters are used only by very large coffee roasting companies, and then only for producing standardized types of roasted coffee in very long runs. In the past thirty years, diverse types of roasts employing wide varieties of coffees and coffee blends and different degrees of roasting have come into use. These roasts are most effectively produced in batch roasters.

Spread of Custom and Specialty Roasters

Custom roasters and specialty roasters have proliferated in the past thirty years. Some, like Starbucks, have become very successful. Thus there are a great many more small and medium sized roasters today than there were thirty years ago. Some medium-size roasters cater mainly to the hotel and restaurant trade; others, e.g. Green Mountain Roasters, are regarded as gourmet roasters. Gourmet roasted coffee produced in small- and medium-size roasting plants is made from green beans from many different growing areas and is available in different kinds of roasts. Many of these roasts are markedly darker than used to be the norm

for the U.S. The impact of small- and medium-size gourmet roasters on the roasted-coffee market has prompted major roasters to offer more varieties of coffees or coffee blends and different degrees of roasts.

Pollution Control

The VOC and CO contained in stack gas that roasters discharge are environmental pollutants that nowadays usually have to be nearly completely destroyed. In most cases, VOC and CO destruction is accomplished in either direct or catalytic afterburners. In direct afterburners, roaster stack gas is heated to 760°C; and in catalytic afterburners to 482°C. To provide enough O₂ to burn VOC, the air:fuel ratios used for afterburner have to be greater than those used in roaster furnaces. Though catalytic afterburners use less energy, they are more costly; and the catalyst has to be replaced from time to time. Afterburners greatly increase energy costs for roasting and produce NOX. Energy costs for afterburning are far greater for single-pass roasters than for recirculating roasters. Felip (1999) claims that afterburning temperatures, energy use and NOX discharge can be reduced by placing the roaster blower before the cyclone and sending recycle gas taken from the cyclone rather than from the roaster furnace to the afterburner.

Roasters have been designed or retrofitted so as to remove VOC internally. In some Gothot roasters, roaster gas is heated to 700°C in the roaster's furnace, thereby greatly reducing the gas's VOC content (Clarke and Macrae, 1987). Part of the furnace gas then discharges directly through a stack; the rest is diluted with room temperature air to provide hot gas at a temperature suitable for roasting. In Praxis International's Mercury system, the recycled roaster gas splits into two streams. One stream enters the furnace, and mixes with products of combustion to provide 760°C gas, which remains in the furnace long enough to provide near complete destruction of VOC. The second stream then mixes with part of the gas flowing out of the furnace to provide hot gas at a temperature suitable for roasting. The rest of the furnace-outflow gas discharges to the atmosphere through a stack

Systems for recovering energy from hot gas discharged from afterburners and roaster systems have been developed. Rothfos (1986) describes some of these systems.. Most involve exchange of heat between after-burner-discharge gas and air flowing to the burner for the roaster. Farina (1994) obtains all the heat required for roasting in a single-pass roaster by transferring heat from afterburner gas to fresh air entering the roaster. Finken et al. (1998) heat warm air discharged from the roasted bean cooler with afterburner-discharge gas to supply burner air and thereby provide additional heat recovery. Exchange of heat between afterburner-discharge gas and roaster gas is more troublesome than heat exchange with incoming air because roaster gas contains tars that foul heat-exchangers.

Roasting Chemistry

Though engineers primarily analyze roasting as a heating process, it involves many chemical reactions and thus also is a complex, reaction process. Much has been learned about coffee roasting chemistry in the past fifty years, e.g. the percent disappearance of reactants in different roasts, the identity of a multitude of roasted coffee aroma compounds and how the concentrations of some these compounds vary with roasting time and roasting weight loss. Thus, 97%, 99% and 100% of coffee's sucrose, 41%, 56% and 85% of its chlorogenic

acid and 50%, 65% and 80% of its trigonelline contents respectively disappear in light, medium and dark roasts. Roughly 25% of coffee's polysaccharide content, 70% of its citric acid, 30% of its malic acid, virtually 100% of its free amino acid and much of its protein also disappear during roasts, particularly parts of protein containing arginine, cysteine, lysine and serine, and some parts containing histidine, methionine and threonine

Green coffee contains roughly 300 volatile compounds that are also present in roasted coffee. Roughly another 650 volatile compounds form during roasting. The combined 950 compounds include: 97 sulfur compounds derived from cysteine and methionine; 66 pyrroles and 11 pyridines derived mainly from trigonelline, 126 furans derived mainly from sucrose and polysaccharides; 70 pyrazines and 35 oxazol(in)es derived from amino acids by Maillard reactions, 48 phenols derived from chlorogenic acids, linalool and myrcen formed from terpenoids, 102 ketones and aldehydes largely produced by Strecker degradations, 31 esters, 25 acids and 20 alcohols.

There are also many non-volatile products, e.g.: caramels derived from sucrose and polysaccharides; brown, condensed, end-stage Maillard reaction products; nicotinic acid and its methyl ester derived from trigonelline; quinic acid and lactones and esters of quinic, caffeic and ferulic acid derived from chlorogenic acids; phenols, e.g. catechol, pyrogallol and hydroquinone derived from quinic acid and caffeic acid; glycolic acid and lactic acid.

Many of these compounds are produced via complex, multi-step reactions involving competitive parallel reactions as well as series reactions, e.g. Maillard reactions, caramelizations, and the breakdowns of trigonelline and chlorogenic acid. Thus the reactions are difficult to wholly characterize from a kinetic point of view. Aside from kinetic data derived from studies on model systems, the most we can do now is characterize kinetics in terms of changes in end-product concentration with time at different T_b . Fig. 7 by Gianturco (1967) shows how the chromatographically measured concentration of some volatile roasting products change with time during roasting. Concentrations of some products e.g. acetic acid, furfural, furfuryl alcohol, peak then decline, with the peak coming either before, at, or after the normal end of a conventional commercial roast (roughly 10.5 minutes). Concentrations that peak and decline indicate the presence of reactions that cause product breakdown. The concentrations of other products, e.g. phenol, pyridine, continue to rise well after the normal end of roasting. These products may also break down, but, if so, the cumulative extent of product breakdown has not yet exceeded the extent of product formation.

Schechter (2000) carried out fluidized-bed coffee roasts, some of which provides constant T_b over most of the roast. Product concentration versus time data for these roasts can be used to characterize the kinetics for some roasting reactions. Thus it may be possible to obtain effective activation energies and prefactors for Arrhenius equations characterizing some reactions. Most product concentration versus time curves for Schechter's isothermal roasts were initially concave upward. It can be shown that these curves must be due to product formation through a series of reactions. Schechter's data (2000, 2002a, 2002b) shows that, even when roasts provide the same roast color, some products appear in greater

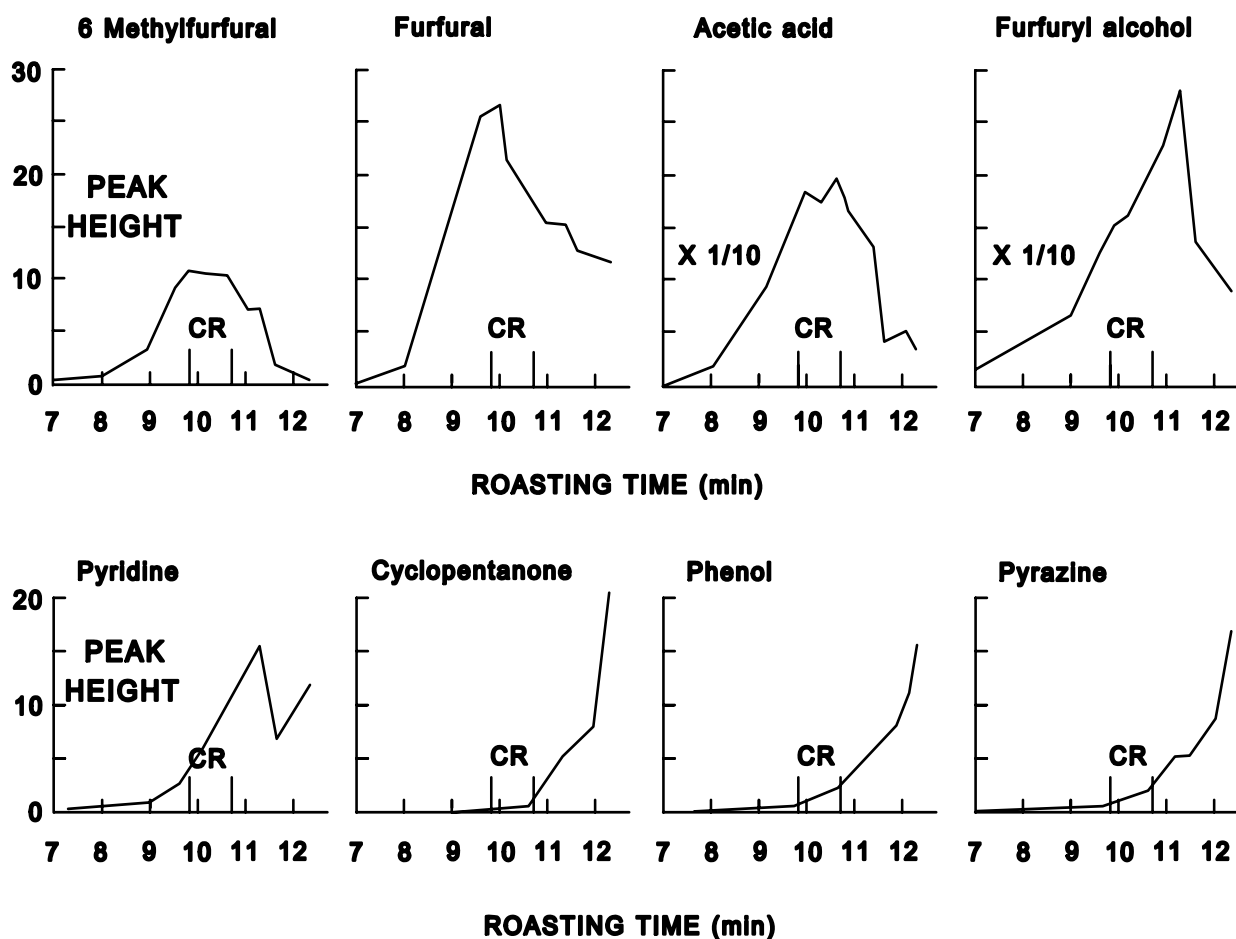


Figure 7 Chromatographically measured concentrations versus roasting time for some volatile compounds found in roasted coffee (Figure by Gianturco 1967).. CR is the roasting time for a normal conventional roast.

concentration in fast roasts and others appear in greater concentration in slow roasts. It is instructive to compare reaction product yields for a fast and a slow roast with similar bean temperature profiles (T_b versus t records), the temperature profile for the fast roast being a temporally shrunken version of the profile for the slow roast. It can be shown that if a product's concentration still is rising at the end of the slow roast, its concentration will always be lower for the fast roast. Further, if a product's concentration peaks and then declines during a slow roast, that product usually (but not always) will be obtained in greater yield during a fast roast. Thus consumers with sufficiently sensitive tastes are likely to be able to taste differences between fast-roasted, high-yield coffee and conventionally roasted coffee.

New Roasting Control Methods

Schechter et al. (2002a, 2002b) also showed that product compositions differed markedly when the same type of coffee beans were roasted to same roast color by means of roasts employing a variety of different bean temperature profiles. This shows that roast color is a far from adequate indicator of roasted coffee composition. It also again illustrates the principle that outcome of incomplete reactions depends on their temperature versus time history.

Well before Schechter even began his research, it had become clear to a number of operators of coffee roasting plants and to suppliers of roasting control equipment that bean temperature profiles for a given type of green beans should be controlled so as to be the same roast after roast in order to obtain the same roast quality roast after roast. Further, the bean temperature profiles used should be tailored for the type of blend of coffee beans involved.

Lee (1999) describes roaster control systems supplies be various companies..Some provide controllers that terminate a roast when a desired T_{bm} is reached. Other companies provide controls based on measurement of whole bean color. Allington et al. (2000) describe how color measurement can be carried out on-line. Neuhaus Neotec provides several different types of controllers including one that programs how T_{gi} and G will vary during a roast. Praxis International, Neuhaus Neotec, Ambex and a number of other companies provide systems that control bean temperature profiles. One can determine which process variables can be used to control bean temperature profiles by examining Eq (3), a simplified version of an equation by Schwartzberg (2002),

$$dT_b/dt = [GC_g(T_{gi} - T_b)E + R_d(Q_R + \lambda dX/dt)]/[R_d(1 + X)C_b] \quad (4)$$

R_d is the dry mass of beans, Q_R is the rate of exothermic heat generation per unit mass of beans, X is the dry basis moisture content of beans and λ is the latent heat of evaporation of water from beans. Schwartzberg (2002) provides equations providing: Q_R as a function of T_b and the cumulative previous extent of exothermic heat generation; C_B as a function of X and T_b ; and dx/DT as a function of T_b , X and bean size.

In most profile-control systems T_{gi} is indirectly adjusted by varying Q_F , the heat output rate of the roaster furnace or burners. In Praxis International's Logofile system, G is adjusted. Changes in G tend to change T_{gi} . Therefore, the Praxis system usually automatically maintains T_{gi} constant by T_{gi} - based feedback control of Q_F . The Logofile system can also provide programmed adjustment of the T_{gi} set point if T_b approaches T_{gi} closely enough to cause dT_b/dt to become relatively insensitive to changes in G . Regardless of whether Q_F or G adjustment is used, the object of adjustment is to make T_{bm} conform to or to home-in on a T_{bm} set point or a series of T_{bm} set points. Most profile control systems rely on feedback control employing a limited number of T_{bm} set points, e.g. 3, and adjust the gain, differential and integral response of the controller so that homing in on the successive T_{bm} set points provides a T_{bm} versus t profile that conforms to the desired profile as well as possible. In some cases, such adjustment causes a marked shift in the control profile itself, e.g. as in graphs 1, 2 and 3 in an article by Davis and Ribich (2005). Praxis International's Logofile controller relies on the T_{bm} versus t records of control roasts that have produced desired products. A programmable logic controller (PLC) then changes the T_{bm} set point every second so as to provide a T_{bm} versus t profile that closely conforms to the profile for the selected control roast.

Roasters are preheated before a load of beans is added to start a roast. Thus, at the start of a roast, the thermocouple probe that measures T_{bm} contacts hot roaster gas rather than beans; T_{bm} is much higher than the true, average bean temperature, T_b . As t increases, T_{bm} first decreases, then passes through a minimum, where $T_{bm} = T_b$, and then increases. Because of preheating and thermometric lag T_{bm} may be more than 200°C higher than T_b at

the start of a roast; and because of thermometric lag, T_{bm} is usually 10°C to 20°C lower than T_b near the end of roasts. T_{bm} versus t profiles must be converted into T_b versus t profiles in order to specify needed G versus t and T_{gi} versus t behavior and to provide bases for predicting the kinetic consequences of choices of T_{bm} -based profiles. If the bean temperature probe is immersed in a dense stream of beans, T_b versus t behavior can be determined from T_{bm} versus t profiles with aid of Eq (5)

$$T_b = T_{bm} + (1/K)(dT_{bm}/dt) \quad (5)$$

K , the thermometric lag coefficient, = $U_t A_t / (M_t C_t)$ where U_t , A_t , M_t and C_t respectively are the effective bean to probe heat-transfer coefficient and the thermal contact area, the mass and heat capacity of the thermometric probe. Eq (5) works well except during and immediately after beans loading.

Conclusions

In the past fifty years, advances in roasting equipment and control methods have permitted roaster operators to roast faster and more effectively. Fast roasting decreases roasted bean densities, increases extraction yields from roasted beans and changes the results of roasting chemistry. Improved knowledge about heat-transfer during roasting and roasting kinetics and improved methods for monitoring and controlling T_b versus t behavior soon should permit roaster operators to provide some measure of predictive control of roasting conditions and some degree of control over roasting reactions.

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