

Batch coffee roasting; roasting energy use; reducing that use

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ABSTRACT

This paper deals with: a) batch roasting of coffee beans, b) energy use for such roasting, and c) means for reducing such use. Overall heat and material balances are used to analyze: roaster energy consumption for batch, gas-fired roasters with afterburners; and the feasibility of methods for reducing such consumption.

Coffee Roasting; Afterburning; Flame Temperature; Volatile Organic Compounds; Stack gas heat recovery

INTRODUCTION

6.7 billion kg of coffee beans are roasted worldwide annually, mostly in batch roasters. Near the end of roasts, roasting coffee emits volatile organic compounds (VOC) and CO, which in many industrialized countries have to be oxidized in afterburners. Roasting and afterburning uses roughly 11.2×10^{12} kJ fuel energy/year and causes emission of roughly 7.0×10^8 kg CO₂/year. This paper aims to help readers understand coffee roasting with afterburning and factors determining energy use for such roasting, and presents and evaluates ways to reduce such use.

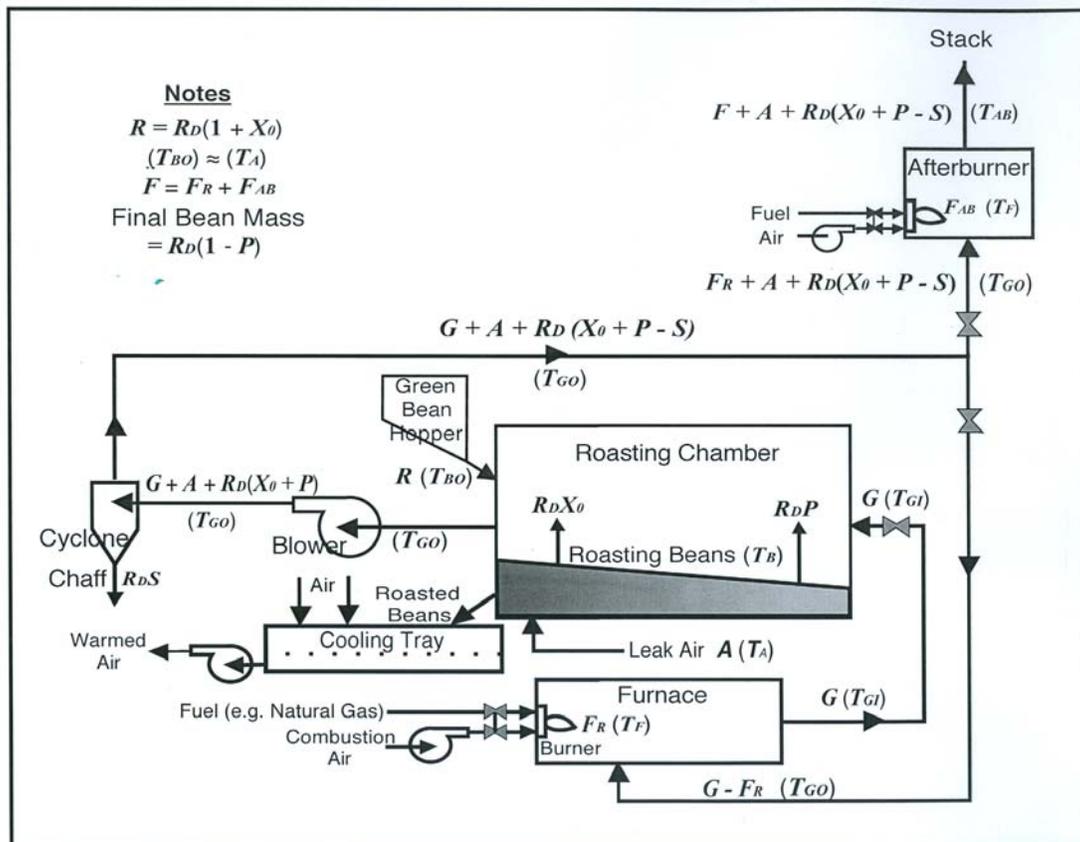


Figure 1 Components, flow layout and stream masses and temperatures for a gas-fired batch coffee roaster where roaster gas recirculates and which is equipped with an afterburner.

Fig. 1 depicts basic components and stream mass flows and temperatures for a gas-fired batch roaster with afterburner. Stream temperatures, e.g. T_{GI} , the temperature of gas entering the roasting chamber, (chamber for short) are enclosed in parentheses in Fig.1, but not in the text of this paper. Most temperatures vary during roasting, e.g. bean temperature, T_B , and T_{GO} , the temperature of gas leaving the roasting chamber, increase progressively. Other stream temperatures may remain constant, e.g. T_{AB} , the temperature at which afterburning occurs, preferably should be automatically kept constant. Mean-effective stream temperatures will sometimes be used later in enthalpy balances. The mass flows, shown in italics, are the total mass of a stream that enters or leaves a roaster component during a roast. Stream flow rates vary during roasts, but total stream masses will be used later for mass and enthalpy balances. The term “gas”, by itself, will be taken to mean air partly depleted in oxygen and containing CO_2 and H_2O produced by combustion of fuel gas (e.g. natural gas) plus H_2O , CO_2 , VOC and CO emitted by roasting coffee. Mass ($G - F_R$) of gas is heated from T_{GO} to T_{GI} by mixing it in the furnace with mass F_R of burner gas (whose temperature is T_F). The blower draws the mixture into the chamber, where it contacts and transfers heat to the batch of coffee beans.

Chamber Gas-Inlet Temperature:

T_{GI} usually ranges from 235°C to 535°C, but T_{GI} as low as 220°C [1] and as high as 650°C [2] have been used. Prolonged use of $T_{GI} > 535^\circ\text{C}$ tends to cause bean tips and edges to burn. The heat capacity of burner gas and roaster gas are roughly equal. Therefore, based on an enthalpy balance around the furnace:

$$T_{GI} = T_{GO} + \frac{F'_R}{G'}(T_F - T_{GO}) \quad (1)$$

F'_R is the burner-gas mass-inflow rate in the furnace and G' the mass flow rate of gas into the chamber. In some roasters, F'_R undergoes one of two step- decreases at late stages of roasting, but remains constant, albeit at a different level, before and after a step. If so, T_{GI} progressively increases while F'_R remains constant (because G' decreases progressively as roasting proceeds), but decreases a step each time F'_R decreases. In other more-modern roasters, F'_R is automatically adjusted so as to keep T_{GI} constant, or to control how T_{GI} varies during a roast. T_F is determined by the combustion-air/fuel-gas ratio used. Since that ratio is automatically kept constant, T_F remains constant.

Green Bean Load:

The total weight of a batch of green coffee bean is R . Its initial temperature is T_{BO} . Its dry weight is R_D ; and the weight of bean moisture is $R_D X_0$. About 75% of beans used in commerce are of Arabica varieties (e.g. Columbians, Santos, Costa Ricans, Kenyans, etc.) and about 25% are of Robusta varieties (e.g. beans from Viet-Nam, Uganda, Ivory Coast). Robustas are of lower quality, but are less costly. With minor exceptions, beans are roughly hemi-ellipsoidal and have a groove on their flatter surface. Green bean lots are graded in size to prevent uneven roasting. Arabica beans in the large-size range are roughly 10.3 mm long, 7.3 mm wide and 4 mm high. In the smallest commercial-size range, Arabica bean dimensions are roughly three quarters as large. Length/width ratios for Robustas are smaller than for Arabicas. 120 kg green beans, a typical load for a medium-size batch roaster, contains roughly 700,000 large beans, or, if the smallest commercial size is used, roughly 1,570,000 beans. Batches for very large roasters are four times as large.

Roasting Induced Changes:

Chamber elements or pneumatic transport continually mix freshly heated beans with the rest of the batch, thereby improving bean-to-bean uniformity of heating. As bean temperature, T_B , rises; moisture vaporizes within beans and diffuses out of them, but not fast enough to prevent steam pressure build up inside the cells in beans. The beans soften; and the internal steam pressure causes them to expand [3]. As the beans expand, they release parchment (chaff) previously covering beans or trapped in the groove in beans. $R_D S$ indicates the mass of chaff released. Moisture loss ultimately causes beans to harden [3], setting the expansion.

Thermally stimulated roasting reactions inside bean cells and in their walls produce over eight-hundred identified reaction products and a wide variety of intermediate compounds. A small fraction of the products have very desirable flavors and aromas prized by consumers in roasted coffee. Pigmented reaction products cause bean color, originally light green or tan, to turn brown and progressively darken [4,5]. The reactions also cause beans to lose dry matter in the form of reaction-generated water vapor, CO_2 , [3,5,6] CO [6,7] and volatile organic compounds (VOC) [6,8]. $R_D P$ indicates the total mass of dry matter mass lost, including chaff. Virtually all of the bean's initial moisture content probably evaporates by the time the beans reach their end-of-roast temperature, T_{BF} . If so, the moisture in roasted beans consists of reaction-formed water that has not yet evaporated plus absorbed quench water; and the mass of beans at the end of the roast, but prior to quenching, = $R_D(1 - P)$. Static pressures are kept negative in most roasting chambers to prevent escape of

gas, vapor and smoke. Therefore fresh air leaks into the chamber. A indicates the total mass of fresh air that leaks into the chamber during a roast.

Gas Temperature Changes:

Since the gas transfers heat to beans, it leaves the chamber at temperature T_{GO} , which is substantially lower than inlet temperature, T_{GI} . The leaving gas contains in-leaked air, entrained chaff, evaporated bean moisture and gas and vapor produced by dry matter breakdown. Thus, its total mass = $G + A + R_D(X_0 + P)$, while the total entering mass = G . The leaving gas then passes through the blower and the cyclone, which removes entrained chaff, i.e. mass R_{DS} . Then the gas splits into two streams: a larger one, which passes through the furnace and recycles to the chamber; and a smaller one, which passes through the afterburner.

VOC Oxidation - Afterburners:

In the afterburner, the gas is heated to T_{AB} by admixing a second stream of burner gas (mass F_{AB} at temperature T_F). If T_{AB} is high enough and gas-residence time in the afterburner is adequately long, enough VOC will oxidize to yield stack gas containing less than 50 ppm VOC, i.e. a VOC level that satisfies German regulations. VOC are also partially destroyed when roaster gas passes through the roaster furnace. Therefore, even without afterburning, stack VOC levels can be as low as 300 ppm when all chamber-discharge gas passes through the furnace [9]. When all chamber-discharge gas does not pass through the furnace and afterburning is not used, VOC levels in stack gas typically are roughly 1,650 ppm [9] and increase markedly as T_{BF} increases [6]. Catalytic afterburners for coffee roasters require $T_{AB} \geq 400^\circ\text{C}$ and 0.05 s to 0.1 s of gas residence time. The catalyst has to be replaced every three or four years, and should be used with a pre-filter to prevent particulate matter from blinding it. A supplementary blower is often required to overcome pressure drop across the catalyst bed and pre-filter. Thermal afterburners are cheaper, but require $T_{AB} \geq 760^\circ\text{C}$ and 0.4 s of gas residence time when used for coffee roasters. VOC levels in feeds for thermal and catalytic afterburner should be less than 25% of their lower explosive limit (L.E.L.). L.E.L typically range from around 10,000 to 30,000 ppm. Peak VOC levels as high as 10,000 ppm [10], i.e. potentially explosive levels, have been reported (very likely for the end of a very dark roast). Regenerative thermal oxidizers (RTO) use regenerative heat exchange to heat afterburner feeds from T_{GO} to appropriate T_{AB} and then cool discharged gas almost to T_{GO} . Thus they require little or no heat input after start-up [11]. RTO should only be used for feed VOC levels less than 10% of their L.E.L. RTO also require frequent switching of flow direction through the regenerator bed or beds and, at present, rarely are used for coffee roasters.

NO_x and CO:

Nitrogen oxides (NO_x) are generated in roaster furnace burners and in the burners used for VOC oxidizers. The higher the burner temperature the greater the NO_x level. Thus afterburning reduces VOC levels, but produces NO_x. NO_x emission levels for coffee roasters are higher for darker roasts [11], i.e. roasts where large amounts of VOC are produced. NO_x levels can be reduced roughly 50% by use of low NO_x burners, i.e. burners where combustion products recycle into the combustion zone. Because little heat production is needed to operate RTO, less NO_x would be emitted if they were used [11]. EU regulations limit NO_x emission to 100 mg/N m³. New catalyst formulations can reduce NO_x levels to 50 ppm ($\approx 52 \text{ mg/N m}^3$).

Many intermediates, including CO are produced as VOC oxidize. EU regulations limit CO emission levels to 100 mg/N m³. CO is emitted by roasting beans; and even more CO can be produced by improperly adjusted burners, partial oxidation of VOC in roaster furnaces or by incomplete oxidation of VOC in afterburners, e.g. due to: loss of catalyst activity, insufficient residence time, channelling, or T_{AB} being too low.

Gas Input and Output:

Gas mass holdup variation in the roaster system is negligible. Therefore the total gas mass leaving the system via the stack equals the sum of the total mass of entering gas and the total mass of gas and vapor emitted by beans, i.e. = $F + A + R_D(X_0 + P - S)$, where $F = F_R + F_{AB}$. Similar mass balances apply for gas stream masses at intermediate points along the gas-flow path.

R Roasters:

The flow layout in Fig. 1 is for an R roaster, i.e. a roaster where most gas leaving the chamber recycles to the chamber. R roasters usually are used for roasting large and medium sized batches, i.e. batches > 60 kg. In many older R roasters, chamber-discharge gas heats to T_{GI} in the furnace before splitting into a recycle stream and afterburner feed, which is not heated further when $T_{GI} > T_{AB}$. Catalytic afterburners usually are used with R roasters [11]. Component sequences for some R roasters may differ from the sequence shown in Fig. 1 [12]; e.g. the cyclone may come before the blower; or an added blower or blowers may be used to

overcome high local pressure drops. In Neohaus Neotec RFB roasters, high-speed gas flow causes spouting-induced bean circulation in the chamber [12]; a blower located just before the chamber provides the needed gas pressure; and static pressures are positive in the chamber, which is well sealed. Then $A = 0$. Air leakage is further minimized by having furnace-discharge gas bypass the chamber during the loading and unloading of beans. A is positive for roughly 90% of roasters.

SP Roasters:

In single-pass (SP) roasters gas passes through the roaster only once. SP roasters usually are used for small batch roasts, where $R < 60$ kg and sometimes is as small as 2.5 kg. In many SP roasters, fresh air, drawn in by the blower, mixes with flames from a set of lance burners. Then the mixed gas flows through the roasting chamber, blower, cyclone and afterburner. Towards the end of a roast, first one burner and then another is turned off, thereby reducing F'_R and T_{GI} in steps. Other SP roasters are equipped with a furnace with a single continuously adjustable burner, where F'_R can be smoothly changed. The furnace output gas flows directly through the roasting chamber, blower, cyclone and afterburner. Thermal afterburners usually are used for small roasters [11].

Ending Roasts – Bean Cooling:

The outcome of coffee roasting reactions depends on initial reactant concentrations, which, in turn, depends on bean variety and source; and on how T_B varies with time, t , i.e. the “ T_B profile”. In industrial roasters, bean temperatures are measured with sturdy sheathed probes, which provide measured temperatures, i.e. T_{BM} , instead of T_B [13]. Often, roasts are ended when T_{BM} reaches a set value that corresponds to T_{BF} . Coffee flavor and aroma development will be inadequate if T_{BF} is less than 190°C. In most R roasters, a controlled volume of quench water is sprayed on the beans when the end-of-roast T_{BM} is reached. Most of the water evaporates, thereby cooling the beans rapidly and stopping the roast. In most cases, the beans then discharge into the cooling tray. There, the beans form a 0.075- to 0.1-m. deep bed, which is stirred and through which room-temperature air is drawn, further cooling the beans. Often, beans at the air-outflow side of the cooler bed still remain quite hot when those at the inflow side already are cool. Strongly agitated air-based coolers that provide good bean mixing and more uniform bean cooling are used with some R roasters. In some of these coolers, beans are quenched while being air cooled, thereby increasing the time available for roasting. Air cooling alone, without quenching, usually is used for small roasters. Beans continue to emit VOC during early stages of air-cooling. Thus, air that has been used to cool beans sometimes has to be subjected to afterburning, which can use large amounts of energy.

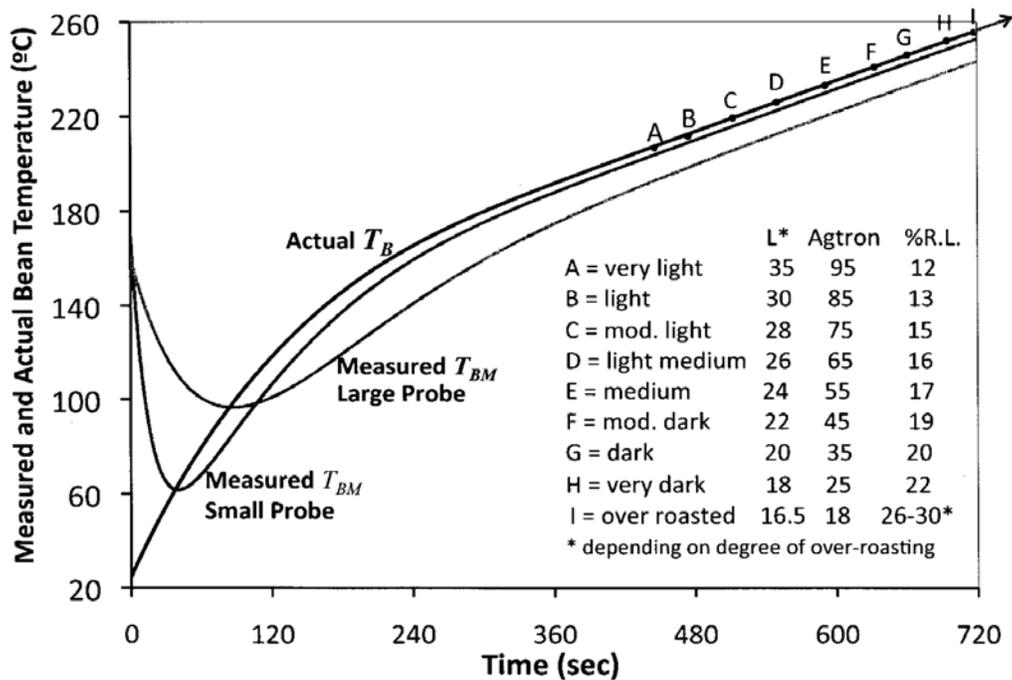


Figure 2 Actual and measured bean temperature profiles for a regular roast and degrees of roast darkness and total roasting loss for different T_{BF} . Agtron and C.I.E. L^* reflectance-based roast colors for those T_{BF} .

Thermometric Lag:

Fig. 2 shows corresponding T_B and two T_{BM} profiles obtained with probes of different diameter during a “regular” roast where the possible roast time, t_R , ranged from 480 to 720 s. Roast times for “regular” roasts can range up to 900 s, or even to 1,200 s for some roasters. Roasting beans closely surrounded the probes, thereby preventing hot gas flow from directly affecting T_{BM} . When probes are heated by hot gas as well as by beans, T_{BM} may always lie above T_B [13]. T_{BM} are initially much higher than T_B because roasting chambers and probes are preheated before bean loading begins. Immediately after beans are added, T_{BM} falls towards T_B , which is rising. Then, for properly positioned probes, T_{BM} falls below T_B , but starts rising, and thereafter always stays below T_B . Thermometric lag increases with probe size. Therefore, after T_{BM} starts rising, it lies farther below T_B for larger diameter probes than for the smaller ones [13]. $(T_B - T_{BM})$ tends to be proportional to dT_B/dt [13] and, as just noted, is larger for large probes than small ones. Therefore it is difficult to correctly compare T_{BM} profiles and T_{BF} from one roaster with those from another, particularly roasters of different design, or with different probe arrangements, and to correctly compare T_{BF} for fast and slow industrial roasts. Researchers at ETH Zurich [3,5,14] obtained highly useful T_B data for fluidized bed roasts by implanting very fine thermocouples in coffee beans. Researchers at the Univ. of Hamburg-Harburg [15] found large T_B gradients within beans when dT_B/dt was large. Schwartzberg [13] developed methods for calculating T_B profiles and T_{BF} from properly measured T_{BM} profiles and also showed that for individual roasters control of properly measured T_{BM} profiles would also control T_B profiles. T_{BM} profiles often are roughly adjusted at late stages of roasting by one or two step reductions in F'_R (and hence step decreases in T_{GI}) or by step decreases in the chamber-inlet gas-flow rate, G' . Advanced control systems, first developed by Eichner in the mid 1990s, now continuously regulate T_{GI} and G' for some roasters, and use T_{BM} -based feedback control to consistently provide T_{BM} profiles that conform to “learned” profiles that yielded desirable roasted coffee.

Roast Color and Total Roasting Loss:

Points A through I on curve T_B in fig. 2 indicate a series of increasing T_{BF} and corresponding increasing degrees of roast darkness. The darkness descriptors, Agtron roast colors and total-roasting-loss values listed in the inset are data by Mondry [4]. The T_{BF} for points A through I were obtained by roughly correcting Mondry's T_{BM} values for thermometric lag. A indicates a very light roast, E a medium roast, H a very dark roast and I over-roasting, i.e. nearly black beans. Agtron colors are instrumentally measured and based on reflectance of narrow-spectrum near I-R light from ground roasted beans [4], and are used by specialty roasters to characterize degree of roast. Other near I-R based roast-color meters are used in industry [4]. C.I.E. L^* roast colors are based on reflectance of broad-spectrum visible light, and have been used in academic research on roasting [3,5,14]. The listed L^* values are rough estimates based on measured L^* values [5] for coffee bought from Swiss retailers. Hunter L roast colors are also based on reflectance of broad-spectrum visible light, are used by Folgers, the largest U.S. roaster of coffee, and are often listed in process descriptions in patents obtained by that company. In the end-of-roast color range, L values are roughly 74% as great as L^* values. Bean darkness increases, roast color decreases and coffee flavor character progressively changes as t_R and T_{BF} increase. Very darkly roasted beans also tend to be oilier or become oily after roasting [3], and do not store as well as lighter roasted beans.

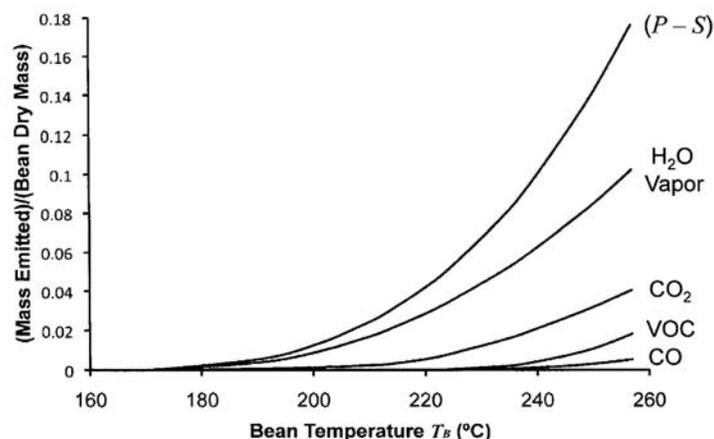


Figure 3 Cumulative mass loss of gas and vapor products emitted from beans due dry matter breakdown versus T_B . The total cumulative mass of all such products is $(P - S)$.

Dry-Matter-Based Emissions:

Fig. 3 shows how: $(P - S)$, the total cumulative mass of emitted gas and vapor products of dry matter breakdown, and the cumulative masses of emitted individual breakdown product components, i.e. reaction-formed H_2O vapor, CO_2 , CO and VOC, increase as T_B increases. Total roasting loss increases as X_0 and chaff loss increases. Therefore, $(P - S)$ values were estimated by subtracting an estimated initial as-is bean moisture content of 0.1 and an estimated as-is chaff loss of 0.01 from Mondry's as-is total-roasting-loss values for points A through I. Irregularities in the calculated $(P - S)$ versus T_B curve were smoothed in drawing the $(P - S)$ curve in Fig. 3. Total roasting losses are up to 1.2% greater for Robusta beans and up to 0.3% greater for Santos beans than for Columbian beans [6]. Data from Geiger [3] (used to help plot the CO_2 and reaction H_2O curves) showed that: a) the main dry matter breakdown products are water vapor (roughly 70% initially), then CO_2 , with the CO_2/H_2O ratio increasing with degree of roast; b) reaction-water emission can start at $T_B \approx 160^\circ C$; c) CO_2 emission starts around $190^\circ C$; and d) both emission rates increase very rapidly thereafter as T_B rises. The CO curve was qualitatively based on: data from Valdovinos-Tijerino [7], which showed CO emission starting when $T_B \approx 220^\circ C$, then rising quite rapidly to very high levels when $T_B = 240^\circ C$; and data from Jansen [6] indicating cumulative CO emission for Columbian beans = $0.001R$ for a medium roast. For Robustas, the corresponding CO loss is $0.0022R$ [6].

VOC-Emission Curve:

The VOC curve is qualitatively based on mass spectrometric data from Dorfner [8] showing VOC-emission rates during a light-medium roast (i.e. like point D in Fig 2) in a 250 kg capacity roaster where convective heating of beans predominated, and on a VOC loss of $0.0034R$ for medium-roast Columbian beans from Jansen [6]. Robustas emit more VOC, e.g. $0.004R$ for a medium roast [6]. In the cited test by Dorfner, VOC emission was small during roughly the first 80% of the roast, and rose rapidly thereafter. The roast time, t_R was 613 s; and the total as-is roast loss 16.3%, which roughly corresponds to $(P - S) = 0.059$ if $X_0 = 0.111$ and $S = 0.011$. However, VOC were emitted 200 to 300 s into a 900 s roast in a conductively heated 0.1 kg sample roaster [8]. VOC were also emitted early when Dutra et al. [16] conductively roasted beans. Very likely, bean hot spots occur when conductive heating is used. Emission also started around 200 s to 300 s in a 1000 s roast in a 15 kg capacity SP roaster that was strongly preheated (T_{BM} initially = $236^\circ C$) [8]. It appears that conductive heating, local hot spots in beans and a high degree of preheating favor early VOC emission. Dutra et al. [16] found that VOC were acidic and that their acidity tended to increase almost until the very end of their test roast. Jansen [6] noted that acetic acid is a major VOC constituent.

Aroma and Flavor Development:

Baggenstoss [14], Schenker [5], and Gianturco [17], each using different means, measured how in-bean concentrations of different important aroma and flavor compounds varied during roasting. For most of these compounds, these variations followed one of three patterns. In two of these patterns, concentrations rose, peaked and then declined. In one of these two patterns, the peaks occurred at light to medium roast colors, e.g. between points B and E for the Fig. 2 T_B profile. In the other of these two, the peaks occurred at darker colors, e.g. between E and G. The declines in aroma concentrations within beans probably are caused by a combination of: 1) loss of aroma as VOC, 2) formation of complexes between aroma compounds and melanoidins (the dark-colored matter in roasted beans), and 3) reactive destruction of aromas. Concentrations of compounds following the third pattern rose progressively without declining as bean color became very dark, e.g. beyond point G. in Fig. 2. Compounds following the first two patterns impart important coffee flavor and aroma attributes valued by those who prefer light or medium roasts. Among compounds that follow the third pattern, e.g. 2-furfurylthiol, pyridine, cyclopentanone, guaiacol, phenol, and various pyrroles, [5,14] are some that impart the burnt, bitter and roasty notes favored by those that prefer dark roasted coffee.

Roasted coffee's character depends more on the T_B profile used for roasting than on roast color. Schenker [5] and Baggenstoss [14] used different T_B profiles (measured with fine thermocouples implanted in beans) to roast identical green coffees to the same roast color. The aroma concentration profiles for the roasted coffees differed when the T_B profile differed, even though their L^* roast colors were the same. For fluidized bed roasts with the same roast color: $T_{BF} = 245^\circ C$ when $t_R = 180$ s, $230^\circ C$ when $t_R = 300$ s, and $212^\circ C$ when $t_R = 720$ s [3,5], i.e. faster roasts require higher T_{BF} . For roasts with roughly equal t_R , higher T_{BF} (by roughly $5^\circ C$) provided the same roast color when T_B initially rose slowly than when T_B initially rose very rapidly [3].

Heat transfer in roasting chambers:

A prime symbol (') added to stream symbols indicates stream mass flow rates or rates of change with time. Thus G' indicates the gas mass flow rate entering the chamber, F'_R , the rate of furnace-burner gas output, and

$R_D X'$ and $R_D P'$ the respective mass rates of moisture evaporation and dry-matter loss from beans. In roasting chambers, beans either fall across, or are thrown across, or entrain in flowing hot gas, and/or encounter hot gas flowing through interstices in beds of beans. The gas transfers heat to part of the beans. Mixing exposes other beans to hot gas contact, causes recently heated beans to transfer heat to beans that have been heated less recently or less strongly and keeps bean-to-bean T_B variation small. Eq. 1 describes bean heating [18].

$$R_D C_B \frac{dT_B}{dt} = EG' C_G (T_{GI} - T_B) + R_D H_{EV} X' + R_D Q'_{REAC} - MC_M \frac{dT_M}{dt} - Q'_{LOSS} \quad (2)$$

C_G is the gas heat capacity. X' is the rate of change of bean dry-basis moisture content. C_B is the beans' dry-basis heat capacity. At bean moisture contents, H_{EV} , the latent heat of evaporation of moisture from beans, ≈ 2760 kJ/kg because latent heats of evaporative desorption then are about 1.2 times water's normal heat of vaporization. Q'_{LOSS} , the rate of loss of heat from the chamber, is small for well-designed roasters, and will usually be neglected hereafter. $E \equiv \Delta T_G / (T_{GI} - T_B)$ is the heat-transfer efficiency, where ΔT_G is the heat-transfer-induced gas-temperature drop in the roasting chamber. $T_{GO} < (T_{GI} - \Delta T_G)$ because of roaster-gas dilution by cool leak air and emissions from beans. E is a function of $(UA_{BE}/G'C_G)$ and f_c , the fraction of gas that actually contacts and transfers heat to beans while passing through the chamber. U is the gas-bean heat-transfer coefficient and A_{BE} the bean surface heat-transfer area, i.e. the part of the bean-load's surface area actively contacted by hot gas. If gas flow is plug-like in the chamber, but some gas flow bypasses the beans:

$$E = f_c \left[1 - \exp\left(-\frac{UA_{BE}}{f_c G'C_G}\right) \right] \quad (3)$$

If complete back-mixing of gas occurs:

$$E = \frac{(UA_{BE})/(G'C_G)}{1 + (UA_{BE})/(G'C_G)} \quad (4)$$

When bean velocities relative to surrounding gas are determined mainly by the gas-flow rate, U increases as $(f_c G')$ increases, but in a less than linear fashion. When bean velocities relative to surrounding gas are determined mainly by mechanically-, centrifugally- or gravitationally-imparted bean motion, U is not greatly affected by $(f_c G')$. In either case, E decreases as G' increases.

Exothermic Heating:

Q'_{REAC} is the rate of heat generation by roasting reactions. DSC measurements carried out at conditions where bean moisture evaporation was suppressed show roasting starts becoming exothermic at T_B around 135°C and is markedly exothermic when $T_B = 190^\circ\text{C}$ [19,20]. In these tests, water evaporation was suppressed to eliminate cooling due to evaporation of original bean moisture, but that created a reaction environment with an unnaturally high water concentration [21], and also prevented evaporation of the most abundant reaction product, water, and the cooling that normally would have been produced by such evaporation. Exothermic heating was evident only at high T_B in DSC measurements made when evaporation was not suppressed [7,15]. T_B profiles for both industrial and experimental roasting usually do not appear to be noticeably affected by exothermic heating [3,5]. Therefore Q'_{REAC} appears to be negligibly small. **However**, one should keep in mind that dangerous T_B increases due to exothermic heating may occur when a process interruption or operator misstep causes fully roasted or nearly fully roasted beans to lie in a pile without agitation. Roasters should be operated and controlled so as to prevent build-up of stagnant piles of hot roasted beans. Means should be provided for automatically and safely quenching and unloading beans if a stagnant pile of beans forms near the end of roasting and T_B is likely to increase dangerously.

Heat Transfer to Chamber Parts:

M , C_M and T_M respectively are the mass, heat capacity and temperature of roaster chamber parts heated by the hot gas or beans. Heat transfers from preheated roaster hardware to beans at the start of roasts, and some heat conductively or radiantly transfers to beans from chamber walls in roasters whose walls are externally heated. Near the end of roasts, beans may transfer heat to roaster hardware. The net effect of $MC_M dT_M/dt$ on dT_B/dt is small when convective transfer of heat from gas to beans is predominant, as it is in most large modern roasters. Hardware-to-bean heat transfer and $MC_M (dT_M/dt)$ will be neglected hereafter.

T_B Profile Shape:

The main factors affecting dT_B/dt are G' , E , $(T_{GI} - T_B)$ and X' . dT_B/dt progressively decreases as roasting proceeds because $(T_{GI} - T_B)$ progressively decreases as T_B rises. dT_B/dt decreases to a greater extent for roasts where T_{GI} is small than for roasts where T_{GI} is large. T_{GI} was 455°C for the roast whose T_B profile was depicted in Fig. 2. There, the profile flattened toward the end of the roast. When lower T_{GI} (e.g. 290°C) are used, T_B profiles for industrial roasts remain upwardly concave till the roast's end. Evaporative cooling depresses dT_B/dt markedly when $(-X')$ is large. Schenker [4] showed that the T_B profile is significantly lower for large X_0 than for small X_0 . Gas mass flow through the blower usually is proportional to gas density at T_{GO} , i.e. inversely proportional to T_{GO} in degrees Kelvin. T_{GO} progressively rises as T_B rises. Thus gas density and G' tend to progressively decrease as roasting proceeds [22]; and the decrease in G' contributes to the dT_B/dt decrease. Roasting-induced increases in C_B and R_D reductions due to dry-matter loss also affect dT_B/dt . F'_R , F'_{AB} and energy-use rates are greatest near the start of roasting when dT_B/dt is largest, and are much smaller near the end of roasting, when VOC and CO output rates are largest, but both dT_B/dt and $-X'$ are small.

Roast Time:

Integration of Eq. 1 with small terms eliminated yields the following approximation for roast time, t_R , in seconds when variables in kg, kJ and °C units are used:

$$t_R \approx \frac{\bar{R}_D \bar{C}_B}{E \bar{G}' C_G} \left[\ln \left(\frac{\bar{T}_{GI} - T_{BO}}{\bar{T}_{GI} - T_{BF}} \right) + \frac{H_{EV} X_0}{C_B (\bar{T}_{GI} - \bar{T}_B)} \right] \approx \frac{0.51 \bar{R}_D}{E \bar{G}'} \left[\ln \left(\frac{\bar{T}_{GI} - T_{BO}}{\bar{T}_{GI} - T_{BF}} \right) + \frac{1250 X_0}{(\bar{T}_{GI} - 160)} \right] \quad (5)$$

High-Speed Roasting:

The terms with bars over them are mean effective values. Increasing \bar{G}'/R and/or \bar{T}_{GI} reduces t_R . If \bar{G}'/R and/or \bar{T}_{GI} are increased enough, t_R will be < 300 s and the roast will be a “high-speed” roast. High-speed roasting is used to produce roasted coffees with bulk densities up to 34% lower than regular roast coffee [23] and which contain more available soluble matter [1,24,25], more sucrose [25], more 3-caffeolquinic acid [25], more aroma [25], and more residual water [9,24]. The soluble-matter increase has been attributed to hydrolytic breakdown of polymeric cell wall carbohydrates [26], most likely arabinogalactans. Roasting times as small as 60 s [25] or even 47 s [26] have been used, and a t_R of 35 s has been cited in one patent [24]. Nowadays, use of $t_R < 180$ s is uncommon. High-speed roasting usually is obtained by increasing \bar{G}' ; but reductions in R have also been used; or have been combined with moderate increases in \bar{G}' and higher T_{GI} [2]. G' can only be increased to levels that will not cause beans to be pneumatically conveyed out of the roasting chamber. Therefore high speed roasting usually is carried out either in newer kinds of batch roasters, e.g. spouted-bed roasters (Neuhaus Neotec RFB roasters) [12], rotating-scoop roasters (Gothot Rapido-Nova roasters or Probat RT roasters) [12] or modified rotating-bowl roasters (i.e. Probat RZ-SY roasters) [12], that accommodate or need to use high \bar{G}' , or in continuous roasters where hot gas issuing from a large number of jets impinges on a moving bed of beans (Probat Cont-Roasters or Wolverine Jet Roasters) [12,24,27]. G'/R can be more than 33 times as great for high-speed roasting as for regular roasting.

$G = \bar{G}(t_R)$, and therefore is inversely proportional to E . Since E decreases as G' increases, G/R is much greater for high-speed roasts than for regular roasts. G/R for regular roasts ranges from 0.9 to 3.3, but for high-speed roasts G/R can be > 10 . Therefore blower energy use per kg bean feed is very much greater for high-speed roasting than for regular roasting. Fluidized bed roasting was once used for high-speed roasting; but sometimes involved use of G/R as great as 60 [26]. This required very large use of energy to run blowers.

MATERIALS & METHODS

Mass Balance:

Overall mass balances were based on the mass flows shown in Fig. 1. Masses: F , A and $R = R_D(1 + X_0)$, enter the roaster. $R_D S$ leaves it as chaff, and $[F + A + R_D(X_0 + P - S)]$ leaves it as stack gas. The mass of roasted beans remaining in the chamber at the end of a roast, but prior to quenching, is $R_D(1 - P)$.

Enthalpy Balance:

Overall enthalpy balances were used to compute Q_{SR} , the kJ energy used to roast a kg of green coffee feed in both R and SP roasters. Stream or stream component masses were divided by R and multiplied by the relevant heat capacity and stream temperature, with T_A used as a reference temperature, to provide specific stream enthalpies: i.e. Q_B for roasted beans, Q_G for stack gas and Q_C for chaff, all on a kJ/kg green beans basis. The heat capacity used for gas and for dry-matter gas and vapor breakdown products was $C_G = 1.12$ kJ/(kg °C). C_B was based on DSC measurements [28] which, when analyzed, appeared to show the C_B could

be broken down into two partial heat capacities: $C_{BD} = [1.099 + 0.007T_B]$ kJ/(kg °C) for bean dry matter, and $C_{BM} = 5.0X$ kJ/(kg °C) for bean moisture. $C_{WV} = 2.09$ kJ/(kg °C) was used as the heat capacity for bean moisture after evaporation. Valdovinos-Tijereno [7] used modulated DSC to measure coffee C_B versus T_B . This procedure eliminated effects of evaporative cooling and exothermic heating and permitted measurement of C_B up to 250°C. Finely ground beans were used; and vapor and gas were allowed to escape. Her C_B increased as T_B increased, but slightly less rapidly than postulated above; and her C_B started to level off at 190°C and then decreased slightly. Her lower C_B rise rate appears to be due to progressive loss of bean moisture and the accompanying progressive reduction in C_{BM} , bean moisture's contribution to C_B . The levelling off and slight decrease in her C_B at high T_B appear to be due to dry matter loss. When these effects are accounted for, her C_B data largely confirms the C_B relationship proposed above.

As noted before, H_{EV} , bean moisture's latent heat of vaporization, ≈ 2760 kJ/kg. Modelling of regular industrial roasts showed that roughly half of bean moisture content is lost when $T_B \approx 160^\circ\text{C}$. Therefore in carrying out enthalpy balances, it was assumed the initial bean water content $R_D(X_0)$ evaporated at an average T_B of 160°C. Moisture evaporation midpoints occur at higher T_B for fast roasts. It was also assumed that: the initial bean temperature, $T_{BO} = T_A = 20^\circ\text{C}$; exothermic heat generation and net heat transfer to or from chamber hardware during a roast were negligible; chaff loss $S = 0.011$ (a typical value for Arabica beans); and chaff was heated to 200°C by roaster gas before being captured in the cyclone. VOC and CO oxidation during afterburning cause a gas-temperature rise, whose magnitude depends on the VOC and CO load. The enthalpy rise due to that gas temperature rise is exactly cancelled by a potential combustion-energy contribution assignable to the green coffee feed. Therefore both effects were neglected in the enthalpy balance.

$Q_{SR} = (FC_G)(T_F - T_A)/[R_D(1 + X_0)]$. Q_{SR} also = $Q_B + Q_G + Q_C$ from the overall enthalpy balance for the roaster. Q_G contains an F dependent term. Therefore the enthalpy balance could be solved for $F/[R_D(1 + X_0)]$, which, in turn, was used, as follows, to evaluate Q_{SR} .

$$Q_{SR} = \frac{(T_F - T_A)(Q_B + Q_C + Q_{PG} + Q_A + Q_X)}{(T_F - T_{AB})(1 + X_0)} \quad (6)$$

$$Q_B = (1 - P)[1.099(T_{BF} - T_A) + 0.0035\{(T_{BF})^2 - (T_A)^2\}] \quad (6a)$$

is the specific enthalpy of roasted beans. The specific enthalpy of chaff discharged from the cyclone is

$$Q_C = S[1.099(200 - T_A) + 0.0035\{(200)^2 - (T_A)^2\}] \quad (6b)$$

The specific-enthalpy rise for air that leaked into the roaster is

$$Q_A = (A/R_D)C_G(T_{AB} - T_A) \quad (6c)$$

The specific-enthalpy rise for bean moisture converted to water vapor is

$$Q_X = X_0[C_{BM}(160 - T_A) + H_{EV} + C_{WV}(T_{AB} - 160)] \quad (6d)$$

I assumed that T_{PE} the average temperature at which breakdown of dry matter to gas and vapor occurred was approximately $(200^\circ\text{C} + T_{BF})/2$. Thus the specific-enthalpy rise of dry matter converted to gas and vapor is

$$Q_{PE} = (P - S)[1.099(T_{PE} - T_A) + 0.0035\{(T_{PE})^2 - (T_A)^2\} + C_G(T_{AB} - T_{PE})] \quad (6e)$$

I also assumed that (A/R_D) was 0.136 for a 600 sec roast and was proportional to t_R and that T_{AB} was automatically kept constant during roasts. Values of $(P - S)$ for different T_{BF} were obtained from the $(P - S)$ versus T_B curve in Figure 3.

Quenching, Preheating, Loading and Unloading:

Gas heating and afterburning usually continue during quenching, bean loading and unloading and roaster preheating. The added kJ energy use/kg bean feed during these periods is:

$$Q_{ADD} = \frac{(T_F - T_A)[C_G(A_Q + A_D + A_P)(T_{AB} - T_A) + W_E C_{WV}(T_{AB} - 100) + Q_M]}{(T_F - T_{AB})R_D(1 + X_0)} \quad (7)$$

A_Q , A_D and A_P respectively are the kg of air in-leakage during quenching, bean discharge from the chamber, and preheating and bean loading. $W_E/[R_D(1 + X_0)]$ is the kg quench water evaporated/kg green beans. $Q_M/[R_D(1 + X_0)]$ is the (kJ heat)/(kg green beans) transferred to roaster hardware during preheating. A_Q , A_D and A_P vary with the type of roaster used, its associated quench time (15 to 30 s), preheat and charge time (30 to 90 s) and bean discharge time (5 to 40 s) and with bean-charge- and discharge-port size. It will be assumed that $(A_Q/R) \approx 0.005$, $(A_D/R) \approx 0.041$ and $(A_P/R) \approx 0.027$, values which appear reasonable for rotating-drum roasters, the most common type of coffee roaster. A_Q , A_D and A_P are zero for roasters where beans are quenched while undergoing air cooling outside the roaster and where furnace gas bypasses the chamber during unloading and loading of beans. Q_M/R depends on chamber mass and on its temperature rise during preheating. It was assumed that $Q_M/R \approx 45$ kJ/kg, which appears reasonable for a large rotating-drum roaster. Since surface to volume ratios for chambers tend to be proportional to $R^{2/3}$, Q_M/R would be larger for most small roasters. W_E/R_D depends on T_{BF} and on T_{BD} , the desired bean temperature after quenching. $W_E/R_D \approx C_{BD}(T_{BF} - T_{BD})/\Delta H_Q$, where $\Delta H_Q \approx 2602$ kJ/kg, the enthalpy rise for water between 20°C liquid and 100°C steam. It was assumed that $T_{BD} = 120^\circ\text{C}$. Quenching usually is not used for small SP roasters. Therefore W_E/R_D was set to zero when determining Q_{ADD} for SP roasters. W_E/R_D also = 0 when beans are quenched outside the roaster while undergoing cooling by air.

Q_{ADD} was added to Q_{SR} to provide Q_{TOT} , the total thermal energy use in kJ/kg green bean feed. Q_{SR} and Q_{TOT} were determined for different T_{BF} , burner flame temperatures, T_F , afterburning temperatures, T_{AB} , initial dry-basis moisture contents, X_0 , and leak air/dry bean ratios, A/R_D , and are presented in Table 1.

Table 1 Q_{SR} and Q_{TOT} for various roasting and afterburning conditions

T_{BF} (°C)	P-S kg loss/ kg dry beans	T_F (°C)	T_{AB} (°C)	X_0 moisture d.b.	A/R_D kg air/kg dry beans	Q_{SR} (kJ/kg)	Q_{TOT} (kJ/kg)
214 ^a	0.022 ^a	1260	400*	0.111	0.109	1308	1491
236 ^b	0.068 ^b	1260	400*	0.111	0.136	1417	1621
255 ^c	0.160 ^c	1260	400*	0.111	0.162	1506	1729
236 ^b	0.068	1530 ^d	400*	0.111	0.136	1313	1502
236 ^b	0.068	1260	400*	0.111	0.068	1379	1584
236 ^b	0.068	1260	480 ^e	0.111	0.136	1615	1878
236 ^b	0.068	1260	760 ^f	0.111	0.136	2807	3426
236 ^b	0.068	1260	400*	0.075	0.136	1273	1477
236 ^b	0.068	1260	400*	0.133	0.136	1500	1705
236 ^b	0.068	1260	760 ^f	0.111	0.733 ^g	3004	3266
236 ^b	0.068	1260	400*	0.111	0.733 ^g	1747	1856

^a very light roast, ^b medium roast, ^c very dark roast, ^d highest T_F without some CO_2 and H_2O decomposition, *catalytic afterburner, ^e catalytic afterburner fed by roaster furnace, ^f thermal afterburner, ^g SP roaster

Comparisons Between Predicted and Reported Q_{SR} and Q_{TOT} :

Operating and feed conditions for a medium, 600 s roast in a R-type roaster were used as reference conditions. The predicted Q_{SR} for that roast is 12% higher than Q_{SR} (1245 kJ/kg) measured by Dorfner [8] for a 613-s, light-medium roast in a modern 250-kg capacity roaster with a catalytic afterburner. Part of that difference is due to Dorfner's roast being somewhat lighter; and part may be due to his T_F possibly being higher and his A/R_D and X_0 possibly being smaller than the reference case. Part of the difference may also be due to small errors in parameters I used when calculating predicted Q_{SR} . The predicted standard-roast Q_{TOT} , i.e. 1621 kJ/kg, is similar to the 1675 kJ/kg values listed by Rothfus [9] for: 1) a R-type Probat rotating-drum roaster with catalytic afterburner; and 2) a R-type Probat rotating-bowl roaster with catalytic afterburner.

Effects of Operating and Feed Conditions:

Operating conditions and Q_{SR} and Q_{TOT} for the reference roast are shaded in Table 1. Operating or feed conditions that differ from reference conditions are also shaded so as to better indicate contrasts between conditions. One can see that: 1) Q_{TOT} is roughly twice as great for thermal afterburning ($T_{AB} = 760^\circ\text{C}$) as for catalytic afterburning ($T_{AB} = 400^\circ\text{C}$); 2) is greater for dark roasts [$T_{BF} = 255^\circ\text{C}$, $(P-S) = 0.160$ and $A/R_D = 0.162$] and less for light roasts [$T_{BF} = 214^\circ\text{C}$, $(P-S) = 0.022$ and $A/R_D = 0.109$]; 3) is greater for high bean moisture contents ($X_0 = 0.133$) and less for low moisture contents ($X_0 = 0.075$); 4) decreases when burner temperature increases ($T_F = 1530^\circ\text{C}$ instead of 1260°C); 5) is reduced by reducing air in-leakage ($A/R_D = 0.068$ instead of 0.136); and 6) is larger when catalytic afterburner feed is heated in the roaster furnace rather than in the afterburner itself ($T_{AB} = 480^\circ\text{C}$ instead of 400°C).

Effects of Using SP Roasting

Q_{TOT} is greater for SP roasters ($A/R_D = 0.733$ in Table 1) than for R roasters, particularly when thermal afterburning is used. An A/R_D of 0.733 was used to account for greater air intake by SP roasters. However, A/R_D , Q_{SR} and Q_{TOT} for SP roasters depend on E and T_G . Both the predicted A/R_D , Q_{SR} and Q_{TOT} would be greater if E or T_{GI} were smaller than I assumed. The predicted Q_{TOT} for SP roasting with thermal afterburning, i.e. 3266 kJ/kg, is 20% less than 4060 kJ/kg listed by Rothfus [9] for a SP type Probat rotating-drum roaster with thermal afterburner and 19% more than 2680 kJ/kg listed for a SP type Gothot Rapido Nova roaster with thermal afterburner [9]. These differences probably are largely due to differences between the actual A/R_D for those roasters and the A/R_D I assumed. E and T_{GI} only slightly affect Q_{TOT} for R roasters.

Other than using catalytic instead of thermal afterburning, Q_{TOT} savings from individual process changes are modest (less than 10%). Combining them provides greater, but slightly less than additive, savings, e.g. low X_0 , low A/R_D and high T_F , when combined, reduce Q_{TOT} 17.4%. Heat savings per kg of roasted coffee are greater than those per kg of green coffee, particularly when $(P + X_0)$ is reduced. For example, the previously cited combined green-coffee-based Q_{TOT} saving of 17.4% is a 20.3% savings when reckoned per kg of roasted coffee. Thus reducing X_0 and, where possible, reducing P by use of lighter roasts can provide attractive thermal-energy and product-yield savings. It has been claimed that pre-drying of beans: 1) reduces differences in roast color within beans, particularly when high-speed roasting is used [29,30]; 2) prevents the formation of rubbery tastes that would normally be generated when coffee beans, particularly Robustas, are dark roasted [30]; and 3) reduces roasting-induced dry-matter loss (when combined with a modified T_B profile) [31].

Problems with Dark Roasting:

T_{AB} probably has to be increased to provide acceptably low stack gas VOC concentrations when VOC generation is large, i.e. when very dark roasting is used. Therefore energy requirements for dark roasting probably are greater than indicated in Table 1. That added energy-use burden and other disadvantages of dark roasting, e.g. lower roasted-coffee yield, increased fouling, reduced catalyst life, provide incentives for dealing with problems caused by dark roasting. While lighter roasts may be difficult to use where dark roasts are strongly preferred, it may be possible to blend light, medium and dark roast coffee so as to retain dark-roast notes, while: a) better utilizing flavor and aroma contributions derived from each type of roast, b) increasing roasted coffee yield, c) improving roasted-bean storage stability, and d) saving energy. It has been claimed [32] that blending small amounts, e.g. 10%, of darkly roasted coffee made from pre-dried Robusta beans with 90% normally roasted coffee will provide coffee that, when brewed, will have a dark brew color, a high flavor strength/rubbery taste ratio and good balance of flavor to strength.

G' , T_{GI} , t_R and E do not affect enthalpy balances for R roasters and thus do not directly affect Q_{TOT} for such roasters, but have slight indirect effects. Reductions in t_R (achieved by increasing G' , T_{GI} or E) reduce A/R_D and thereby slightly reduce Q_{TOT} . More blower energy and higher T_{BF} are needed when high-speed roasting is used. These cause overall-energy-use increases that exceed the Q_{TOT} savings derived from the marked decrease in t_R and consequent decreases in A/R_D and heat loss from the roaster to its surroundings.

Energy Saving Methods:

Nearly 75% of heat input to roasters can go out the stack. Part of that heat, e.g. the latent heat of stack-gas water vapor, cannot be readily recovered. Nevertheless, reducing stack-gas temperature (called T_{OUT} hereafter) or stack-gas mass outflow can reduce Q_{TOT} significantly. Table 2 lists Q_{SR} and Q_{TOT} for standard roasting conditions, i.e. line 2 in Table 1, and Q_{SR} and Q_{TOT} for the same conditions when different methods for reducing T_{OUT} are used.

Table 2 Q_{SR} and Q_{TOT} at standard roasting conditions both when energy saving methods are and are not employed

T_{BF} (°C)	P - S kg loss/ kg dry beans	T_F (°C)	T_{OUT} (°C)	X_0 moisture d.b.	A/R_D kg air/kg dry beans	Q_{SR} (kJ/kg)	Q_{TOT} (kJ/kg)
236	0.068	1260	400 ^A	0.111	0.136	1417	1621
236	0.068	1260	120 ^B	0.111	0.136	943	1005
236	0.068	1260	200 ^C	0.111	0.162	1053	1148
236	0.068	1260	300 ^D	0.111	0.136	1216	1360
236	0.068	1260	280 ^E	0.111	0.136	1180	1314

^A Reference. ^B Heat transfer from stack gas to: afterburner feed, roaster gas and roaster furnace air and fuel. ^C Same setup as B, but heat transfer is less efficient. ^D Heat transfer from stack gas to afterburner feed only. ^E Afterburner largely bypassed when VOC levels acceptably low.

Use of Heat Exchange to Save Energy:

Transferring heat from stack gas to cooler gas streams and/or green beans is one way to reduce T_{OUT} . Stack gas contains a great deal of water vapor. Therefore T_{OUT} cannot be reduced much below 100°C without water condensing on heat-exchange surfaces and reducing heat-exchange capacity. Stepwise transfers of heat from stack gas to: a) afterburner feed; b) then chamber discharge gas; and c) burner air and fuel can reduce T_{OUT} to 120°C (line 2 in Table 2), thereby reducing Q_{TOT} by 38%. Line 3 (where $T_{OUT} = 200^\circ\text{C}$) shows Q_{TOT} for the same heat-exchange scheme, but with less efficient heat exchange because of use of smaller and less costly heat exchangers. Line 4 (where $T_{OUT} = 300^\circ\text{C}$) shows what Q_{TOT} would be if stack gas only transferred heat to afterburner feed.

Transferring heat to combustion air and fuel gas for the roaster-furnace burner may significantly increase NO_x production in that burner [32]. Therefore it may be preferable to replace step c) in the previously considered three-step heat-transfer arrangement with a step in which partly cooled stack gas transfers heat to green beans in the bean-feed hopper for the roaster. Schmidt [11] described use of a mini rotating-scoop roaster to accomplish that process.

Fouling:

Heat-exchange-based Q_{TOT} reduction will be feasible only if: condensable VOC can be prevented from fouling the heat exchangers or regenerators used; those units are not too large or too costly; and heat-exchange pinches are minimized. Fouling is a problem mainly for roasters where G' is low, and is aggravated when dark roasts are used. Low G' lead to: 1) less reduction of VOC partial pressures by dilution; 2) lower T_{GO} because low G' increase E ; and 3) greater T_{GO} reduction due to dilution of roaster gas by leak air and by heat losses. Thus T_{GO} is likely to fall enough for some VOC to condense on duct walls or as smoke droplets (which later impact on and foul surfaces). If G' is low and E is high enough, T_{GO} may even be low enough to permit tarry VOC to condense on roasting beans, thereby adversely affecting their flavor. Temporarily admixing furnace-discharge gas with chamber-discharge gas, or heat exchange with stack gas itself could raise T_{GO} and heat-exchanger-surface temperatures enough to prevent VOC condensation and consequent fouling. Thus passing stack gas or partly cooled stack gas through a shell surrounding ducts through which chamber-discharge gas flows could prevent those ducts from fouling. Condensed VOC initially are oily, but harden and solidify as time goes by. It is sometimes possible to burn off fouling by passing 400°C gas through the empty roaster for 720 to 900 s [33]. The burn-off process is automatically repeated every 24 to 40 hours for roasters that foul particularly rapidly. This procedure cannot be used for some roasters. Burn-off procedures might possibly be used to remove fouling from heat exchangers and to burn-off fouling and blinding material on afterburner catalysts.

Fouling of heat exchangers could also be avoided by allowing stack gas to exchange heat only with VOC-free streams, e.g. furnace-burner air and fuel. The mass-flow rate of stack gas exceeds the mass-flow rate of furnace-burner air and fuel. This mass-flow rate imbalance creates a heat-exchange pinch that limits how much heat can be extracted from hot stack gas by such heat transfer. Heat transfer from stack gas to other VOC-free heat-absorbing loads in a coffee roasting plant has also been considered [34].

Compact Heat Exchange

Roasters are designed to occupy a small area and to minimize duct length and consequent loss of heat from ducts. Therefore, heat-exchange systems used to recover energy used for roasting also have to be compact. Finken [35] described a compact heat exchanger and afterburner in which afterburner discharge gas was used to heat afterburner feed and roaster gas for SP roasters. The system might be adapted to recover heat in R roasters. Regenerators could also provide heat exchange compactly, but, if fouled, might be very difficult to clean. Regenerators also cannot be used when VOC levels are likely to exceed 10% of their L.E.L. Such VOC levels might easily occur when very dark roasts are produced. Heat-transfer fluids or heat pipes might be used to exchange heat compactly in the third and/or second stages of the proposed three-stage heat-exchange scheme, i.e. after stack gas has cooled enough to prevent thermal degradation of such media.

Afterburner Bypassing:

VOC levels are acceptably low during the first 75% to 80% of regular roasts, i.e. when roughly 90% of heat use occurs. If most stack gas bypasses the afterburner during this period, Q_{TOT} could be significantly reduced. A small portion, e.g. 10%, of stack gas would still be sent to the afterburner then to keep it at operating temperature. All stack gas would go through the afterburner after VOC levels start rising. The estimated average T_{OUT} for this arrangement is 280°C and could be even lower if E is high. The last line in Table 2 (where $T_{OUT} = 280^\circ\text{C}$) indicates Q_{TOT} could be reduced 19% by use of this arrangement. Alternatively, afterburner bypassing could be gradually reduced as VOC levels rise. F_R is the main contributor to stack gas

outflow, and decreases markedly towards the end of roasting. Therefore stack-gas outflow rates will be low when the afterburner is fully on-line. Consequently, smaller afterburners can be employed if afterburner bypassing is used; and total gas flow through the afterburner will be small. Reducing total flow through the afterburner, particularly reducing afterburner flow during times when beans release chaff (which occur relatively early in roasts) may reduce rates of catalyst blinding and deactivation and extend catalyst life.

Stack VOC levels were excessive when intermittent afterburning was used in the past with SP roasters [9], but should be substantially lower if intermittent afterburning is used with R roasters (where substantial in-furnace destruction of VOC occurs) and if excessive roaster preheating is avoided. Suitably low VOC levels can reliably be obtained by using on-line detection of VOC increases or critical T_{BM} to initiate full afterburning. T_{BM} profiles could also be adjusted so as to limit VOC and CO production time. For example, VOC emission could be reliably confined to the last 20% of a roast by slightly decreasing T_{BM} during the first 80% and then increasing dT_{BM}/dt roughly 25% or 30% thereafter. This probably would also increase in-bean generation of methanethiol, a valuable coffee aroma [36]. Similarly limiting VOC production to the last 10% of roasting would save even more energy. Afterburner bypassing would not be effective for T_B (and T_{BM}) profiles that are fairly level during mid and late stages roasting and probably would be difficult to utilize for high-speed roasting.

Effects of T_{AB} Control:

The Q_{SR} and Q_{TOT} values in Table 1 are based on implicitly assuming that F'_{AB} was automatically regulated so as to maintain T_{AB} constant. If F'_{AB} remained constant instead, T_{AB} would progressively increase and would be much higher at the end of the roast than at the beginning. In such a case, Q_{SR} and Q_{TOT} would be larger than listed in Table 1; and T_{AB} might become high enough at the end of roasts to damage the afterburner catalyst. Conceivably, F'_{AB} could possibly be set at a level that would provide low T_{AB} at the beginning of roasts, i.e. when VOC emission is negligible, but which would also provide acceptably high T_{AB} close to the end of roasts when VOC are emitted. This might possibly save energy, but it probably would be difficult to ensure reliable and predictable provision of adequately low VOC levels.

Combining Savings:

Stack-gas heat exchange and afterburner bypassing cannot be effectively combined without losing much of the energy saving provided by heat exchange. However, each of these methods can be effectively combined with other energy-saving steps, e.g. reducing X_0 and A/R_D and raising T_F . The percent Q_{TOT} savings for the added steps would only apply to energy not already saved; but total Q_{TOT} savings can be as high as 49% if stack-gas heat exchange is combined with these added steps, and as high as 33% if afterburner bypassing is combined with these steps. In the first case, as much as 57% of the energy input per kg of roasted coffee could be saved, and in the second case, as much as 38%.

Proper Purging:

Markedly reductions in Q_{TOT} cause F_R as well as F_{AB} to decrease. F_R reductions reduce stack gas outflow and consequent purging of combustible VOC and CO from the roaster. Thus, when G/R is small and/or very dark roasts are used, large Q_{TOT} reductions could cause VOC concentrations near the end of roasts to become high enough within roasters to cause puffing (oscillatory non-explosive ignitions) or even an explosion. VOC concentrations in the afterburner feed would also probably exceed their allowable percentage L.E.L. limit, i.e. 25%. These problems can be circumvented by: a) using roasters that utilize larger G/R ; or, if this approach is not feasible, b) temporarily using sufficient extra burner air to thereby increase F'_R and venting enough to prevent VOC and CO concentrations from becoming excessive. This should be automatically done whenever monitored VOC and/or CO concentrations start to approach dangerous levels. Adding extra burner air will reduce T_F , but good burner-control systems will automatically adjust F'_R further so as to keep T_{GI} constant. The amount of purging required will in part depend on how much VOC is destroyed in the roaster furnace and on whether destruction of VOC there results in production of significant amounts of CO.

Bean Cooling – Recovering Heat from Roasted Beans:

Part of the heat content of roasted beans could be recovered by passing air leaving the bean cooler through green beans held in an added hopper upstream from the green-bean-feed hopper for the roaster. The added hopper's bottom would have a perforated, sloping inner wall and solid outer wall with an air-flow channel in between, and would be loaded so that the upper surface of the beans it contains lies roughly parallel to the hopper's bottom (whose slope would only slightly exceed the angle of repose for coffee beans). Air drawn from the cooling tray by a blower would be also drawn upward through the perforated sloped bottom and bed of beans in the added hopper, thereby preheating the green beans. Heat recovery by this scheme can be

maximized by: 1) limiting quenching to the minimum that will arrest roasting; and 2) increasing stratification of heat transfer in cooling trays. At most, use of this approach would save roughly 134 kJ/kg green beans and raise T_{BO} to 87°C. Based on records of measured bean-cooler outlet-air temperature versus time [34], actual energy saving currently obtainable by use of this approach might be around 80 kJ/kg green beans.

Reduction of VOC Levels in Cooler Air:

In some locales, air used to cool roasting beans also has to be subjected to afterburning to oxidize VOC it contains. Afterburning should only be used only during the brief time at the start of cooling when VOC emission is significant (e.g. roughly 15 s out of a 210 to 240 s cooling period for a regular roast). If beans are cooled in a moderately stratified fashion, limiting afterburning of discharged cooler air to the first 15 s of discharge would require roughly 50 kJ/kg green beans compared to the roughly 810 kJ/kg that would be used if all discharged cooler air were subjected to afterburning. If the beans were thoroughly mixed during cooling, limiting afterburning of discharged cooler air to the first 15 s of discharge would require roughly 175 kJ/kg green beans compared to the roughly 2,740 kJ/kg that would be used if all discharged cooler air was subjected to afterburning. Thermal stratification during bean cooling causes different bean strata to cool at different rates, but saves energy when cooler air has to be subjected to afterburning. Use of quenching that adequately stops all roasting reactions should minimize adverse consequences of bean-cooling-time unevenness.

Alternatively, cooler-discharge air could be sent through a bed of an adsorbent during the time that VOC are emitted. The adsorbed VOC could be periodically desorbed in concentrated form later and sent to the afterburner. This would greatly reduce the mass of air that has to be heated to T_{AB} . Use of the previously described green-bean-preheating scheme would reduce the temperature of discharged cooler air and facilitate VOC adsorption. The VOC contained in cooler air could also be absorbed in oil and the burned with that oil.

CONCLUSIONS

Wherever feasible, existing thermal afterburners should be replaced by catalytic afterburners. Catalytic afterburner feeds for R roasters should be heated in the afterburner itself rather than in the roaster furnace. Energy consumption for coffee roasters with afterburners can be reduced 30% to 40% by sequentially transferring heat from roaster stack gas to afterburner feed gas, chamber discharge gas, and then to burner air and fuel or to green beans. The feasibility of this approach depends on whether its use reduces or enhances fouling of heat exchangers and roaster hardware by condensable VOC. Largely bypassing afterburners when VOC concentrations are acceptably low can reduce energy use by about 20%. In each case, added energy could be saved by also increasing T_F , reducing air in-leakage, use of lighter roasts and reducing the moisture content of green beans, e.g. by storing them at conditions that promote bean drying. When steps providing large energy-use reductions are utilized, care should be taken that VOC and CO are adequately purged from roasters at late stages of roasting. This can be done by temporarily increasing the air/fuel ratio used for the burner in the roaster furnace. If bean-cooler-discharge air has to be subjected to afterburning, such afterburning should be restricted to periods when that air contains appreciable amounts of VOC. Requiring more extensive afterburning of cooler air would have negative environmental effects.

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