

INDICATORS AND SIGNIFICANCE OF AIR SUPPLY IN THE COMBUSTION OF WOOD FOR HEAT

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ABSTRACT

Wood burning completely consumes 6 grams of air per gram of oven-dry wood. With less air the combustion cannot be complete, while excessive amounts of air will carry heat out the smokestack or chimney. Contents of carbon dioxide and oxygen in the flue gases serve as reliable indicators of the air supply. The gas percentages and amounts of heat escaping with the flue gases are calculated and are compared with values in the literature. Excessive air causes small heat losses compared to the loss of chemical energy in combustible fire effluents, such as carbon monoxide.

Keywords: Combustion, air supply, heating, flue gases, energy loss.

INTRODUCTION

When wood is burned to gain heat, the fire should be supplied with a certain amount of air. In air-starved fires the fuel burns incompletely under emission of numerous combustible compounds, which cause chimney deposits, pollute the air, and amount to wasted energy. Excessive air, on the other hand, carries heat out the chimney (Tidona et al. 1983). The air supply is crucial for efficient utilization of the fuel.

At first glance the proper supply is impossible to achieve, the main reason being that wood does not burn as such. First heat disintegrates (pyrolyzes) the wood into combustible gases, charcoal, and some tar-mist. The charcoal burns in two steps, first in a solid-surface reaction to form carbon monoxide gas, which in the second step combines with oxygen to form carbon dioxide. The air supply should be continuously adjusted to the ever-changing evolution of the pyrolysis products, which depends on temperatures in all parts of the fire chamber and on the decreasing sizes of the wood pieces.

Fortunately, one can take a completely different approach and admit air according to the fire effluents, which show whether the fire has received too much or too little air, even indicating how much the air supply deviated from the optimum. The fire effluents are known as *flue gases* of stoves and furnaces, and as *stack gases* of the much larger boilers. In the following, *flue gas* stands for the fire effluents of all devices in which wood is burned for heat.

This article concerns the relation between air supply and flue gas composition, as well as loss of energy in air and through incomplete combustion. Information of this kind is available in the combustion-engineering literature (Stamper and Koral 1979) and in engineering handbooks (Hawkins 1967). Publications of these kinds deal mainly with natural gas, fuel oil, and coal, but they pay little or no attention to the unique features of wood fuel (ASHRAE 1985). Conditions such as wood moisture content are typically not specified, and the authors do not explain how the information has been developed. The data given for wood fuel

are dubious, besides being difficult to locate and to understand for people who are not combustion engineers.

Studies by Corder (1973), Hughes (1976), Ince (1979), and Roberts and Austin (1982) deal specifically with wood or bark fuel. These authors treat heat losses mainly from an economical point of view, whereas this article focuses on combustion control and on implications of that control. The four authors apparently worked with general concepts and formulas of combustion engineering that are not explained. They calculated heat losses for a wide variety of conditions, having especially wood-fired boilers in mind. By contrast, in this article formulas for determining heat losses are developed to show how the heat losses come about, what can be done to reduce them, and to compare the various kinds of heat losses. The losses calculated by Corder (1973) and Hughes (1976) cannot be in exact agreement with this article, because Hughes worked with a somewhat atypical composition of wood (52.3% carbon, 6.3% hydrogen, and 40.5% oxygen), while Corder (1973) considered mainly bark fuel with a chemical composition resembling that assumed by Hughes (1976) for wood. The article deals especially with components of flue gases that are suited as basis for control of the air supply.

FLUE GASES OF COMPLETELY BURNED WOOD

Wood on average consists of about 50% carbon (C), 6% hydrogen (H), and 44% oxygen (O) (Kollmann 1951). It also contains many minor elements, which in the majority of wood species total less than 0.5%, and can be ignored here. The minor elements remain largely in the ashes of burned wood. Some wood species contain several percentages of resins and other extractives, particularly in the heartwood. But the extractives have little influence on wood's ultimate analysis, because like wood's main constituents, they consist essentially of C, H, and O. Most extractives contain little oxygen, some being practically oxygen-free.

The Swedish wood chemist P. Klason, who is best known as author of the Klason-lignin-determination, suggested for temperate-zone woods the average empirical formula $C_{42}H_{60}O_{28}$ (Klason et al. 1910). The formula is based on the ultimate analysis mentioned and will be used here for combustion calculations.

Wood burns to carbon dioxide (CO_2) and water vapor (H_2O) as shown in the *combustion equation* (Fig. 1). The combustion proceeds in many intermediate steps and with the various wood pyrolysis products on different routes, but for our purposes we may disregard the highly dependent intermediate steps and the different routes, since only final combustion products enter the chimney flue.

According to the combustion equation, wood reacts with 1.358 mass units of oxygen. Dry air contains 23.15% oxygen by weight (ASHRAE 1981). Taking ever-present water vapor into account and assuming an average kind of air, at 20 C with 50% relative humidity (holding 0.007595 gram vapor per gram), its oxygen content is only 22.9755%. Wood combustion will consume $1.358/0.229755 = 5.9123$ grams of such air per gram of oven-dry wood. Ince (1979) assumed 6.03 g, Stamper and Koral (1979) 5.8 and 6.34 g, while Shelton (1976) settled for the average of 6 g. Combustion engineers rely on 23% oxygen in air and calculate the air a required for fuels in general with the formula $a = (2.67C + 8H - O)/0.23$ (Hawkins 1967). For contents of carbon (C), hydrogen (H) and oxygen (O) as listed in Fig. 1 but expressed in gram per gram, the formula gives 5.953 g air.

Combustion equation	C ₄₂	H ₆₀	O ₂₈	+	43 O ₂	→	42 CO ₂	+	30 H ₂ O		
Atomic weight total	504.468	60.478	447.983	+	1375.948	→	504.468	1343.950	+	60.478	479.982
Percent of wood mass	49.803	5.971	44.227	+	135.838	→	49.803	132.679	+	5.971	47.386
Molecular weight total		1012.930		+	1375.948	→	1848.418		+	540.460	
Percent of wood mass		100		+	135.838	→	182.482		+	53.356	

FIG. 1. Stoichiometric combustion of wood. Atomic weights based on C-12 scale (mass of nuclidic carbon = 12, mass of common carbon = 12.01115).

The following paragraphs concern gas volumes rather than masses, as generally needed in flue gas analysis for combustion control.

The number of carbon dioxide molecules in the flue gases is according to the combustion equation in Fig. 1

$$\text{CO}_2 = \text{O}_s 42/43. \quad (1)$$

O_s stands for the *stoichiometric* or *theoretical* oxygen required to oxidize all carbon and hydrogen. A great deal of the oxygen in carbon dioxide and in the water of the combustion equation originates from wood rather than from the air, but Eq. (1) takes this fact into account.

Using the symbol O_a for the number of oxygen molecules admitted to the fire, the number O_r of oxygen molecules in the flue gases becomes

$$\text{O}_r = \text{O}_a - \text{O}_s. \quad (2)$$

The ratio of flue gas oxygen to the stoichiometric oxygen (O_r/O_s) is known as excess oxygen or *excess air factor* (E), also defined as the air in excess of the need for stoichiometric combustion. With that follows

$$E = \text{O}_a/\text{O}_s - 1 \quad (3)$$

$$\text{O}_r = \text{O}_s E \quad (4)$$

$$\text{O}_a = \text{O}_s (E + 1). \quad (5)$$

The combustion literature expresses excess air (E') in percent (E' = 100E). Admitted air O_a = 1.5O_s, for example, means E = 0.5 or 50% excess air E'.

From Eqs. (1) and (4), Eq. 6 follows for the sum of carbon dioxide and oxygen molecules in the flue gas

$$\text{CO}_2 + \text{O}_r = \text{O}_s (E + 42/43) \quad (6)$$

The sum is almost as large as the number O_a of oxygen molecules in the admitted air [compare Eqs. (5) and (6)], the reason being that only one of the 43 stoichiometric oxygen molecules "disappears" in water, which largely condenses out when flue gas samples are cooled for analysis.

According to Avogadro's Law, same numbers of gas molecules occupy equal volumes. Consequently, the total volumetric proportion of carbon dioxide plus oxygen in cooled flue gases roughly equals the proportion of oxygen in the admitted air—that is 20.95% in the dry state (ASHRAE 1985). The air's carbon dioxide can be ignored inasmuch as the gas occupies only about 0.03% of the air volume (ASHRAE 1985).

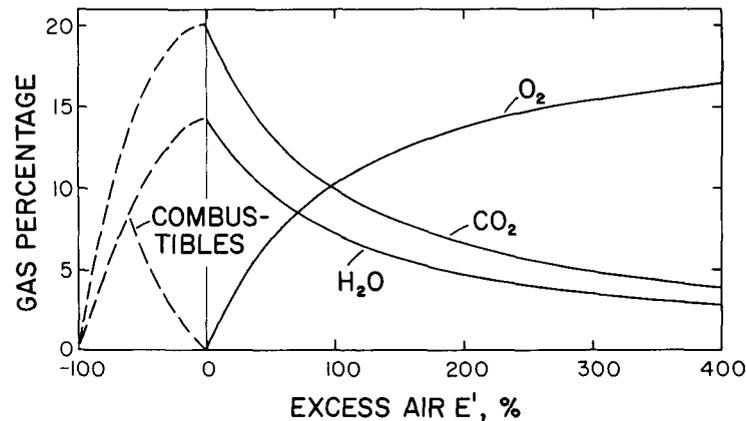


FIG. 2. Volumes of flue gases of completely burned wood as related to excess air, expressed in percent of dry gas ($N_2 + CO_2 + O_2$), calculated with the formulas (9), (11), and (16), respectively. Gas percentages in the range $E' < 0$ are indefinite due to variable amounts of combustible gases.

Water vapor lowers the air's oxygen percentage somewhat. At 20 C, for example, saturated air contains 2.4% vapor by volume (ASHRAE 1985), which leaves only 20.5% space for oxygen, besides the space for nitrogen and traces of inert gases in air. Hot flue gases contain combustion water vapor in quantities by far exceeding air vapor, so that on cooling of flue gas samples, most of the combustion water condenses out. Flue gas without the condensing water vapor is known as *dry flue gas*. The proportions of oxygen and of carbon dioxide in the following concern this dry flue gas.

Proportion of oxygen in flue gases

Besides carbon dioxide and oxygen, the flue gases contain nitrogen and traces of other not-reacting gases from the air. With the proportion of oxygen in air 0.205, the volume of the not-reacting gases is $N = O_a (1 - 0.205)/0.205$. Use of Eq. (5) for O_a leads to

$$N = 3.878O_s(E + 1). \quad (7)$$

With Eqs. (6) and (7), the sum of the dry flue gases, $S = CO_2 + O_f + N$, is

$$S = O_s(4.878E + 4.8548). \quad (8)$$

With Eqs. (4) and (8), we arrive at the proportion of oxygen

$$O_f/S = E/(4.878E + 4.8548) \quad (9)$$

depicted in Fig. 2. Graphs published by Corder (1973), Hughes (1976), and Roberts and Austin (1982) are in fair agreement. The authors calculated the oxygen contents probably on the basis of the fuel's carbon, hydrogen, and oxygen percentages mentioned in the Introduction.

To calculate excess air for measured oxygen proportions, Eq. (9) has to be solved for E:

$$E = 1/[0.206/(O_f/S) - 1.0048]. \quad (10)$$

Proportion of carbon dioxide in flue gases

With the terms for CO₂ in Eq. (1) and for S in Eq. (8) follows

$$\text{CO}_2/\text{S} = 0.9767/(4.878\text{E} + 4.8548) \quad (11)$$

$$\text{E} = 0.20023/(\text{CO}_2/\text{S}) - 0.9952. \quad (12)$$

A simplified route leads to the approximate equations

$$\text{CO}_2/\text{S} \approx 0.205/(\text{E} + 1) \quad (13)$$

$$\text{E} \approx 0.205/(\text{CO}_2/\text{S}) - 1. \quad (14)$$

The approximation involves only small, acceptable errors. In case the exact excess air (E') amounts to 0% and 300%, for example, Eq. (14) gives 2% E' and 309% E', respectively. Combustion engineers use a modified form of Eq. (13): CO₂/S = 0.21/(E + 1) (Hawkins 1967), assuming 21% oxygen in air rather than 20.5%. Values calculated with Eq. (11) are shown in Fig. 2; they differ only little from the ones published by Corder (1973), Hughes (1976), Stamper and Koral (1979), and Roberts and Austin (1982).

Under most favorable, ideal conditions of complete wood combustion, the flue gases contain 20.12% carbon dioxide, no oxygen, and no combustible substances (Fig. 2). When excess air enters the fire chamber, oxygen appears in the flue gas, and the carbon dioxide content drops. Later under the heading *Excess air for complete combustion*, I shall explain that the ideal combustion state cannot actually be achieved.

The total of carbon dioxide and oxygen—20.12% at the point of zero excess air—slightly increases as excess air increases, reaching 20.44% at 500% excess air and approaching the oxygen content 20.5% of air. The average total of around 20.3%, as well as the countermovement of carbon dioxide and oxygen contents, has been observed in many measurements, most of which have been reviewed by Hartmann and Rives (1985). For example, in 35 tests on wood-burning stoves, the total of CO₂ + O₂ decreased as carbon monoxide increased; but the regression line of the total as a function of carbon monoxide percentages intersected the ordinate of 0% carbon monoxide at the 20.4% total (DeAngelis et al. 1980). Similar results were found in many other experiments with wood-burning stoves (Dyer et al. 1978a, b; Cooke et al. 1982; Jaasma 1982; Curkeet and Husom 1983).

Proportion of combustion water vapor in flue gases

In the traditional analysis of flue gases, water vapor condenses out of the gas sample. This proportion of the vapor in the gases is needed for calculating the condensation temperature (dew point). The number of stoichiometric combustion water molecules and their share in the gas volume equals

$$\text{H}_2\text{O} = \text{O}_3/43 \quad (15)$$

(see the combustion equation in Fig. 1). The ratio of this H₂O to the dry-flue-gas sum S [Eq. (8)] is

$$\text{H}_2\text{O}/\text{S} = 1/(6.992\text{E} + 6.9585). \quad (16)$$

Use of the base S rather than S + H₂O facilitates comparisons with O₂/S and CO₂/S (Fig. 2), but to determine the dew point, the H₂O-proportion has to be

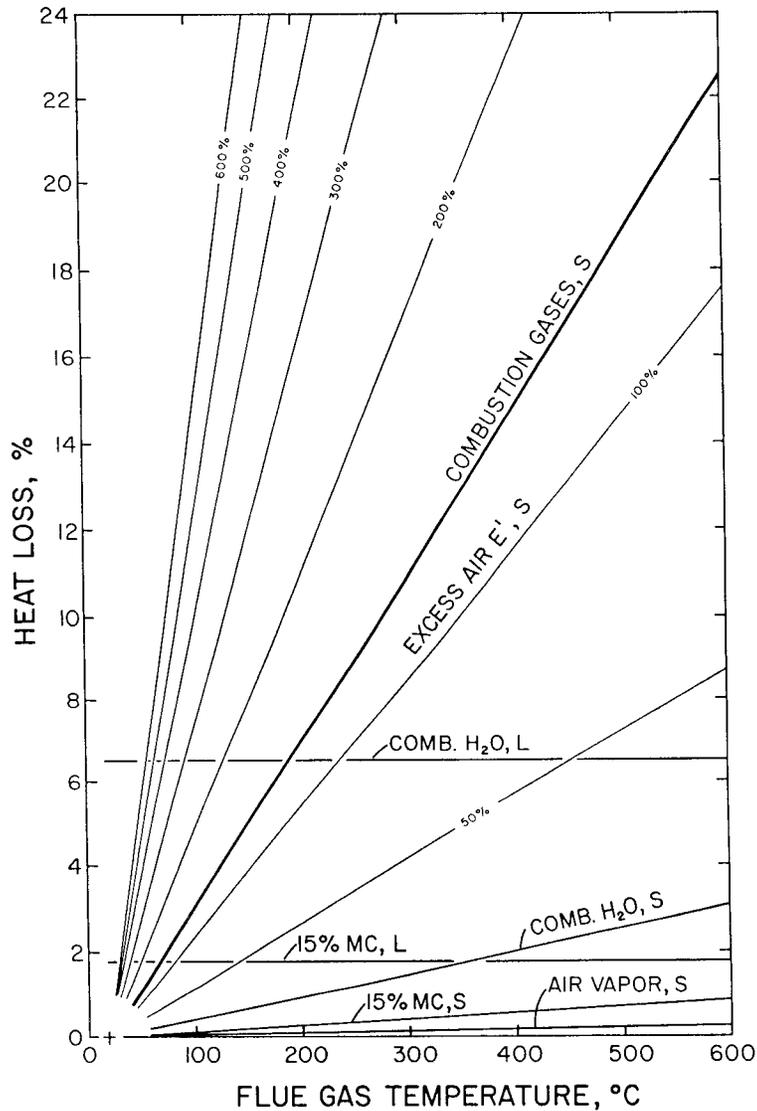


FIG. 3. Heat loss in flue gases of completely burned wood, expressed in percent of oven-dry wood's high heat value (20 kJ/g), in relation to flue gas temperature. L = latent heat. S = sensible heat. Combustion gases: $N_2 + CO_2 + H_2O$ of stoichiometric combustion. 15% MC: vapor from 15% moisture content, oven-dry wood basis. Air vapor: vapor in admitted air at 20 C and 50% relative humidity.

based on the entire volume:

$$H_2O/(S + H_2O) = 1/(6.992E + 7.9585). \quad (17)$$

With $E = 0$, for example, this proportion equals 0.12565, which is also the proportion of the vapor's partial pressure in the total pressure or atmospheric pressure, 101,325 Pa. The vapor's partial pressure, $0.12565 \times 101,325 = 12,731.486$ Pa, appears as the saturation pressure of water at 50.6 C in vapor pressure tables, meaning the vapor condenses in the cooled gas sample at 50.6 C.

Excess air lowers the proportion of vapor [Eq. (17)] as well as the dew point. With 100% excess air ($E = 1$), for example, the dew point drops to 38.7 C. The effect of fuel moisture and of vapor in the admitted air can be calculated by adding corresponding numbers of water molecules to Eqs. (15–17). Adding the vapor originating from 15% moisture content and from air at 20 C with 50% relative humidity, for example, gives the dew point 56.1 C for $E = 0$, and 43.8 C for $E = 1$.

Heat loss in flue gases

Amounts of heat that hot fire effluents carry out the chimney will vary mainly with flue gas temperatures. The heat loss depends also on the temperature of air as it enters the fire chamber, here assumed to average 20 C (68 F). Authors working with British units of measurement generally assume 70 F (21.1 C) air temperature.

The losses occur in the forms of sensible heat that one can feel and of latent heat in gases. Latent heat is released as heat of fusion when gases condense, while it has to be added as heat of vaporization to convert liquid into gas. Water vapor in fire effluents of wood holds substantial amounts of latent heat; other effluents can be ignored in this regard, as they occur only in tiny amounts or do not condense. The latent heat of water vapor—listed in handbooks of physics, chemistry, and engineering—decreases as temperature rises, especially when the temperature approaches water's critical point (374 C), above which the vapor cannot be liquified any more by means of compression. I chose the latent heat of 20 C, 2.446 kJ/g.

Sensible heats of the various fire-effluent gases are calculated with heat capacities or specific heats listed in handbooks. The capacities, expressed in J/g C, slightly increase with increasing temperature. I am calculating with the capacity at the average, between 20 C and the flue gas temperature. Ince (1979) used simplified, practical formulas for estimating the losses in sensible and latent heat.

Figure 3 illustrates the losses in the various gases. The combustion gases (CO_2 , H_2O , and N) deserve special attention in this context. Among them, nitrogen holds 63% of the heat, as its proportion in air amounts to 76.85% by weight, with traces of inert gases included (ASHRAE 1981). Note that the combustion gases curve represents only sensible heat; latent heat of the combustion H_2O appears separately in Fig. 3, and by far exceeds the latent heat of the fuel's 15% moisture content (15% MC), since water formed in the combustion process amounts to 53.4% of the oven-dry wood mass (Fig. 1). (The fuel's high heat value, in contrast to the low heat value, includes that latent heat of the combustion water.) The shown 15% MC losses agree with values graphed by Corder (1973) for zero to 200% fuel moisture at 400 F (204.4 C) and 660 F (315.6 C) flue gas temperature. Excess air losses would equal the combustion gases losses at the point of 126% excess air. The zero-percent-excess air curve coincides with the abscissa of Fig. 3, of course.

Corder (1973) and Hughes (1976) segregated dry gas losses of carbon dioxide, oxygen, and nitrogen. In terms of Fig. 3 dry gas = combustion gases – comb. H_2O + excess air. Corder (1973) did not give the fuel's moisture content; his loss numbers agree with Fig. 3 for the realistic moisture content of 66%.

The combustion gases curve and the excess air curves represent losses in the form of sensible heat, which depend on the flue gas temperature by definition.

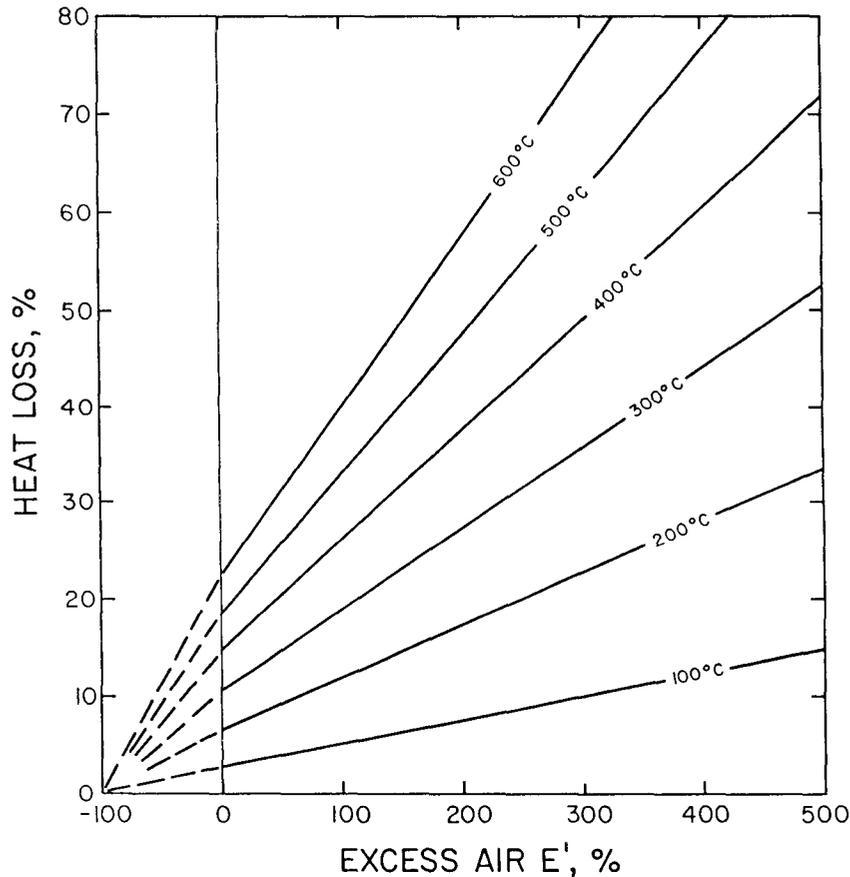


FIG. 4. Heat loss in the form of sensible heat with excess air and combustion gases, including water vapor, for stoichiometric combustion, expressed in percent of oven-dry wood's high heat value (20 kJ/g), at various flue gas temperatures. Losses in the range $E' < 0$ are indefinite, because in that range kinds and quantities of the fire effluents vary due to incomplete combustion.

Figure 4 combines the two. The curves for the different flue gas temperatures have a bend at the line of 0% excess air, which separates different substances. At and to the right of 0% excess air, only carbon dioxide, oxygen, water vapor, and nitrogen constitute the fire effluents; whereas to the left the effluents include numerous other substances because air shortage causes the wood to burn incompletely under evolution of indefinite amounts of combustible gases. A similar graph for wood fuel by Stamper and Koral (1979) does not agree with Fig. 4; this discrepancy cannot be explained with different assumed chemical composition of wood (41.25% oxygen versus 44.23%; Fig. 1). Stamper and Koral (1979) give little detail and do not tell exactly what their calculated heat losses include.

Figure 5 illustrates recoverable heat, which remains when all losses in the form of sensible and of latent heat are subtracted from wood's heat value. (Recoverable heat, expressed in percent of the heat value, can also be termed energy efficiency.) For example, at zero excess air and 200 C flue gas temperature, 84.2% of the fuel's chemical energy remains available, while 15.8% is lost—6.7% as sensible

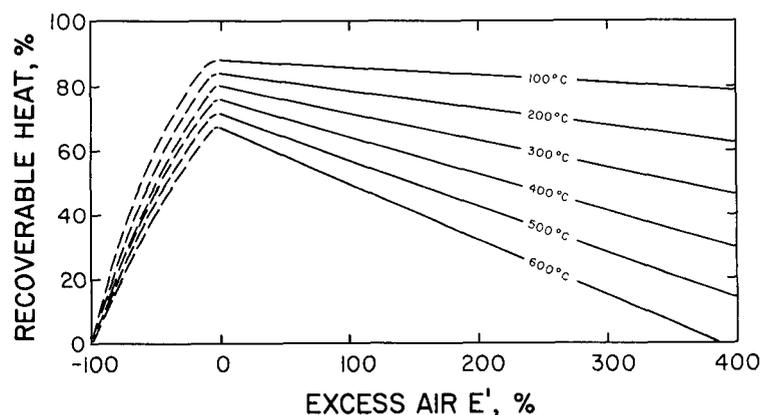


FIG. 5. Effect of excess air on recoverable heat at various flue gas temperatures. Air supplied at 20 C and 50% relative humidity. The heat is expressed in percent of oven-dry wood's high heat value (20 kJ/g). At $E' > 0\%$ complete combustion is assumed. At $E' < 0\%$ heats are indefinite due to incomplete combustion.

heat in combustion gases, 6.5% as latent heat in combustion vapor, 2.5% as sensible heat and latent heat in fuel moisture, and 0.1% as sensible heat in vapor of the admitted air. Highly variable energy losses due to incomplete combustion, thermal radiation, conduction, and convection are not considered here. Mainly because of these losses and higher moisture contents of the fuel, "boiler efficiencies" given by Corder (1973), Hughes (1976), and Roberts and Austin (1982) are much lower than the recoverable heats in Fig. 5.

According to Fig. 5, recoverable heat reaches an optimum at the point of zero excess air, when stoichiometrically exact air enters the fire chamber. Air shortage causes incomplete combustion and drastically curtails combustion efficiency, and for these reasons must be avoided. In case the optimum at zero excess air cannot be achieved exactly, one should operate on the safe side with excess air, since it involves much smaller losses than insufficient air.

Excess air for complete combustion

Exact stoichiometric oxygen does not reach all pyrolysis-gas molecules, and reacts only with a part of them; the others remain unburned and form various combustible compounds. According to a general rule, complete combustion requires the three *T*'s, meaning sufficiently high *Temperature*, strong *Turbulence* of the air-gas mixture, and a long residence *Time* of the mixture in the fire chamber. Turbulence and long residence bring each pyrolysis-gas molecule close to oxygen and provide chances for combustion. Fuel molecules as such, however, do not react; they have to break up (*dissociate*) first into reactive atoms, which then readily combine with oxygen atoms. The molecules dissociate on impact when they collide at the high speed of intense molecular motion, which actually is the characteristic of high temperature. For this reason, wood-pyrolysis gases burn only above 600 C (Shelton 1976; Calvert and Englund 1984).

Natural gas and "atomized" or dispersed fuel oil mix with air more thoroughly and uniformly than pyrolysis products of solid fuels, one reason being that gas

and oil flow steadily into a mixing zone, whereas pyrolysis products of solid fuels evolve unsteadily as time passes. Nevertheless, gas and oil burners need at the very least 10% excess air (Cone 1980). Stamper and Koral (1979) recommend 15–30%, while ASHRAE (1981) mentions 5–50% as general practice, “depending on the type of fuel burned, combustion equipment, and other factors.”

Dyer et al. (1978b) demonstrated that the excess air required for complete combustion in wood stoves depends on temperature: it was around 110% at 315 C but only 20% at 600 C flue gas temperature. [Fire chamber temperatures were much higher, of course; I calculated the excess air percentages with Eq. (10) for oxygen contents measured by Dyer et al. (1978b).] Wood-fired boilers generally admit 25–50% excess air; more air would lower combustion temperatures, combustion rates, and boiler efficiencies. Hughes (1976) lists 50–100% excess air as the desired range for boilers burning moist wood, while Curkeet and Husom (1983) consider 55% excess air as the prerequisite for complete combustion. Fireplaces receive much more air; Snowden et al. (1975) mention for them 4,900% excess air as an example.

The fact that complete combustion requires excess air does not invalidate Figs. 1 to 5. In Fig. 3 the combustion gases loss applies to ideal, stoichiometric combustion. Flue gases of real complete combustion with excess air include additional nitrogen and oxygen, which are considered in the excess air curves. In other words, adding up the various losses of Fig. 3 leads to the correct total.

ENERGY LOSS DUE TO INSUFFICIENT AIR

Under ideal conditions, recoverable heat peaks at the point of stoichiometric or zero excess air (Fig. 5). In reality, the peak occurs somewhere between 10 and 100% excess air, the minimum required for complete combustion. In the air-shortage range from –100% to zero percent excess air, the temperature curves of Fig. 5 appear dashed to indicate that the recoverable heats are indefinite and highly variable.

Whether in the air-shortage range recoverable heat increases more than in proportion to excess air, as shown in Fig. 5, depends mainly on what remains unburned—pyrolysis volatiles or solid charcoal. Unburned volatiles amount to lost fuel, whereas residual charcoal may burn later together with new fuel. Many residential wood burners suddenly shut off the air, so as to bank the fire overnight or to reduce heat output; in the slowly cooling fire chamber, the pyrolysis process continues while the resulting charcoal essentially remains, so that up to one half of the original wood mass may be left as charcoal (Klason et al. 1910). Since the heat value of a mass unit of charcoal by far exceeds the heat value of wood on a weight basis, the charcoal may retain more than one half of the original wood's chemical energy (Shelton 1976). In that case substantial heat remains recoverable, so that in Fig. 5 near the point of –100% excess air, the temperature curves will be relatively steep, as shown.

Effluents of air-starved fires contain plenty of carbon monoxide (Hawkins 1967). Wood that theoretically reacts with one half of stoichiometric oxygen, forming carbon monoxide rather than carbon dioxide, releases 40% of wood's chemical energy; 60% remains in the carbon monoxide; according to my calculation on the basis of the heat value of carbon monoxide. [Heat released by carbon burning to carbon monoxide amounts to 28% of the heat released by carbon burning to

carbon dioxide (ASHRAE 1985).] These facts speak for a relationship that differs somewhat from that shown in Fig. 5 for the air-shortage range, as the recoverable heat would increase less than in proportion to the admitted air.

Fire effluents of incompletely burning wood contain numerous other combustible gases and some tars (DeAngelis et al. 1980), whose effect on recoverable heat as a function of admitted air may vary, but the combined effect of all unburned substances probably comes close to a linear relationship.

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