OXYGEN SENSOR FOR CONTROL OF WOOD COMBUSTION: A REVIEW

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ABSTRACT

Zirconia type oxygen sensors, installed in the exhaust manifold of combustion engines, generate a voltage that drastically changes when the carburetor's air/fuel ratio deviates from the stoichiometric optimum. On this basis such sensors automatically regulate the supply of air and fuel in modern automobiles and in large wood-burning boilers. The literature is reviewed for use of the sensors in residential wood-burning furnaces and stoves, whose fires generally receive either too little or too much air. Unfortunately the sensors' temperature should be above 300 C, a temperature that fire effluents of the residential heating implements reach only near the end of the combustion zone, and then rapidly cool off on their further path to the chimney. Therefore, the sensors are far from ideal for residential heating implements, least of all for small stoves operated batchwise. They are more promising for the combustion control of continuously fueled pellet furnaces.

Keywords: Residential heating, combustion efficiency, flue gasses, air pollution, pellet furnace.

INTRODUCTION

Stoves, furnaces, and boilers need certain amounts of combustion air. Excessive air carries heat up the chimney, while too little air evokes incomplete combustion and emission of many undesired substances. Effluents of partly burned wood include poisonous carbon monoxide and carcinogenic hydrocarbons, both notorious air pollutants. The smoke of air-starved fires also contains mists, condensing gases, and tiny carbon particles—a group of substances that form or contribute to the combustible chimney deposits creosote and soot.

Internal combustion engines that burn gasoline and diesel oil involve similar problems. Wood differs chemically from these hydrocarbon fuels essentially only in that it contains oxygen and has a correspondingly lower heat value. In gasoline engines of modern automobiles, an oxygen sensor in the exhaust manifold controls the air/fuel ratio in the carburetor to achieve efficient combustion; whenever the exhaust contains too much oxygen, the sensor signals *reduce the air supply,* or *inject more fuel,* while calling for more air when oxygen drops below the desired level.

The sensors may be suited also for controlling the air damper in wood-burning implements. However, even though the proper amounts of combustion air are admitted, fuel may still burn incompletely when the fire chamber is too cool, or when wood-pyrolysis gases mix inadequately with the air. The chamber temperature is relatively easy to monitor; and in stoves of good design, the gases do mix adequately. Regulation of air supply on the basis of monitored smoke opacity or of carbon monoxide or of hydrocarbons is not feasible, because the fire effluents have too many possible causes. Control of air supply based on temperatures in a primary pyrolysis chamber, as well as in a secondary combustion chamber, is a promising alternative to monitoring oxygen contents in the flue gases (Lamppa and Lamppa 1989), although theoretically the temperature method is not foolproof.

Oxygen contents of flue gases can be deter-

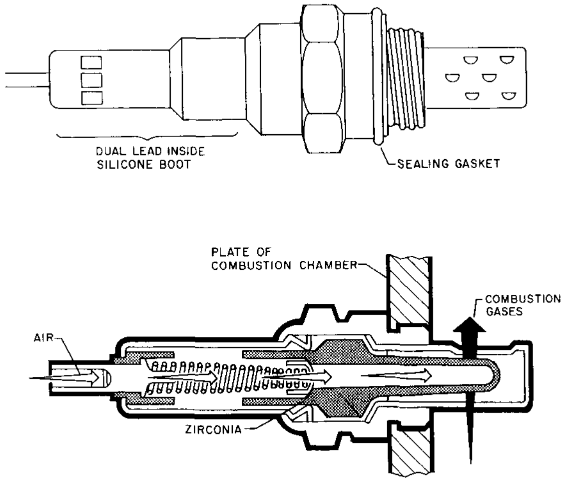

FIG. 1. Oyxgen sensor type EC-700. The sensor shield is 18 mm long and 10 mm in outside diameter. (Adapted from General Motors literature.)

mined accurately through Orsat gas analysis; that is, by bubbling a sample of the gas mixture through a solution which absorbs the oxygen. However, this grab sample method takes too much time. The flue gases should be monitored continuously and effortlessly. Boilers and other large heat-generating facilities are equipped with automatic indicators for oxygen and other gases. Some of their oxygen sensors are of the zirconia type used in automobiles, but together with the associated signal processors they cost at least $2,000, which is far too much for residential use. Oxygen monitors based on electrical resistance, thermal conductivity, and paramagnetic analyzers of the gases are not cheap either. Operators of large boilers monitor not only oxygen but also carbon dioxide, carbon monoxide, hydrocarbons, and particulates. The comprehensive controls cost thousands, but are justified by fuel savings through efficient operation with exactly metered air supplies.

Residential wood-burners need inexpensive automatic control devices. The mass-produced zirconia-type oxygen sensors for automobiles are indeed cheap. They cost only $50 and are readily available in auto parts stores. The sensors' electrical signal of up to 1 V can be measured with meters that cost less than $40, or the meter may be hooked up to an air vent actuator.

DESCRIPTION OF THE SENSOR AND HOW IT FUNCTIONS IN AUTOMOBILES

A common sensor type is illustrated in Fig. 1. It contains a ceramic thimble of zirconium dioxide [ZrO_2, also called zirconia, zirconium (Zr) being a metallic element]. The zirconia functions like the solid electrolyte of a galvanic cell, as different oxygen concentrations at the thimble's inner and outer surfaces generate voltage (Eddy 1974). A barely visible capillary tube in the protective boot connects the thimble chamber with ambient air, while exhaust gases bathe the thimble's outside surface. One-sided partial oxygen pressure drives oxygen across the thimble wall, generating a voltage. Actually both surfaces of the thimble are coated with porous platinum, which serves as conductive electrodes and as catalyst for reactions at the two surfaces. Two wires, shown in Fig. 1 at the top left, lead to the electrodes. The louvered metal shield protects the sensor from particulates in the exhaust and from mechanical damage. Overall the sensor is a simple electrochemical cell that develops a voltage between the two electrodes and functions as a voltaic oxygen concentration cell.

Figure 2 depicts the sensor output in effluents of burning gasoline for different air/fuel ratios. The voltage changes abruptly near the stoichiometric point, where the supplied air-fuel-mixture contains exactly the amount of oxygen for reaction with all carbon and hydrogen in the fuel. The step change follows the relationship governing the millivolt (E) output of galvanic zirconia cells

$$E = 0.02154T \ln(20.5/p) \qquad (1)$$

(Badwal et al. 1988). T stands for the absolute temperature (K) of the electrolyte, and p for the volumetric oxygen percentage in the combustion effluents, which is 20.5 in ambient air (Kubler 1991).

Values of ln(20.5/p) increase substantially when p approaches 0%. According to Eq. (1), at 400 C the output E reaches 1,000 mV for p

$= 2.26 \times 10^{-29}\%$ oxygen, that is, essentially an oxygen-free effluent. The output drops to 100 mV at p = 0.021% and to 50 mV at 0.65%. Note that the voltage step from 800 mV to 50 mV, for example, is associated with an extraordinary oxygen-percentage change by a factor of more than 10^{20}. The more common oxygen contents 5% and 10%, for example, correspond to the voltages 20.5 mV and 10.4 mV, respectively.

The abrupt voltage step near the stoichiometric point results partly from carbon monoxide, hydrogen, and residual hydrocarbons in the effluents of combustion with insufficient air (Valasco and Schnell 1983). The plain electrode catalyzes oxidation of the residual fuels, which in turn depletes the oxygen at the sensor surface, with the effect of increasing voltage output. Additionally, the unburned fuels themselves generate a galvanic zirconia voltage, which obeys the Nernst equation on which Eq. (1) is based. Because of the effects of these unburned substances, the sensor may generate more voltage than calculated with Eq. (1), and the knees of the theoretical curve in Fig. 2 wash out. The sensor essentially works as an oxygen detector for lean air/fuel (A/F) ratios, and as a combustible gas detector for rich A/F ratios. It cannot be used to detect exact oxygen contents when unburned gases remain in the effluents. Therefore, for heating implements Beckley (1980) recommended combining the oxygen sensor with a sensor for combustibles.

The zirconia is generally doped and sintered with metal oxides for stabilization. For this reason, unburned gases may have varying effects, and zirconia sensors are not all the same. The voltage step may be somewhat blunt, it may not coincide exactly with the stoichiometric point, and the shift away from the stoichiometric point may depend on temperature (Saji et al. 1988a).

Since catalytic devices for reducing exhaust emissions of combustion engines reach maximum efficiency near the stoichiometric point, catalytic converters in the exhaust system of automobiles require regulation of the A/F ratio close to that point—an ideal task for zirconia oxygen sensors. Fortunately, the abrupt voltage step of the sensors is practically not temperature-dependent (Fig. 2), and the sensors have short response times in the order of milliseconds. They adjust the A/F ratio many times in each second by sending a voltage signal to the engine's electronic control module, essentially a computer, which in turn informs the mixture control solenoid in the carburetor to change the A/F mixture. Since 1976, millions of zirconia oxygen sensors have been installed in the exhaust manifold of gasoline engines.

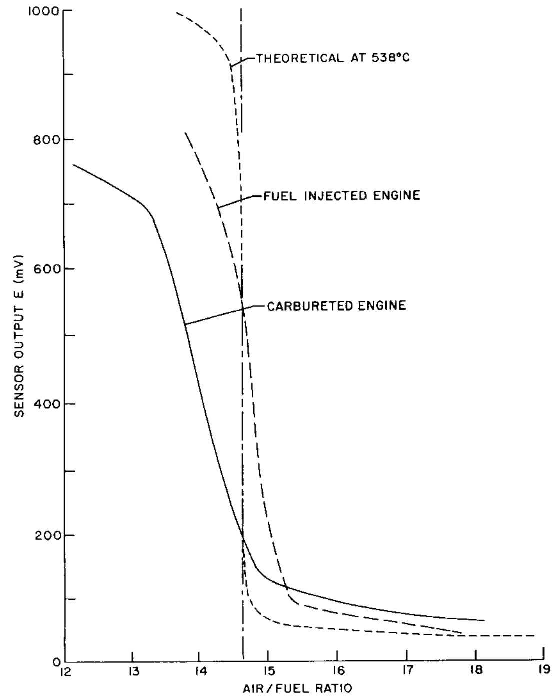

FIG. 2. Comparison of experimental and theoretical sensor responses, as related to the supplied air/fuel ratio for $C_xH_{1.84x}$ fuel. The vertical line marks the stoichiometric ratio near 14.6. (Adapted from Fleming et al. 1973.)

USE FOR CONTROL OF WOOD COMBUSTION

In implements that burn solid fuel, air and combustible pyrolysis gases do not mix as well as gasoline vapors mix in the carburetor of internal combustion engines. Even in efficient boilers for coal and wood, air enters the fire chamber relatively far away from the zone where pyrolysis gases effuse out of the ther-

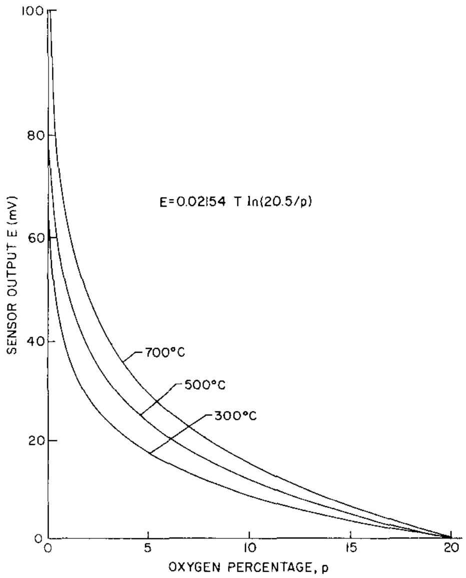

FIG. 3. Effect of temperature on sensor output according to Eq. (1).

mally decomposing fuel, so that many molecules of combustible gases tend to remain apart from oxygen and do not burn. Therefore, solid-fuel-burning implements require more than stoichiometric air, that is to say *excess air*, defined as the ratio of flue-gas-oxygen mass to the stoichiometric-oxygen mass. Excess air is usually expressed in percent; the ratio 1.0, for example, equals 100% excess air.

Desirable oxygen contents in the effluents of wood-burning boilers are in the order of 5%, in stoves about 10%. At oxygen contents of this magnitude, the sensor output of E of Eq. (1) varies little as oxygen percentages change; the voltage does not change abruptly as it does near the stoichiometric point in gasoline combustion engines. In view of this fact, zirconia oxygen sensors appear to be poorly suited for wood-burning implements.

Due, however, to the explained effects of unburned pyrolysis gases in the fire effluents, the sensor should nevertheless signal incomplete combustion and inadequate air supply. For continuously working heating devices, such as automatically fueled pellet stoves, the sensor is more promising than in batchwise operated devices, in which new charges drastically change the fire effluents and cool the sensor below its minimum functioning temperature.

Hickam and Zamaria (1967) tried a zirconia oxygen detector to control a gas-fired heating furnace at the Westinghouse Research Laboratories. The detector promptly responded to change in oxygen content in the smoke stack, as air-flow and fuel-flow to the furnace were manually adjusted. Next the signal voltage from the oxygen detector was amplified and used to control the fuel valve and the furnace air damper actuators. In following years, zirconia oxygen sensors became common for continuous monitoring of flue gases in boilers, including solid-fuel boilers (Helmer et al. 1988). The sensors permitted operation with greatly reduced excess air (Fouletier 1983), and seemed to work adequately in an experimental burner for wood-coal pellets (Chen and Workman 1990).

EFFECT OF SENSOR TEMPERATURE

Since the mobility of oxygen ions in zirconia is thermally activated, zirconia becomes an ionic conductor only at high degrees of heat (Fouletier 1983). One cannot, however, specify a certain temperature above which a particular sensor responds. The minimum working temperature depends on the impedance of the measuring voltmeter, which should be small compared with the zirconia thimble's temperature-dependent impedance.

The sensor of Fig. 1 is supposed to reach more than 300 C. Other brands require at least 500 C (Eddy 1974), especially for high oxygen percentages (Maskell and Steele 1986). At lower than recommended degrees of heat, response times deteriorate rapidly because the response is essentially determined by the mass transport through the porous electrodes, rather than by the kinetics of catalyzed gas reactions. According to Eq. (1), the sensor output increases in proportion to the absolute temperature, as shown in Fig. 3. The stronger signals at higher temperatures are more discriminating as to different oxygen concentrations.

To achieve sufficiently high temperatures in the active ceramic and in the coating electrodes, the sensor should be installed near the hottest region of the heating implement, where flames almost lick it. In properly designed sensors, a nonmetallic housing insulates the active parts from the relatively cool holding plate (Fig. 1). The vital ceramic is less hot than the fire effluents also because the sensor's body and the connecting, heat-conducting wires are exposed to ambient air. In one experimental setup, actual fire effluent temperatures were 50 C, 75 C, and 90 C above the sensor tip temperatures of 150 C, 350 C, and 800 C, respectively (Young and Bode 1979).

IMPROVED ZIRCONIA TYPE OXYGEN SENSORS

Efforts were made and are going on to develop more versatile zirconia type oxygen sensors (Maskell and Steele 1986), one objective being measurements in the range of several percent of oxygen, which is of interest for wood burning. The automobile industry attempts "lean-burn" operating conditions with less than stoichiometric oxygen, in order to lower fuel consumption and improve economy (Westbrook 1989). The wider range is achieved through electrochemical oxygen pumping through electric current imposition, in which external voltage forces oxygen ions to migrate across the ceramic. Through ion pumping, sensor output follows a linear relationship to oxygen concentration rather than the logarithmic relationship of traditional sensors, and makes the sensors more sensitive at higher oxygen concentrations (Hetrick et al. 1981; Saji 1987; Saji et al. 1988b; Whelan and Borbidge 1988).

Efforts aimed at lowering the operating temperature by means of new types of electrodes had some success (Badwal and Ciacchi 1986; Inoue et al. 1990). More recent research did lead to zirconia-base sensors which are operable at 400 C (Usui et al. 1989), and even down to room temperature (Miyahara et al. 1988), but it remains to be seen whether and for what purpose the new types are feasible. Of course, heating the ceramic by means of an integrated resistor breaks the temperature barrier, as less than 3 W power maintains the sensor on a very favorable temperature level above 600 C (Valasco and Schnell 1983). Sensors of this kind, marketed as 3-wire HEGO (Heated Exhaust Gas Oxygen) sensors are available. So far, apparently only zirconia oxygen sensors are used in automobiles (Valasco and Schnell 1983), but other electrochemical sensors may make inroads, especially for purposes other than in automobiles (Maskell 1987; Inoue et al. 1990).

CONCLUSION

Zirconia type oxygen sensors appear to be suited for monitoring flue gases of wood-burning furnaces and stoves, provided the sensor is installed where the gases are adequately mixed and still very hot. Reliable, universal application of the sensors in wood-burning implements may require further research and development work by manufacturers of the implements, in cooperation with producers of the sensors.

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