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CONFIRMATION NO. 3216

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JED MARGOLIN
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CORRECTED FILING RECEIPT

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The country code and number of your priority application, to be used for filing abroad under the Paris Convention, is **US 63/373,995**

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Early Publication Request: No
** SMALL ENTITY **

Title

> System for controlling premixed flames

Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications: No

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UNITED STATES PROVISIONAL APPLICATION FOR PATENT

FOR

SYSTEM FOR CONTROLLING PREMIXED FLAMES

INVENTOR: JED MARGOLIN

SYSTEM FOR CONTROLLING PREMIXED FLAMES

BACKGROUND OF THE INVENTION - Field of Invention

[001]   This invention relates to the field of determining and controlling the air/fuel mixture in a premixed gas flame. This is important for producing a flame with reasonable efficiency but with low pollutants.

The term "combustion" means the process of oxidation of molecules of combustible substances that occurs readily at high temperatures with the release of energy. It is accompanied by that phenomenon which is called "flame" and by the generation of "heat energy".

The term "flame" means a self-sustaining propagation of a localized combustion zone at subsonic velocities.

The term "combustion burner" means a device used for facilitating the combustion of a gas or a liquid. The term "burner" means the same as combustion burner.

The term "flame conductivity" means the electrical conductivity of a flame. The unit of conductivity is the "mho". The term "flame conduction" means the same as flame conductivity.

The term "flame resistance" is the reciprocal of flame conductivity. The unit of resistance is the Ohm.

The term "flame capacitance" means the property of a flame that makes the flame act like a capacitor. The term "flame capacitor" is the manifestation of flame capacitance.

The term "flame rectification" means the property of flames to preferentially conduct electrical current depending on the direction of the electrical current.

The term "flame electrode" means an electrically conducting material immersed in a flame (when a flame is present), and which is electrically isolated from the combustion burner (except for a flame) and which may be electrically connected to something outside of the flame. The term "flame probe" means the same as flame electrode. The term "flame rod" means the same as flame electrode. The term "flame sensor" means the same as flame electrode.

The term "flame battery" means the voltage produced between a combustion burner and a flame electrode that is immersed in the flame produced by the combustion burner. The term "flame voltage" means the same as flame battery.

The term "flame proof" means proof that a flame exists. The term "proof of flame" means the same as flame proof.

The term "plasma" means a collection of gas where a large proportion of atoms have enough energy that their electrons have been stripped away, creating ions, and that the proportion of ions to intact atoms is high enough that Coulomb forces have a significant effect on the behavior of the collection of gas. The ions creating the plasma will be termed "plasma ions".

The term "chemical ions" means reactive molecules, or atoms, that have unpaired electrons. The term "chemi-ionization" means the process by which molecules, or atoms, come to have unpaired electrons. The terms "chemi-ions" , "radical" , and "free radical" mean the same as chemical ions.

The term "thermionic emission" means the emission of electrons from the surface of an electrically conducting material when the material is heated to a temperature high enough to overcome the work function of the material, typically several electron volts. One electron volt is equal to approximately 1.602×10^{-19} Joules.

The terms "amplifier" and "buffer" will mean the same thing regardless of the gain of the circuit.

The term "mixer" means a circuit that accepts two signal inputs and forms an output signal at the sum and difference frequencies of the two signals. The term "mixing" means using a mixer. When two signals are mixed in this manner it is also called heterodyning.

The term "symmetrical square wave" means a square wave having a duty cycle of substantially 50%.

BACKGROUND OF THE INVENTION – Prior Art

[002]   U.S. Patent 4,585,161 **Air fuel ratio control system for furnace** issued April 29, 1986 to Kusama, et al. teaches the use of a first sensor to measure the gas flow rate and second sensor to measure the air flow rate with controls to control the amount of gas and air provided. It does not use a feedback mechanism that is responsive to the results of combustion. (*Reference 1*)

U.S. Patent 4,942,832 **Method and device for controlling NOx emissions by vitiation** issued July 24, 1990 to Finke teaches the use of various sensors, including an oxygen sensor to determine the ideal quantity of vitiated combustion air to be supplied to the burner to minimize NOx emissions. The sensors are positioned throughout the furnace to measure flow rate, temperature, oxygen concentration and pressure. (*Reference 2*)

U.S. Patent 10,151,483 **Method for monitoring and controlling combustion in fuel gas burner apparatus, and combustion control system operating in accordance with said method** issued December 11, 2018 to Abate, et al. teaches the use of alternating positive and negative pulses applied to the flame to charge the flame capacitor and then observe its discharge through flame resistance and/or the resistance of the circuit connected to it. Their preferred pulse repetition frequency uses the power that comes from the power delivered to burner. See Column 7 lines 35-39. Although not stated, that would be 50Hz/60Hz because those are the common frequencies of power used worldwide. (*Reference 3*)

U.S. Patent 9,784,449 **Flame Sensing System** issued 10/10/2017 to Margolin (also the present inventor) teaches the use of flame rectification to heterodyne two signals supplied to a flame and use quadrature synchronous detection for detecting the resulting sum and/or difference signals. The same mechanism causes a single signal introduced to a flame to produce the second harmonic of the signal and quadrature synchronous detection is used for detecting this second harmonic. These effects of flame rectification are produced only when a flame is present and can therefore be used for flame proof. (*Reference 4*)

BACKGROUND OF THE INVENTION – Processes That May Produce or Contribute to the Electrical Properties of Flames

[003]   The investigation of the electrical properties of flames goes back to at least the early 1900s with the work of J. J. Thomson. See *Reference 5* for an excerpt from Thomson's work **Conduction of Electricity Through Gases** (1903, 1906) Chapter IX **Ionization in Gases from Flames**.

Thomson begins the chapter with an observation that modern researchers in the field should take notice of. Writing in 1903 he observed:

> 121. It has been known for more than a century that gases from flames are conductors of electricity; a well-known application of this fact—the discharge of electricity from the surface of a non-conductor by passing a flame over It—was used by Volta in his experiments in Contact Electricity. We shall not attempt to give any historical account of the earlier experiments on this subject, because the conditions in these experiments were generally such that the interpretation of the results obtained is always exceedingly difficult and often ambiguous: the reason of this is very obvious—to investigate the electrical conditions of the flame wires are generally introduced, these become incandescent and so at once add to the electrical phenomena in the flame the very complicated effects we have been discussing in the last chapter.

[004] The electrical properties of flames comprise flame conduction, flame capacitance, flame rectification, and the generation of a flame voltage between a metal burner and a flame rod (flame battery).

There are several processes which may account for the electrical properties of flames.

From *Reference 6* **Ionic structure of methane flames**, Timothy Wayne Pedersen, Iowa State University, 1991:

1. A natural gas flame is a weakly ionized plasma.

2. 99% of the negative charge is carried by free elections.

[It isn't much, which is why the flame resistance is so high.]

3. The dominant positive chemi-ions are $CHO+$, H_3O+, C_3H_3+ , and CH_3+. This list was increased by one species when C_2H_3O+ was found to be the dominant ion in lean acetylene flames.

From the Pederson paper:

> Lawton and Weinberg [8] have shown that by placing an ion-producing flame in an electric field, the saturation current for that flame can be measured. In general, ions are removed from a flame by recombination with electrons. When the flame is immersed in an electric field, ions are removed by recombination as well as by the electric field. The positive ions are attracted to

the cathode. The negative charge, 99% of which is carried by free electrons [9], is attracted to the anode. As the potential is increased, removal of the ions due to the electric field becomes dominant over removal by recombination. Eventually the electric field will remove the ions from the flames as fast as they are produced by chemiionization. The current produced by the movement of these ions when this phenomena occurs is called the saturation current, j_s. It is defined as the rate of ion removal from the flame per unit area of flame front.

.....

It was Arrhenius [15] in 1891 who proposed that the negative charge carrier in the flame was free electrons. He based his conclusion on results obtained through mobility measurements. In 1965 Calcote [9] used electric probes and a mass spectrometer to show that 99% of the negative charge was indeed carried by free electrons.

.....

In 1910 Thompson [16] suggested that electrons play an important role in flame propagation. Since the electrons are much smaller than positive ions, it was thought that they diffused quickly into the unburned gases. Therefore, electrons initiated or assisted in the initiation of reactions that produced free radicals. Tanford and Pease [17] in 1947 proposed a similar theory for H atoms. Because the H atom is also very small, it too was thought to diffuse upstream and participate in initiation reactions. Up until 1947, it was thought that ions in flames were produced by thermal ionization. It was Calcote [18] who first disproved the general belief that ionization in flames was thermal in origin. In his review of ions in flames, he showed sufficient data existed in literature to support his theory that ions in flames were formed by a different mechanism. He proposed a kinetic mechanism as opposed to an equilibrium mechanism as being responsible for the formation of ionic species. This mechanism responsible for the formation of ions in flames was termed chemiionization.

.....

Information pertaining to the identities of ions in flames has been obtained directly from the flame using a mass spectrometer. Numerous ions, including CHO"*", have been identified by researchers as being present in hydrocarbon flames. Green and Sugden [31] were the first to divide the ions into three categories: true flame ions, ions formed in the mass spectrometer, and ions of unknown origin. In doing so, the list of major true flame ions present in all hydrocarbon flames was reduced to only four: $CHO+$, H_3O+, C_3H_3+, and CH_3+. This list was increased by one species when C_2H_3O+ was found to be the dominant ion in lean acetylene flames [30, 32].

The present inventor believes that flame capacitance is caused by the inertia resulting from the masses of the various chemi-ions.

The temperature of a gas is a measure of the average kinetic energy of the gas molecules as they collide with each other and with the walls of the container. If the container walls are rigid the molecules will bounce off. With a flame the walls are the atmosphere, and the boundary between the flame and the atmosphere is a function of atmospheric pressure. The collisions between the molecules in the flame and the molecules in the atmosphere produce diffusion. It is this diffusion that makes diffusion flames possible. An example of a diffusion flame is the flame produced by a wax candle. The other type of flame is called a premixed flame and is where the oxidizer (the oxygen in the atmosphere) is mixed with the fuel before combustion. Premixed flames produce a more stoichiometric mixture than diffusion flames, so they burn more completely (and hotter). For this reason most furnaces use premixed flames. In a liquid the molecules slide past each other. In a solid the molecules vibrate.

Therefore, the higher the temperature the faster the chemi-ions move which results in a lower flame capacitance and lower flame resistance.

There is another electrical property of flames, namely that flames absorb microwave radiation. See *Reference 7* **Prediction and Measurement of Electron Density and Collision Frequency in a Weakly Ionised Pine Fire** by Mphale, Mohan, and Heron. The absorption of microwaves appears to be a function of electron density and density and types of chemi-ions.

[005] There are more chemi-ions in flames than the dominant positive chemi-ions listed by Pederson (above).

From **Introduction to Combustion** by Stephen R. Turns *{Reference 8, page 108, PDF page 3}*:

> The use of global reactions to express the chemistry in a specific problem is frequently a "black box" approach. Although this approach may be useful in solving some problems, it does not provide a basis for understanding what is actually happening chemically in a system. For example, it is totally unrealistic to believe that *a* oxidizer molecules simultaneously collide with a single fuel molecule to form *b* product molecules, since this would require breaking several bonds and subsequently forming many new bonds. In reality, many sequential processes can occur involving many **intermediate species.** For example, consider the global reaction

$$2H_2 + O_2 \rightarrow 2H_2O. \hspace{3cm} (4.3)$$

To effect this global conversion of hydrogen and oxygen to water, the following **elementary reactions** are important:

$$H_2 + O_2 \rightarrow HO_2 + H, \hspace{3cm} (4.4)$$
$$H + O_2 \rightarrow OH + O, \hspace{3cm} (4.5)$$
$$OH + H_2 \rightarrow H_2O + H, \hspace{3cm} (4.6)$$
$$H + O_2 + M \rightarrow HO_2 + M, \hspace{3cm} (4.7)$$

among others.

In this partial mechanism for hydrogen combustion, we see from reaction 4.4 that when oxygen and hydrogen molecules collide and react, they do not yield water, but, instead, form the intermediate species HO_2, the hydroperoxy radical, and a hydrogen atom, H, another radical. **Radicals** or **free radicals** are reactive molecules, or atoms, that have unpaired electrons. To form HO_2 from H_2 and O_2 only one bond is broken and one bond formed. Alternatively, one might consider that H_2 and O_2 would react to form two hydroxyl radicals (OH); however, such a reaction is unlikely since it requires the breaking of two bonds and the creation of two new bonds. The hydrogen atom created in reaction 4.4 then reacts with O_2 to form two additional radicals, OH and O (reaction 4.5). It is the subsequent reaction (4.6) of the hydroxyl radical (OH) with molecular hydrogen that forms water. To have a complete picture of the combustion of H_2 and O_2 more than 20 elementary reactions can be considered [1, 2]. These we consider in Chapter 5. The collection of elementary reactions necessary to describe an overall reaction is called a reaction **mechanism.** Reaction mechanisms may involve only a few steps (i.e., elementary reactions) or as many as several hundred. A field of active research involves selecting the minimum number of elementary steps necessary to describe a particular global reaction.

Turns reports (citing GRI Mech 2.11) that at least 325 intermediate reactions have been found in the combustion of methane (natural gas). *See Reference 8, page 159, PDF bottom of page 5.* A portion of the list is reproduced in Figure 7.

The presence of nitrogen in some of the equations indicates that the methane is being burned using air. By volume dry air contains 78.09% nitrogen, 20.95% oxygen, 0.93% argon, 0.039% carbon dioxide, and small amounts of other gases.

Nitrogen compounds form starting at about 800 degrees Celsius, much lower than the temperature at which methane burns. The various species of nitrogen are generally represented as NO_x which is toxic and considered a pollutant.

[006] <u>**Additional Components in Natural Gas and Propane**</u>

There are more components in natural gas and propane. Since methane and propane are odorless, an odorant is added to make leaks easy to detect. The odorant most often used is mercaptan, which is methanethiol (also known as methyl mercaptan). Mercaptan is an organic compound with the chemical formula CH_3SH (also written as CH_4S). The sulfur no doubt produces the putrid smell. The flue of a gas furnace does not have this smell because the mercaptan is broken down and forms sulfur oxides (SO_2 and SO_3). As long as the temperature of the flue gas is above the gas dewpoint temperature the sulfur oxides will vent into the air where they may combine with water to form H_2SO_4 (sulfuric acid). Furnaces that recapture heat from the flue gas may cause the flue gas to drop below the gas dewpoint temperature resulting in H_2SO_4 precipitating in the equipment. *{Reference 9}*

Also, in the data reported by Turns a number of the formulas contain the letter "M". "M" is not an element. In chemistry the letter "M" is used to represent an alkali metal. *{Reference 10}.*
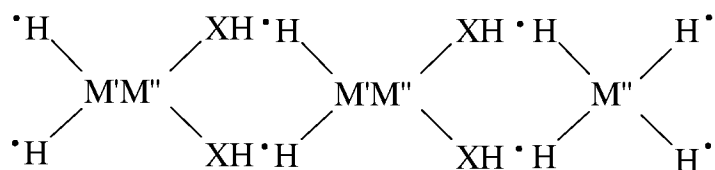
From Wikipedia *{Reference 11}*:

> The alkali metals are the elements in Group 1 (1A). They are lithium, sodium, potassium, rubidium, cesium, and francium. These elements are best marked by their reactivity. Physically they are soft, shiny (when freshly prepared) solids with low melting points; they conduct electricity well. They all have one valence electron that they lose easily to almost any electronegative substance.

Why are there alkali metals in natural gas?

[007] Some may be there naturally but some are there because of hydraulic fracturing, or "fracking". See U.S. Patent 4,317,487 **Method of recovering oil and other hydrocarbon values from subterranean formations** issued March 2, 1982 to Merkl, and assigned to Molecular Energy Research Company, Inc. *{Reference 12}*

After discussing various methods for enhancing the recovery of petroleum values from subterranean formations Merkl teaches (Column 2, line 59 – Column 3, line 11):

> The preferred method according to the present invention involves the introduction into the reservoir and into contact with the oil within the formation of an aqueous solution of a multi-metal, inorganic polymeric complex containing releasable active hydrogen in the form of one or more groups selected from NH, PH or SH. Specific inorganic, polymeric complexes have been used according to the method of the present invention have been analyzed to consist essentially of an inorganic polymer having the following repeating structure:

```
·H              XH ·H              XH ·H              H·
   \          /      \          /      \          /
     M'M"              M'M"              M"
   /          \      /          \      /          \
·H              XH ·H              XH ·H              H·
```

> Wherein M' is an alkali metal, and
>
> M" is a non-alkaline metal from groups I-VIII of the periodic table, and
>
> X is selected from nitrogen, phosphorus or sulfur.

[008]   There are even more components in the natural gas and propane used in furnaces and other equipment because Natural Gas is not 100% methane (CH_4) and Propane is not 100% propane (C_3H_8).

Natural Gas - From Turns pages 657-659 *{Reference 8 – Turns pages 657-659; PDF pages 22-24}*

Natural gas is typically found within or near oil fields. Natural gas is classified as *associated* or *nonassociated*, depending upon whether it is a product from an oil well (associated gas) or is the product of a gas well (nonassociated). Depending upon its composition, wellhead natural gas, particularly associated gas, must be processed before it can enter distribution pipeline systems. Unprocessed natural gas is primarily methane, with smaller quantities of other light (C_2-C_8) hydrocarbons. Noncombustible gases, N_2, CO_2, and He, are also frequently present. Hydrogen sulfide, mercaptans, water, oxygen, and other trace contaminants may be present. Separation of dissolved associated gas from crude oil is frequently not economical [9]; nevertheless, the amount of gas flared or vented annually worldwide is huge - 110 billion cubic meters, the equivalent to the combined annual natural gas consumption of France and Germany [25]. However, initiatives are in place to significantly reduce flaring of associated gas [25].

Although there are no industry or governmental standards for pipeline natural gas, contracts between producers and pipeline companies define general ranges of composition and other properties [26, 27]. Processing removes solid matter (e.g., sand), liquid hydrocarbons, sulfur compounds, water, nitrogen, carbon dioxide, helium, and any other undesirable compounds to meet contract specifications. The removal of sulfur compounds results in making an acidic, i.e., *sour*, gas *sweet*. Table 17.11 shows typical values, or ranges, of important properties of pipeline gas based on the General Terms and Conditions of a set of geographically dispersed pipeline companies in the United States and Canada.

The composition of natural gas varies widely depending upon the source. Examples for U.S. sources of natural gas are shown in Table 17.12. Compositions for natural gases from a variety of non-U.S. sources are provided in Table 17.13.

The following table (Table 1) is an abridged reproduction of Table 17.12 from Turns. The complete Turns Table 17.12 has been reproduced as Figure 8.

Table 17.12 Composition (mol%) and properties of natural gas from sources in the United States [28][a]

Location	CH_4	C_2H_6	C_3H_8	C_4H_{10}	CO_2	N_2
Alaska	99.6	—	—	—	—	0.4
Birmingham,	90.0	5.0	—	—	—	5.0
East Ohio[b]	94.1	3.01	0.42	0.28	0.71	1.41
Kansas City,	84.1	6.7	—	—	0.8	8.4
Pittsburgh,	83.4	15.8	—	—	—	0.8

Table 1 (Abridged Turns Table 17.12)

Thus, in Turns' sample natural gas ranged from a high of 99.6% in Alaska to a low of 83.4% in Pittsburgh.

[009] **Propane**

There are three basic grades of propane: HD5, HD10, and Commercial Grade. From *Reference 13* (Propane101):

HD-5 Propane

HD5 grade propane is "consumer grade" propane and is the most widely sold and distributed grade of propane in the U.S. market. HD5 is the highest grade propane available to consumers in the United States and is what propane companies ordinarily sell to their customers. What does HD5 propane mean in terms of specification to an ordinary consumer? It means that the propane is suitable and recommended for engine fuel use, which was the original purpose of the HD5 grade propane specification. HD5 spec propane consists of:

Minimum of 90% propane

Maximum of 5% propylene - propylene is used in the manufacture of plastics

Other gases constitute the remainder (iso-butane, butane, methane, etc.)
.....

HD-10 Propane and Commercial Propane

HD10 propane is a grade below HD5 and is commonly found in California. HD10 grade propane allows up to 10% propylene in the propane/propylene mixture and is still labeled as "propane". Because propylene is used in creating plastics, HD10 can possibly create problems in some engines and vehicle applications. Propylene can cause engine components to "gum" or stick during operation. However, HD 10 spec propane works just fine in domestic and commercial propane powered appliances. The only problem that may be encountered in using HD-10 propane involves its use as an engine fuel (vehicles, forklifts, etc.).
.....

Commercial grade propane and HD10 grade propane are sometimes used interchangeably due to the fact that both grades are sub-HD5 spec product and do not meet the standards of engine grade propane. Refineries use commercial propane in their processes and fractionation of chemicals for end use in numerous industries. Although commercial grade propane can be used in a manner similar to that of HD10 propane, it is not used in vehicle applications.

The article **The Truth About Propane** *[Reference 14]* goes a little farther. After discussing the Gas Processors' Association standard for propane, GPA 2140 (1932) which was the original HD5 standard, it then addresses the commercial grade of propane:

By contrast, since 1975, oil refineries were able to take advantage of the definition of propane in the ASTM (American Society for Testing and Materials) standard, ASTM Standard D1835, to market oil refining "odds and ends," known by chemical engineers as "slop," because they

could claim that the slop fit the definition of "commercial grade" propane: any hydrocarbon mixture that held a flame.

With HD5 and HD10 you have an idea of what you are getting. Apparently, commercial grade propane is the hotdog of the oil and gas refining business.

[010] The different components in natural gas and propane have their own heat content, burn at different temperatures, and require their own air/fuel mixture to burn at stoichiometric. There is no guaranty that the composition of natural gas and propane being delivered will always be the same. Therefore it is useful to be able to optimize the air/fuel mixture at least periodically.

[011]   Gas Pressure

A flame is not a bunch of chemical ions and free electrons in a sealed container. Gas and air come into the burner under pressure and combusts, producing chemical ions and free electrons which then form a large number of short-lived intermediate species ending with CO_2, H_2O, NOx, sulfur oxides, and probably more types of molecules. Then they go shooting off into the atmosphere. This process continues as long as there is new gas (unless the flame goes out for some reason). Because the gas pressure moves the gas molecules before combustion it is likely that after combustion this gas pressure gives the chemical ions and electrons a group velocity. But because different ions may have different masses, and because of the much smaller mass of the electrons, the negative chemical ions and the electrons may get to the flame rod first. And the free electrons are not just from chemical ionization.

[012] BACKGROUND OF THE INVENTION – Summary of the Processes that May Produce or Contribute to the Electrical Properties of Flames

A. The electrical properties of flames comprise:
1. Flame conduction.
2. Flame capacitance.
3. Flame rectification.
4. The generation of a flame voltage between a metal burner and a flame rod.

Figure 1 shows a representative Combustion Burner 1, Flame 2, and Flame Rod 3. Figure 2 is a representative electrical model of the electrical properties of Figure 1. This is an AC model and the flame battery is an integral part of the Flame Diode D (24). The values of Resistor R1 (21), Resistor

R2 (22), and Capacitor C (23) are functions of the flame temperature. In the absence of a flame (Figure 3) the representative electrical model is an open circuit (Figure 4).

[013]   BACKGROUND OF THE INVENTION – The Math

In this invention the flame rectifier is used as a mixer. A mixer is a circuit that accepts two signal inputs and forms an output signal at the sum and difference frequencies of the two signals. See *Reference 15* (Horowitz).

One type of mixer is a four-quadrant multiplier. For example, if you multiply two sine wave signals:

$$\sin(\omega 1 t) * \sin(\omega 2 t) \qquad\qquad \text{Equation 1}$$

and use a well known trigonometric identity you get:

$$\tfrac{1}{2} * \cos(\omega 1 - \omega 2)t - \tfrac{1}{2} * \cos(\omega 1 + \omega 2)t \qquad\qquad \text{Equation 2}$$

Horowitz uses the example of multiplying two cosines:

$$\cos(\omega 1 t) * \cos(\omega 2 t) \qquad\qquad \text{Equation 3}$$

and uses a well known trigonometric identity to get

$$\tfrac{1}{2} * \cos(\omega 1 - \omega 2)t + \tfrac{1}{2} * \cos(\omega 1 + \omega 2)t \qquad\qquad \text{Equation 4}$$

Both are equivalent because $\cos(\omega) = \sin(\pi/2 - \omega)$

Because multiplying two sine waves produces the sum and difference frequencies (Equation 2), if $\omega 1 = \omega 2$ you get

$$\tfrac{1}{2} * \cos(0)t - \tfrac{1}{2} * \cos(2\omega)t \qquad\qquad \text{Equation 5}$$

which is

$$\tfrac{1}{2} - \tfrac{1}{2} * \cos(2\omega)t \qquad\qquad \text{Equation 6}$$

which is a DC term and a signal at the second harmonic of the original signal.

Because a symmetrical square wave contains only odd harmonics the presence of the second harmonic can be produced only by flame rectification.

OBJECTS AND ADVANTAGES

[014]   The objects and advantages of the current invention are to optimize the air/fuel ratio in a combustion burner without using expensive sensors such as O_2 sensors, CO sensors, or NO_x sensors.

SUMMARY OF THE INVENTION

[015]   U.S. Patent 9,784,449 **Flame Sensing System** issued 10/10/2017 to Margolin (also the present inventor) teaches the use of flame rectification to heterodyne two signals supplied to a flame and use quadrature synchronous detection for detecting the resulting sum and/or difference signals. The same mechanism causes a single signal introduced to a flame to produce the second harmonic of the signal and quadrature synchronous detection is used for detecting this second harmonic. These effects of flame rectification are produced only when a flame is present and can therefore be used for flame proof. (*Reference 4*)   The goal of the invention was to provide a reliable system for flame proof and did not take it any further.

The present invention (also by Margolin) uses the property of flames that the flame resistance and flame capacitance are functions of the flame temperature. The higher the flame temperature the lower the flame resistance and the lower the flame capacitance. Conversely, the lower the flame temperature the higher the flame resistance and the higher the flame capacitance. Figure 5 shows that the flame temperature peaks with 100% air (for stoichiometric) and goes down when the mixture is either richer or leaner. Figure 5 also shows that the Angle between the In-Phase and Quadrature-Phase signals is at a minimum at stoichiometric and goes up when the mixture is either richer or leaner.

The flame resistance and flame capacitance cause a time delay of the signals applied to it. The time delay manifests itself as a phase difference between the In-Phase and Quadrature-Phase signals detected using quadrature synchronous detection as taught by Margolin's '449 patent.

In the following preferred embodiments the changes of the phase between the In-Phase and Quadrature-Phase signals detected using quadrature synchronous detection are used to control the air/fuel mixture of the premixed flame. The air/fuel mixture can be controlled to produce a maximum temperature (stoichiometric) or a lower temperature resulting from a lean air/fuel mixture to reduce NO_x.

[016] In the first preferred embodiment a flame rod is located where it will be immersed in a flame (when a flame is present) and flame rectification is used to cause **distortion in a selected waveform**. Because the distortion caused by the flame rectifier produces harmonics of interest the waveform is selected to not contain those harmonics such as the second harmonic. Since the flame's electrical characteristics constitute a high impedance circuit a high impedance buffer is used to buffer the signal.

The selected harmonic of the selected waveform is detected by a **quadrature synchronous detector** of standard design where the quadrature synchronous detector consists of two multipliers. The output of the high impedance buffer goes to a first input of the first multiplier and also to a first input of the second multiplier. A second input to the first multiplier receives a first reference signal having the same frequency as the selected harmonic to be detected and is derived from the fundamental frequency of the selected waveform. A second input to the second multiplier receives a second reference that is substantially 90 degrees out of phase with the first reference signal.

The output of the first multiplier is filtered and is the In-Phase output. The output of the second multiplier is filtered and is the Quadrature-Phase output.

The angle between the In-Phase and Quadrature-Phase signals is calculated using the standard method of:

Magnitude = SQRT(In-Phase^2 + Quadrature-Phase^2)

Angle = ArcSine(Quadrature-Phase / Magnitude)

[017] In the second preferred embodiment a flame rod is located where it will be immersed in a flame (when a flame is present) and flame rectification is used as a mixer to **cause two signals having selected waveforms to produce sum and difference signals**. The two signals having selected waveforms should be of different frequencies. Since the flame's electrical characteristics constitute a high impedance circuit a high impedance buffer is used to buffer the signal.

The selected sum or difference signal is detected by a **quadrature synchronous detector** of standard design. The quadrature synchronous detector consists of two multipliers. The output of the high impedance buffer goes to a first input of the first multiplier and also to a first input of the second multiplier. A second input to the first multiplier receives a first reference signal having the same frequency as the selected signal to be detected. A second input to the second multiplier receives a second reference that is substantially 90 degrees out of phase with the first reference signal.

The output of the first multiplier is filtered and is the In-Phase output. The output of the second multiplier is filtered and is the Quadrature-Phase output.

The angle between the detected In-Phase and Quadrature-Phase signals is calculated using the standard method of:

Magnitude = SQRT(In-Phase^2 + Quadrature-Phase^2)

Angle = ArcSine(Quadrature-Phase / Magnitude)

[018]   The following applies to both preferred embodiments.

The flame is started with reference flow levels of air and fuel and allowed to stabilize. The Angle is noted. The air flow is decreased slightly to make the mixture richer and the new Angle is noted. If the new Angle is greater than the old Angle it means the flame temperature has decreased and we are in the rich part of the curve in Figure 5 so the mixture is rich. If the new Angle is less than the old Angle it means the flame temperature has increased and we are in the lean part of the curve in Figure 5 and the mixture is lean. If the mixture is rich the air flow is increased slightly to make it leaner. If the mixture is lean the air flow is decreased slightly to make the mixture richer. In either case the flame is given time to stabilize and the new Angle is noted. We do this until the minimum Angle (highest temperature) is found. This is the stoichiometric mixture. A dead zone should be established around stoichiometric to prevent the system from oscillating. Once the stoichiometric mixture is found the mixture can be made leaner to reduce NO_x emissions. However, when the mixture is too lean that flame begins to lift off from the burner. When flame liftoff is too great the flame will go out. This is called Lean Burn Out (LBO) and is generally undesirable. When flame liftoff begins to happen the circuit from the Flame Rod to the Combustion Burner will become much less conductive and the In-Phase and Quadrature-Phase signals will decrease markedly, thus limiting how lean the flame can be made before LBO. This range can be increased by adding a Ground Rod between the Combustion Burner and the Flame Rod. See Figure 6.

As an alternative to adjusting the air flow to control the air/fuel mixture, the gas flow can be adjusted or a combination of air flow and gas flow can be adjusted.

This procedure can be performed as often or as rarely as desired. For example, in a furnace it can be performed as part of the startup sequence whenever there is a call for heat. It can be limited to be performed only once in any 24 hour period. It can be run only when the equipment is first installed because this system will automatically adjust itself for the altitude where the equipment is installed.

The system can also adjust for the air temperature because some furnaces are located in attics or garages which can experience a wide swing in temperatures during the day. With an appropriate air compressor supplying air 911 it will not be necessary to derate the equipment for operation at altitudes above sea level which is the common practice for furnaces and hot water heaters.

The data produced by the procedure can be used for maintenance purposes. If the data starts to show marked changes from normal it may indicate an impending failure of the equipment or it may mean the quality of the fuel has changed.

If the equipment is equipped with WiFi Direct the data can be retrieved using a cell phone (with the WiFi Direct as a Master) or it can connect to a wireless network (with the WiFi Direct as a Slave). Or the system can use a wired connection to a network. When connected to a network the system data can be retrieved periodically for maintenance purposes. With a number of systems in the same geographic area it can indicate a change in the quality of the fuel being delivered to that area.

[019]   In both of the preferred embodiments the circuitry can be a combination of analog and digital and the digital can be performed mostly in software by a microcontroller or DSP. However, if a microcontroller or DSP is used, and it uses an operating system, it must be a real-time operating system so that the various signals have exactly the proper frequencies and phase.

[020]   In addition to its uses in gas furnaces the embodiments of the invention may also be used in other appliances such as gas hot water heaters and gas ovens or in any equipment which uses a flame. It can also be used in a jet engine (pure jet or turbofan) as a secondary or tertiary backup sensor.

BRIEF DESCRIPTION OF THE DRAWINGS

[021]   The invention may best be understood by referring to the following description and accompanying drawings which illustrate the invention. In the drawings:

[022]   Figure 1 is a general illustration showing a flame rod immersed in a flame produced by a combustion burner.

[023]   Figure 2 is a general illustration showing an electrical model of a flame rod immersed in a flame produced by a combustion burner.

[024]   Figure 3 is a general illustration showing a flame rod and a combustion burner but no flame.

[025]   Figure 4 is a general illustration showing an electrical model of a flame rod and a combustion burner but no flame.

[026]   Figure 5 is a graph showing how flame temperature changes with air/fuel mixture and how the Angle between In-Phase signal and Quadrature-Signal changes with air/fuel mixture and therefore the flame temperature.

[027]   Figure 6 is a general illustration showing a ground rod added to the system to extend the range at which lean flames can be characterized..

[028]   Figure 7 is a reproduction of Table 5.4 from the Turns reference (*Reference 12*).

[029]   Figure 8 is a reproduction of Table 17.12 from the Turns reference (*Reference 12*).

[030]   Figure 9 is a general illustration showing the block diagram of the first embodiment where flame rectification is used to cause **distortion in a selected waveform**. and the second harmonic of the selected waveform is detected using quadrature synchronous detection.

[031]   Figure 10 is a general illustration showing the electrical circuit for Flame Driver 902.

[032]   Figure 11 is a general illustration showing the electrical circuit for High Impedance Buffer 904.

[033]   Figure 12 is a general illustration showing the electrical circuit for Multiplier/DC Filters 909 and 910.

[034]   Figure 13 is a general illustration showing the block diagram of the second embodiment where flame rectification is used as a mixer to **cause two signals having selected waveforms to produce sum and difference signals** and the difference signal is detected using quadrature synchronous detection.

[035]   Figure 14 is a general illustration showing the electrical circuit for Flame Driver 1301.

[036]   Figure 15 is a general illustration showing the electrical circuit for High Impedance Buffer 1304.

DETAILED DESCRIPTION

[037] In the following description, numerous specific details are set forth to provide a thorough understanding of the invention. However, it is understood that the invention may be practiced without these specific details. In other instances well-known circuits, structures, and techniques have not been shown in detail in order not to obscure the invention.

[038] In the first embodiment flame rectification causes **distortion of a signal source having a selected waveform**, producing a selected harmonic signal that does not otherwise exist in the selected waveform. In this specific example the selected harmonic is the second harmonic but other harmonics may be selected. The selected harmonic is detected by using a **quadrature synchronous detector**.

The system is shown in Figure 9. Controller 901 produces a 1 KHz Selected Waveform that is selected to not contain even harmonics. Examples of selected waveforms that do not contain even harmonics include low distortion sine waves and symmetrical square waves. The 1 KHz Selected Waveform is applied to Flame Driver 902 (shown in more detail in Figure 10). The Output of Flame Driver 902 is applied through Source Resistor 903 to Flame Rod 905. Flame Rod 905 is also connected to the input of High Impedance Buffer 904 (shown in more detail in Figure 11).

Controller 901 also produces a first 2 KHz signal that is exactly twice the frequency of the 1 KHz Selected Waveform (and in phase with it) as well as a second 2 KHz signal (2Q KHz) that is 90 degrees out of phase with the first 2 KHz signal.

The output of High Impedance Buffer 904 is connected to a first input of Multiplier/DC Filter 909 as well as to a first input of Multiplier/DC Filter 910. A second input of Multiplier/DC Filter 909 is connected to the first 2 KHz signal. A second input of Multiplier/DC Filter 910 is connected to the second 2 KHz signal which is 90 degrees out of phase with the first 2 KHz signal. Multiplier/DC Filter 909 and Multiplier/DC Filter 910 perform quadrature synchronous detection of the 2 KHz second harmonic of the 1 KHz Selected Waveform created when a flame is present (and only when a flame is present).

The details of Multiplier/DC Filter 909 and Multiplier/DC Filter 910 are shown in Figure 12. Analog Switch 1203 switches OpAmp 1204 between being having a gain of -1 and having a gain of +1. Resistor R1 (1201) and Resistor R2 (1202) should be 1% tolerance or better. This makes the

circuit a 4-quadrant multiplier where one signal is a bipolar analog signal and the other signal is a square wave.

The output of Multiplier/DC Filter 909 is connected to a first Analog-to-Digital input to Controller 901 (ADC 0). The output of Multiplier/DC Filter 910 is connected to a second Analog-to-Digital input to Controller 901 (ADC 1). Depending on the circuitry used in Controller 901 it may be necessary to scale the voltage and provide an offset to the ADC inputs to Controller 901 using circuits well known in the art.

[039] Controller 901 processes the data from the first ADC input and the second ADC by first calculating the magnitude of the two vectors: In-Phase and Quadrature-Phase using the equation:

$$\text{Magnitude} = \text{SQRT}(\text{In-Phase}^2 + \text{Quadrature-Phase}^2)$$

and then doing the divide: Quadrature-Phase / Magnitude.

This gives the Sine of the angle between the detected In-Phase and Quadrature-Phase signals.

The Angle is therefore the ARCSIN of this value.

For angles less than 30 degrees, SIN(Angle) = Angle when Angle is in radians.

The Angle is used to control the air/fuel mixture as required.

Controller 901 uses Air Signal 911 to control the Air Controller 912. Air Controller 912 may be as simple as a fan or it may be an air compressor. Air Signal 911 may be a pulse-width modulated signal or may use a different interface.

Controller 901 may use Gas Signal 909 to control the Gas Valve 910. Gas Signal 909 may be a pulse-width modulated signal or may use a different interface.

Controller 901 may use a WIFI interface to connect to a network for monitoring the operation of the system. Controller 901 may, either instead of or in addition to a WIFI interface, use an SPI interface to continuously send the system data to a local display.

The Start Switch Input to Controller 901 may be used to initiate system operation or system operation can be initiated through the WIFI or SPI interfaces.

[040] The flame is started with reference flow levels of air and fuel and allowed to stabilize. The Angle is noted. The air flow is decreased slightly to make the mixture richer and the new Angle is noted. If the new Angle is greater than the old Angle it means the flame temperature has decreased and we are in the rich part of the curve in Figure 5 so the mixture is rich. If the new Angle is less than the old Angle it means the flame temperature has increased and we are in the lean part of the curve in Figure 5 and the mixture is lean. If the mixture is rich the air flow is increased slightly to make it leaner. If the mixture is lean the air flow is decreased slightly to make the mixture richer. In either case the flame is given time to stabilize and the new Angle is noted. We do this until the minimum Angle (highest temperature) is found. This is the stoichiometric mixture. A dead zone should be established around stoichiometric to prevent the system from oscillating. Once the stoichiometric mixture is found the mixture can be made leaner to reduce NO_x emissions. However, when the mixture is too lean that flame begins to lift off from the burner. When flame liftoff is too great the flame will go out. This is called Lean Burn Out (LBO) and is generally undesirable. When flame liftoff begins to happen the circuit from the Flame Rod to the Combustion Burner will become much less conductive and the In-Phase and Quadrature-Phase signals will decrease markedly, thus limiting how lean the flame can be made before LBO. This range can be increased by adding a Ground Rod between the Combustion Burner and the Flame Rod. See Figure 6.

As an alternative to adjusting the air flow to control the air/fuel mixture, the gas flow can be adjusted or a combination of air flow and gas flow can be adjusted.

This procedure can be performed as often or as rarely as desired. For example, in a furnace it can be performed as part of the startup sequence whenever there is a call for heat. It can be limited to be performed only once in any 24 hour period. It can be run only when the equipment is first installed because this system will automatically adjust itself for the altitude where the equipment is installed. The system can also adjust for the air temperature because some furnaces are located in attics or garages which can experience a wide swing in temperatures during the day. With an appropriate air compressor supplying air 911 it will not be necessary to derate the equipment for operation at altitudes above sea level which is the common practice for furnaces and hot water heaters.

[041] In the second preferred embodiment flame rectification is used as a **mixer to cause two signals having selected waveforms to produce sum and difference signals**. The sum and/or difference frequencies are detected using a **quadrature synchronous detector**.

The system is shown in Figure 13. Controller 1301 produces four signals: Signal Source 1 at 1,262 Hz, Signal Source 2 at 874 Hz Hz, Reference Signal 1 at 388 Hz which is exactly the same frequency as the difference between Signal Source 1 and Signal Source 2, and a Reference Signal 2 which is at the same frequency as Reference Signal 1 but has a phase delay of approximately 90 degrees. As long as the frequency relationship is exact the frequencies need not be exact. For example, with a 16-bit microcontroller (the Texas Instruments MSP430G2553) running at 16 MHz it is possible to generate interrupts at 90,909.1 Hz. Every 72 interrupts produces 1,262.6263889 Hz (Signal Source 1). Every 104 interrupts produces 874.1259615 (Signal Source 2). Every 234 interrupts produces 388.5004274 Hz (Reference Signal 1). The ratios produce signals where Reference Signal 1 is exactly the difference between Signal Source 1 and Signal Source 2. (The ratios are divided by two in order to produce symmetrical square waves.) Reference Signal 2 is offset in time by 90 degrees from Reference Signal 1. Other frequencies and other ratios may be used as long as the difference frequency (Reference Signal 1) is exactly the frequency and phase of the difference between Signal Source 1 and Signal Source 2. And Reference Signal 2 is offset in time from Reference Signal 2 by 90 degrees.

Signal Source 1 (1,262 Hz) and Signal Source 2 (874 Hz) are summed in Flame Driver 1302 (shown in more detail in Figure 14). The Output of Flame Driver 1302 is applied through Source Resistor 903 to Flame Rod 905. Flame Rod 905 is also connected to the input of High Impedance Buffer 1304 (shown in more detail in Figure 15).

The output of High Impedance Buffer 1304 is connected to a first input of Multiplier/DC Filter 909 as well as to a first input of Multiplier/DC Filter 910. A second input of Multiplier/DC Filter 909 is connected to Reference Signal 1 (388 Hz). A second input of Multiplier/DC Filter 910 is connected to Reference Signal 2 (388Q Hz) which is 90 degrees out of phase with Reference Signal1. Multiplier/DC Filter 909 and Multiplier/DC Filter 910 perform quadrature synchronous detection of the 388 Hz difference signal between Signal Source 1 (1,262 Hz) and Signal Source 2 (874 Hz) which is created when a flame is present (and only when a flame is present).

The details of Multiplier/DC Filter 909 and Multiplier/DC Filter 910 are shown in Figure 12. Analog Switch 1203 switches OpAmp 1204 between being having a gain of -1 and having a gain of +1. Resistor R1 (1201) and Resistor R2 (1202) should be 1% tolerance or better. This makes the circuit a 4-quadrant multiplier where one signal is a bipolar analog signal and the other signal is a square wave.

The output of Multiplier/DC Filter 909 is connected to a first Analog-to-Digital input to Controller 1301 (ADC 0). The output of Multiplier/DC Filter 910 is connected to a second Analog-to-Digital input to Controller 1301 (ADC 1). Depending on the circuitry used in Controller 1301 it may be necessary to scale the voltage and provide an offset to the ADC inputs to Controller 1301 using circuits well known in the art.

[042] Controller 1301 processes the data from the first ADC input and the second ADC by first calculating the magnitude of the two vectors: In-Phase and Quadrature-Phase using the equation:

$$\text{Magnitude} = \text{SQRT}(\text{In-Phase}^2 + \text{Quadrature-Phase}^2)$$

and then doing the divide: Quadrature-Phase / Magnitude.

This gives the Sine of the angle between the detected In-Phase and Quadrature-Phase signals.

The Angle is therefore the ARCSIN of this value.

For angles less than 30 degrees, SIN(Angle) = Angle when Angle is in radians.

The Angle is used to control the air/fuel mixture as required.

Controller 1301 uses Air Signal 911 to control the Air Controller 912. Air Controller 912 may be as simple as a fan or it may be an air compressor. Air Signal 911 may be a pulse-width modulated signal or may use a different interface.

Controller 1301 may use Gas Signal 909 to control the Gas Valve 910. Gas Signal 909 may be a pulse-width modulated signal or may use a different interface.

Controller 1301 may use a WIFI interface to connect to a network for monitoring the operation of the system. Controller 1301 may, either instead of or in addition to a WIFI interface, use an SPI interface to continuously send the system data to a local display.

The Start Switch Input to Controller 1301 may be used to initiate system operation or system operation can be initiated through the WIFI or SPI interfaces.

[043] The flame is started with reference flow levels of air and fuel and allowed to stabilize. The Angle is noted. The air flow is decreased slightly to make the mixture richer and the new Angle is noted. If the new Angle is greater than the old Angle it means the flame temperature has decreased and we are in the rich part of the curve in Figure 5 so the mixture is rich. If the new Angle is less than the old Angle it means the flame temperature has increased and we are in the lean part of the curve in Figure 5 and the mixture is lean. If the mixture is rich the air flow is increased slightly to make it leaner. If the mixture is lean the air flow is decreased slightly to make the mixture richer. In either case the flame is given time to stabilize and the new Angle is noted. We do this until the minimum Angle (highest temperature) is found. This is the stoichiometric mixture. A dead zone should be established around stoichiometric to prevent the system from oscillating. Once the stoichiometric mixture is found the mixture can be made leaner to reduce NO_x emissions. However, when the mixture is too lean that flame begins to lift off from the burner. When flame liftoff is too great the flame will go out. This is called Lean Burn Out (LBO) and is generally undesirable. When flame liftoff begins to happen the circuit from the Flame Rod to the Combustion Burner will become much less conductive and the In-Phase and Quadrature-Phase signals will decrease markedly, thus limiting how lean the flame can be made before LBO. This range can be increased by adding a Ground Rod between the Combustion Burner and the Flame Rod. See Figure 6.

As an alternative to adjusting the air flow to control the air/fuel mixture, the gas flow can be adjusted or a combination of air flow and gas flow can be adjusted.

This procedure can be performed as often or as rarely as desired. For example, in a furnace it can be performed as part of the startup sequence whenever there is a call for heat. It can be limited to be performed only once in any 24 hour period. It can be run only when the equipment is first installed because this system will automatically adjust itself for the altitude where the equipment is installed. The system can also adjust for the air temperature because some furnaces are located in attics or garages which can experience a wide swing in temperatures during the day. With an appropriate air compressor supplying air 911 it will not be necessary to derate the equipment for operation at altitudes above sea level which is the common practice for furnaces and hot water heaters.

[044] While preferred embodiments of the present invention have been shown, it is to be expressly understood that modifications and changes may be made thereto.

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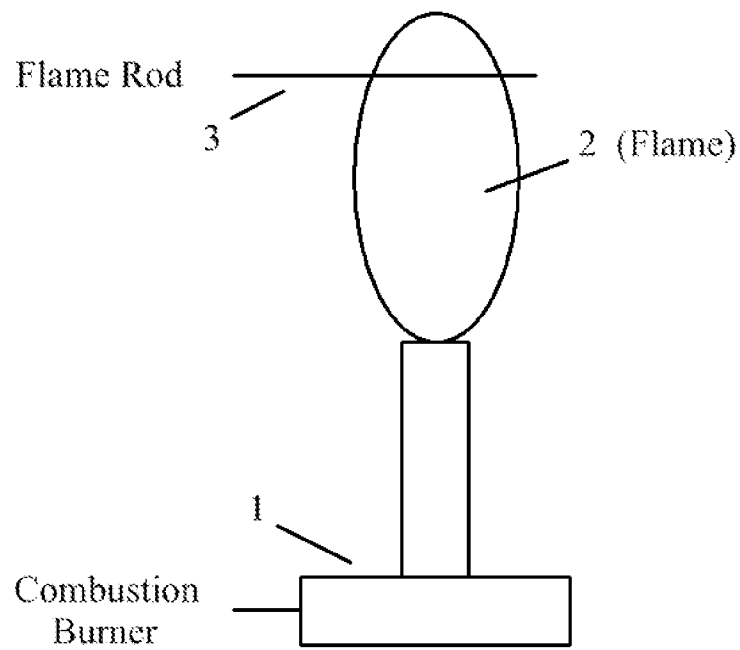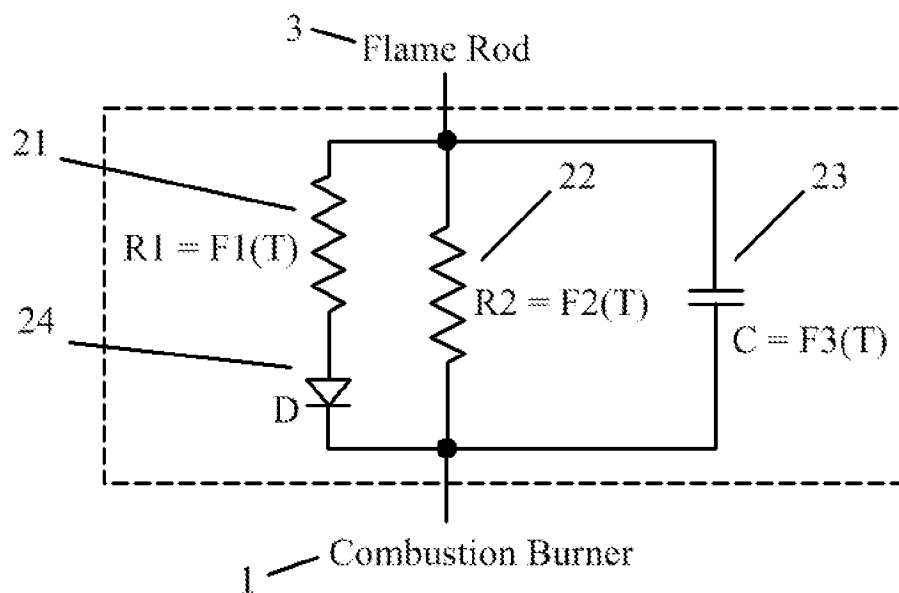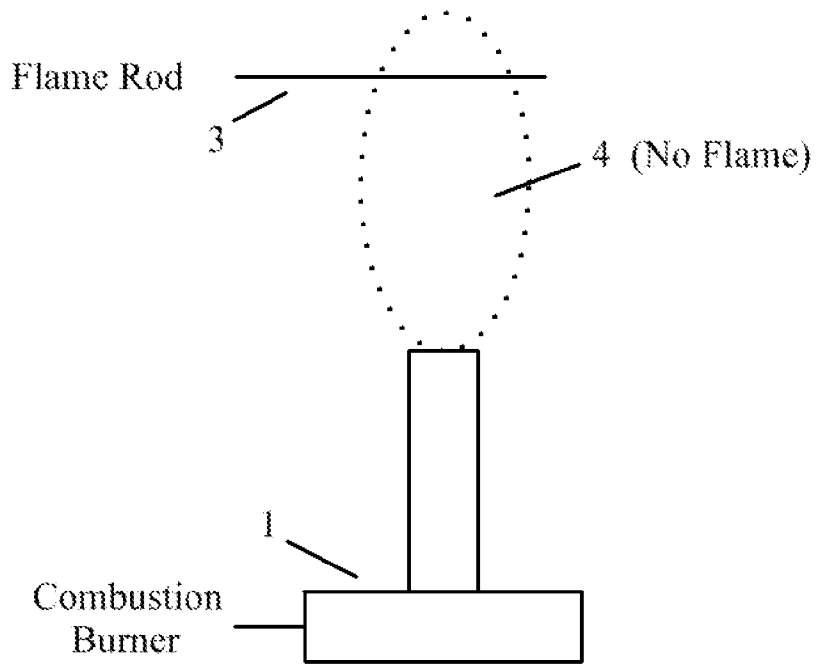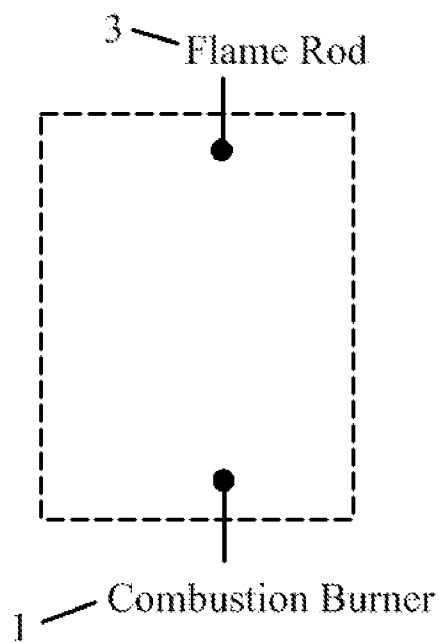
DRAWINGS

Figure 1

Figure 2

Flame Rod

3

4 (No Flame)

1

Combustion
Burner

Figure 3

3 — Flame Rod

Combustion Burner

1
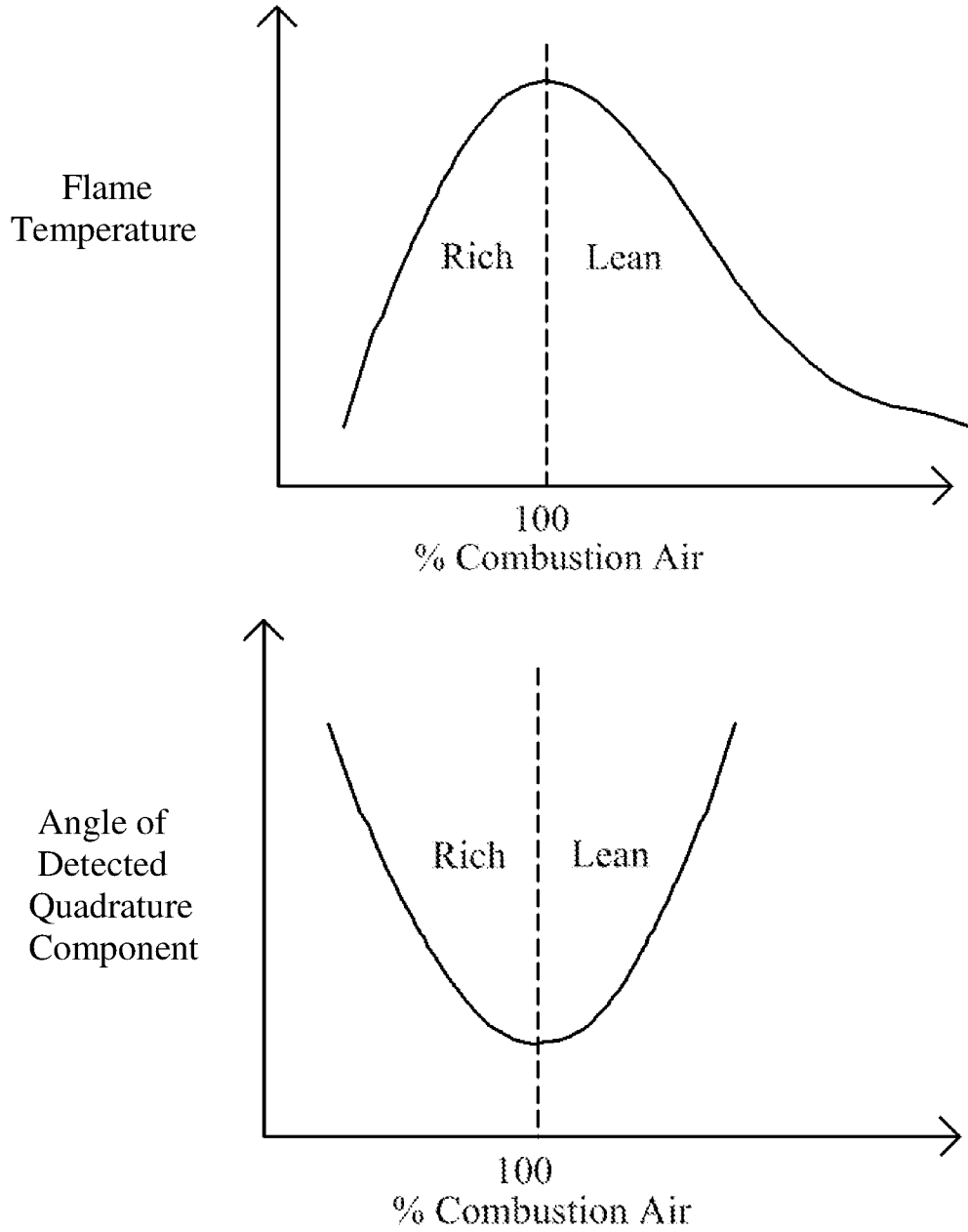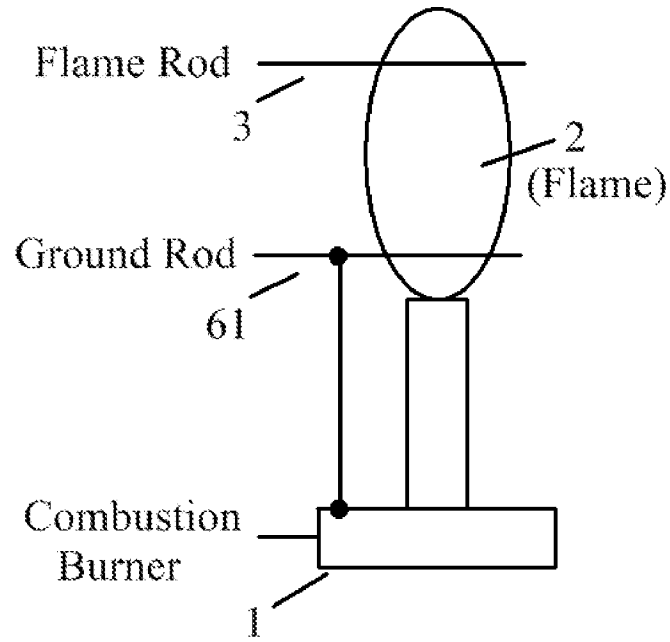
Figure 4

Figure 5

Figure 6

Table 5.4   (continued)

| | | Forward Rate Coefficient[a] | | |
No.	Reaction	A	b	E
N-Containing Reactions (continued)				
201	$NH_2 + O \rightarrow H + HNO$	3.9E + 13	0.0	0.0
202	$NH_2 + H \rightarrow NH + H_2$	4.00E + 13	0.0	3,650
203	$NH_2 + OH \rightarrow NH + H_2O$	9.00E + 07	1.5	−460
204	$NNH \rightarrow N_2 + H$	3.30E + 08	0.0	0.0
205	$NNH + M \rightarrow N_2 + H + M$	1.30E + 14	−0.1	4,980
206	$NNH + O_2 \rightarrow HO_2 + N_2$	5.00E + 12	0.0	0.0
207	$NNH + O \rightarrow OH + N_2$	2.50E + 13	0.0	0.0
208	$NNH + O \rightarrow NH + NO$	7.00E + 13	0.0	0.0
209	$NNH + H \rightarrow H_2 + N_2$	5.00E + 13	0.0	0.0
210	$NNH + OH \rightarrow H_2O + N_2$	2.00E + 13	0.0	0.0
211	$NNH + CH_3 \rightarrow CH_4 + N_2$	2.50E + 13	0.0	0.0
212	$H + NO + M \rightarrow HNO + M$	4.48E + 19	−1.3	740
213	$HNO + O \rightarrow NO + OH$	2.50E + 13	0.0	0.0
214	$HNO + H \rightarrow H_2 + NO$	9.00E + 11	0.7	660
215	$HNO + OH \rightarrow NO + H_2O$	1.30E + 07	1.9	−950
216	$HNO + O_2 \rightarrow HO_2 + NO$	1.00E + 13	0.0	13,000
217	$CN + O \rightarrow CO + N$	7.70E + 13	0.0	0.0
218	$CN + OH \rightarrow NCO + H$	4.00E + 13	0.0	0.0
219	$CN + H_2O \rightarrow HCN + OH$	8.00E + 12	0.0	7,460
220	$CN + O_2 \rightarrow NCO + O$	6.14E + 12	0.0	−440
221	$CN + H_2 \rightarrow HCN + H$	2.95E + 05	2.5	2,240
222	$NCO + O \rightarrow NO + CO$	2.35E + 13	0.0	0.0
223	$NCO + H \rightarrow NH + CO$	5.40E + 13	0.0	0.0
224	$NCO + OH \rightarrow NO + H + CO$	2.50E + 12	0.0	0.0
225	$NCO + N \rightarrow N_2 + CO$	2.00E + 13	0.0	0.0
226	$NCO + O_2 \rightarrow NO + CO_2$	2.00E + 12	0.0	20,000
227	$NCO + M \rightarrow N + CO + M$	3.10E + 14	0.0	54,050
228	$NCO + NO \rightarrow N_2O + CO$	1.90E + 17	−1.5	740
229	$NCO + NO \rightarrow N_2 + CO_2$	3.80E + 18	−2.0	800
230	$HCN + M \rightarrow H + CN + M$	1.04E + 29	−3.3	126,600
231	$HCN + O \rightarrow NCO + H$	2.03E + 04	2.6	4,980
232	$HCN + O \rightarrow NH + CO$	5.07E + 03	2.6	4,980
233	$HCN + O \rightarrow CN + OH$	3.91E + 09	1.6	26,600
234	$HCN + OH \rightarrow HOCN + H$	1.10E + 06	2.0	13,370
235	$HCN + OH \rightarrow HNCO + H$	4.40E + 03	2.3	6,400
236	$HCN + OH \rightarrow NH_2 + CO$	1.60E + 02	2.6	9,000
237	$H + HCN + M \rightarrow H_2CN + M$	pressure dependent		
238	$H_2CN + N \rightarrow N_2 + CH_2$	6.00E + 13	0.0	400
239	$C + N_2 \rightarrow CN + N$	6.30E + 13	0.0	46,020
240	$CH + N_2 \rightarrow HCN + N$	3.12E + 09	0.9	20,130
241	$CH + N_2 (+ M) \rightarrow HCNN (+ M)$	pressure dependent		
242	$CH_2 + N_2 \rightarrow HCN + NH$	1.00E + 13	0.0	74,000
243[b]	$CH_2(S) + N_2 \rightarrow NH + HCN$	1.00E + 11	0.0	65,000

Figure 7 (from Turns)

Table 1

Table 17.12 Composition (mol%) and properties of natural gas from sources in the United States [28][a]

Location	CH$_4$	C$_2$H$_6$	C$_3$H$_8$	C$_4$H$_{10}$	CO$_2$	N$_2$	Density[c] (kg/m^3)	HHV[d] (kJ/M^3)	HHV[d] (kJ/hg)
Alaska	99.6	—	—	—	—	0.4	0.686	37,590	54,800
Birmingham,	90.0	5.0	—	—	—	5.0	0.735	37,260	50,690
East Ohio[b]	94.1	3.01	0.42	0.28	0.71	1.41	0.723	38,260	52,940
Kansas City,	84.1	6.7	—	—	0.8	8.4	0.772	36,140	46,830
Pittsburgh,	83.4	15.8	—	—	—	0.8	0.772	41,840	54,215

[a] Although not explicitly stated in Ref. [28], these gases appear to be pipeline gases.
[b] Also contains 0.01 % H$_2$ and 0.01% O$_2$.
[c] At 1 atm and 15.6°C (60 F).
[d] Higher heating values for 1 atm and 15.6°C (60 F) [28].
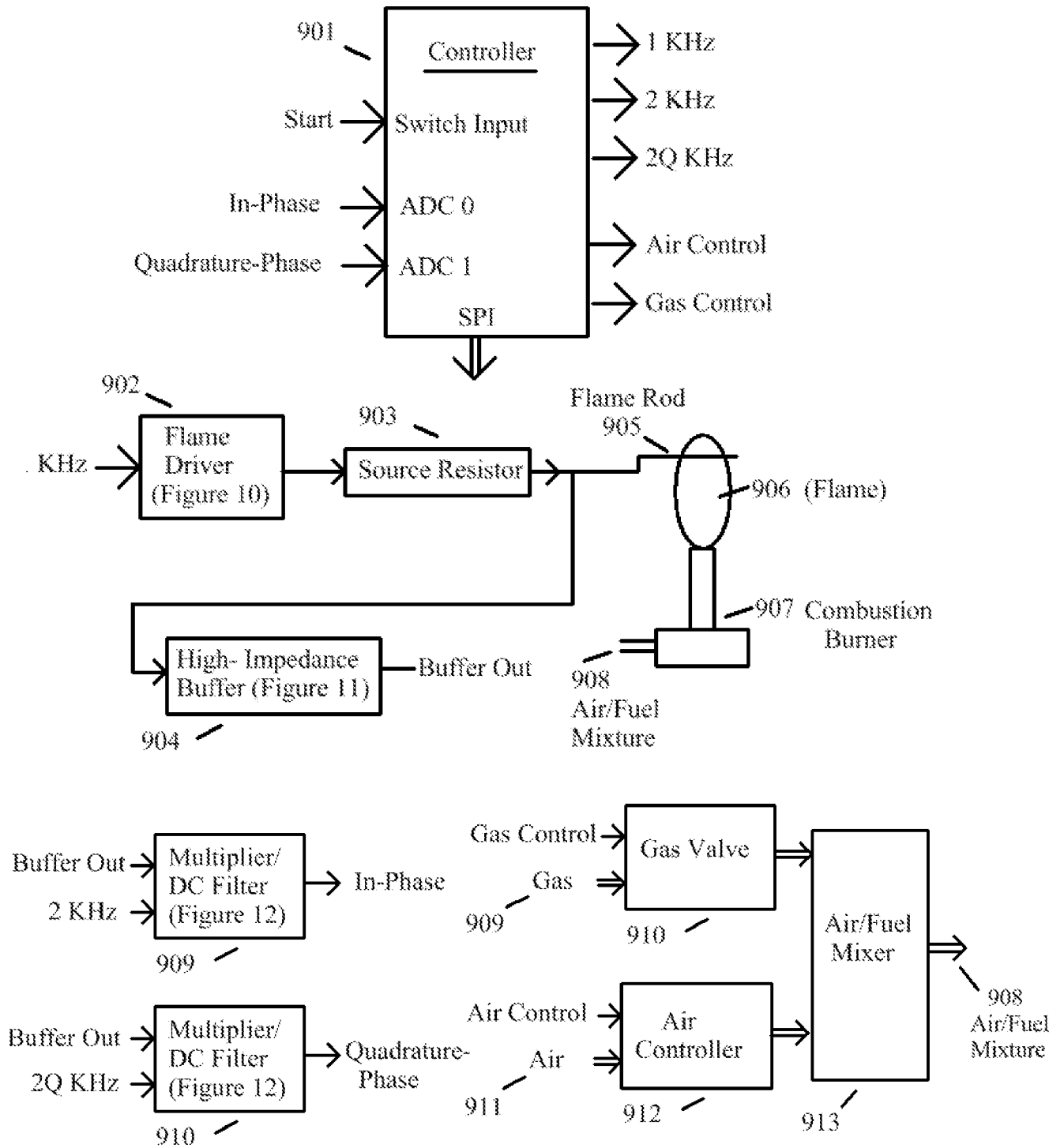
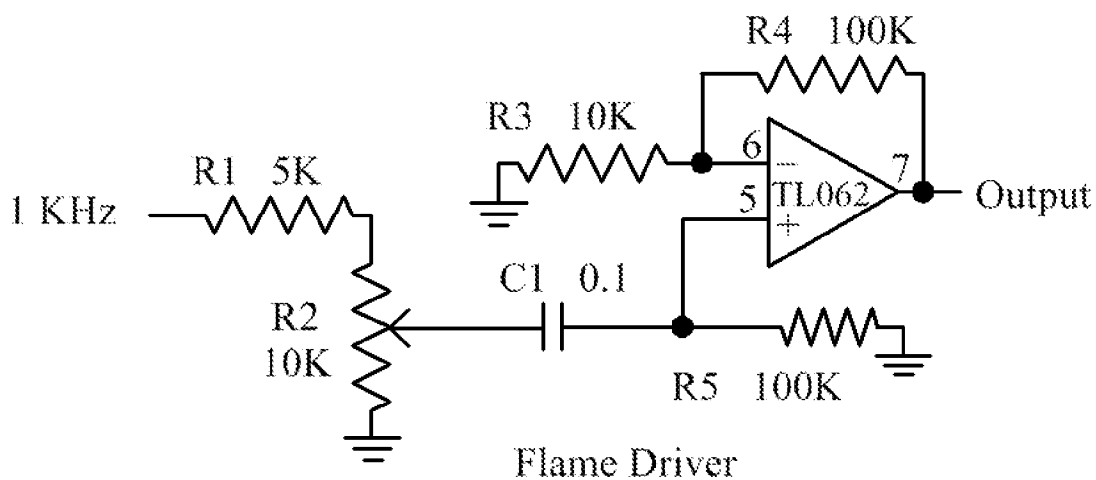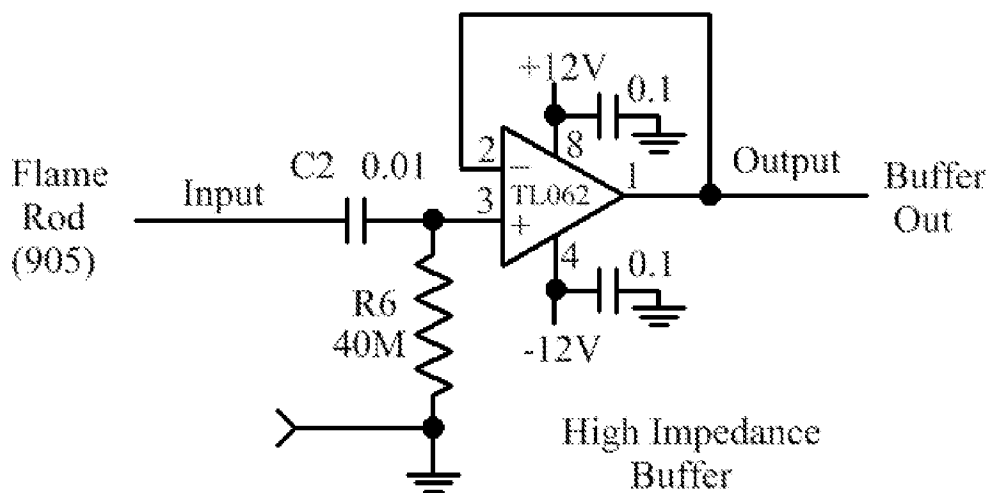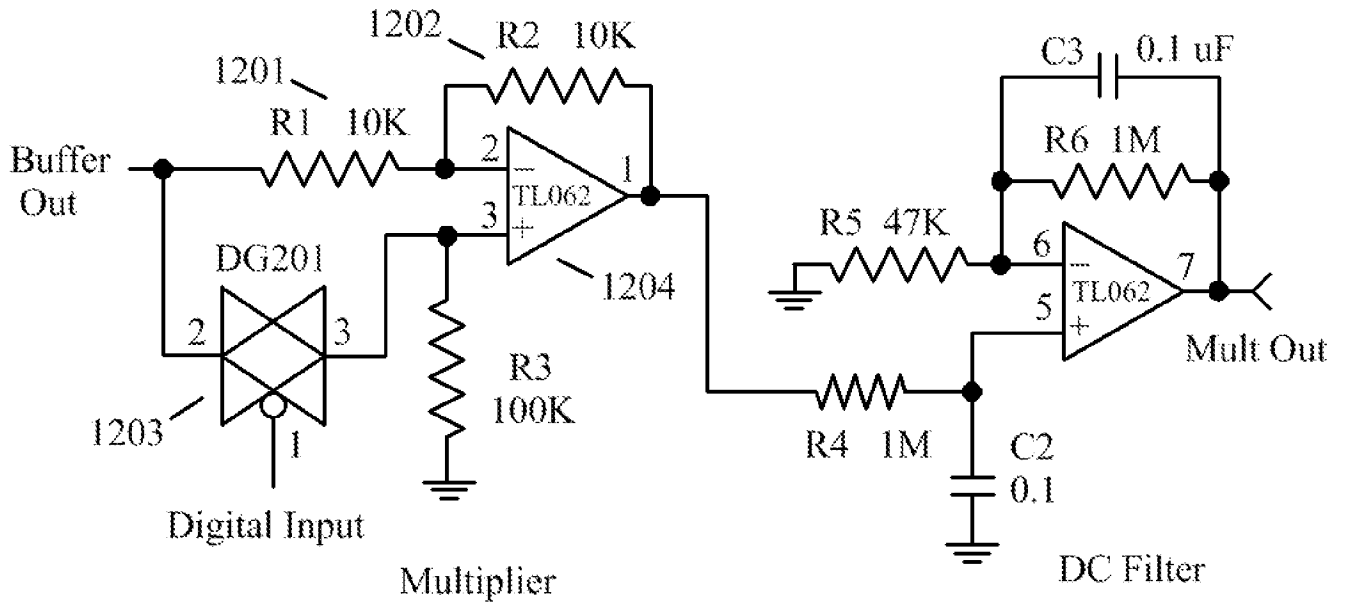## Figure 8 (Turns Table 17.12)

Figure 9

Flame Driver

Figure 10

High Impedance
Buffer

Figure 11

Figure 12   Multiplier and DC Filter

1301

Controller

Start → Switch Input

In-Phase → ADC 0

Quadrature-Phase → ADC 1

SPI

1262 Hz (Signal Source 1)

874 Hz (Signal Source 2)

388 Hz (Reference Signal 1)

388Q Hz (Reference Signal 2)

Air Control

Gas Control

1302

1262 Hz →
874 Hz →
Flame Driver (Figure 14)

903
Source Resistor →

Flame Rod
905

906 (Flame)

907 Combustion Burner

High- Impedance Buffer (Figure 15) — Buffer Out

1304

908 Air/Fuel Mixture

Buffer Out →
388 Hz →
Multiplier/ DC Filter (Figure 12)
→ In-Phase

909

Buffer Out →
388Q Hz →
Multiplier/ DC Filter (Figure 12)
→ Quadrature-Phase

910

Gas Control →
Gas →
909
Gas Valve

910

Air Control →
Air →
911
Air Controller

912

Air/Fuel Mixer
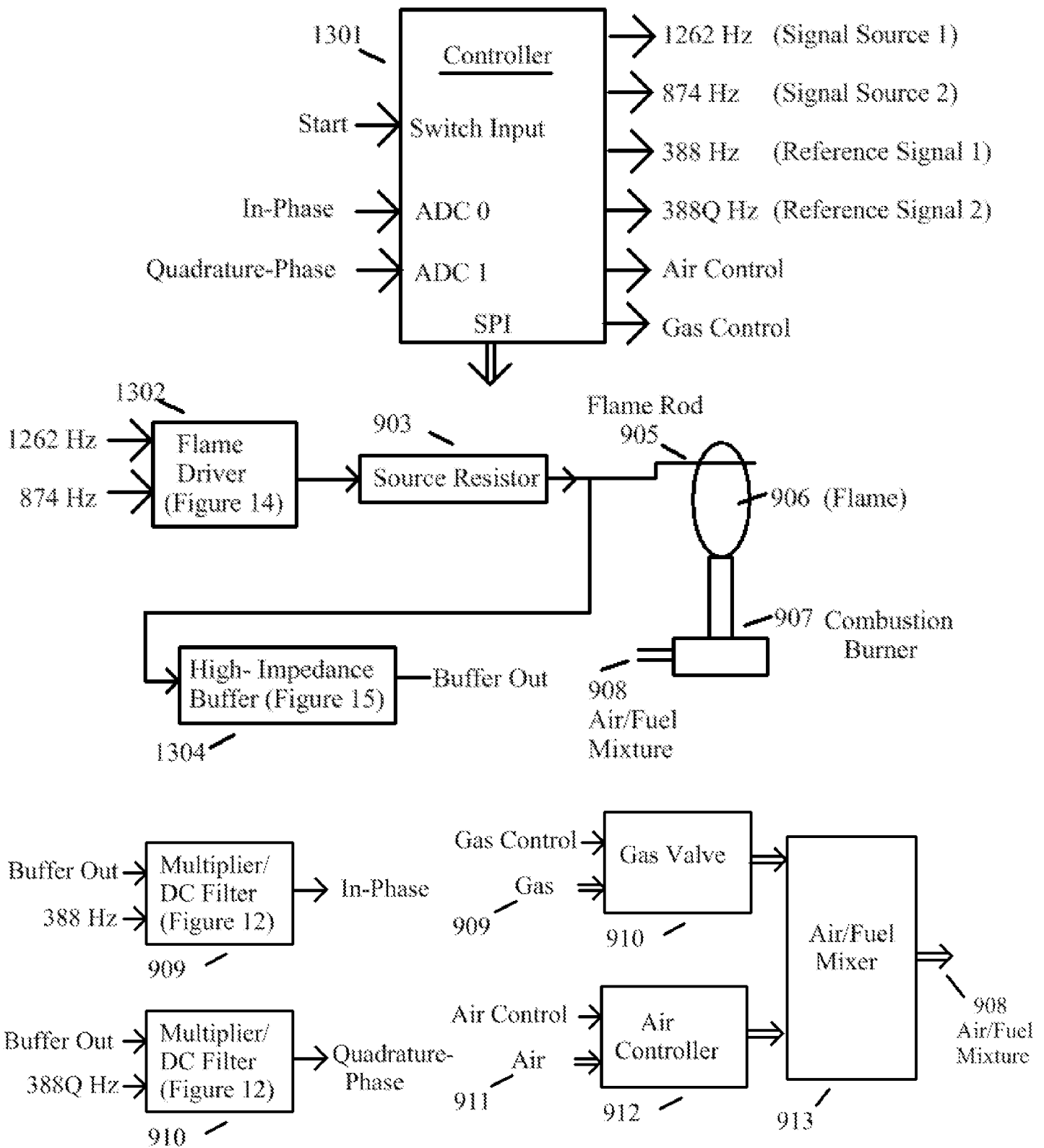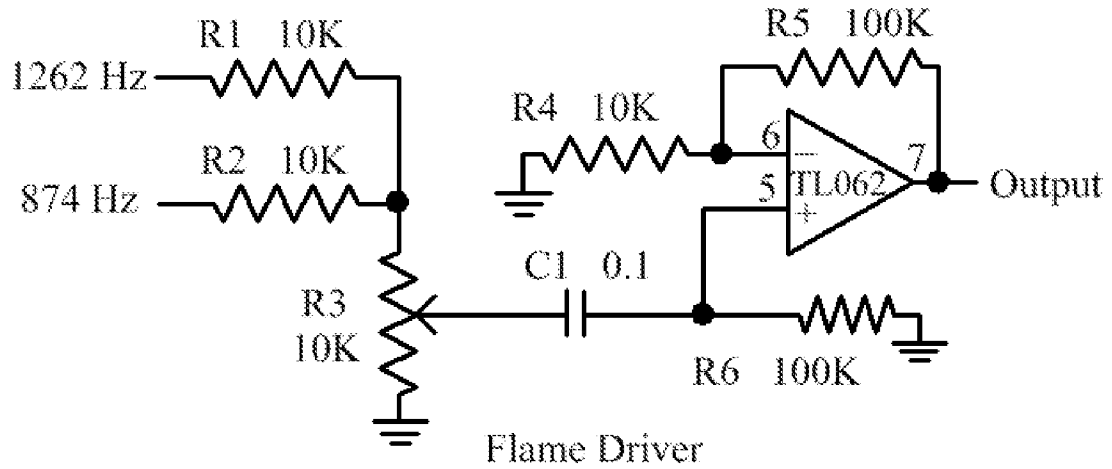
913

908 Air/Fuel Mixture
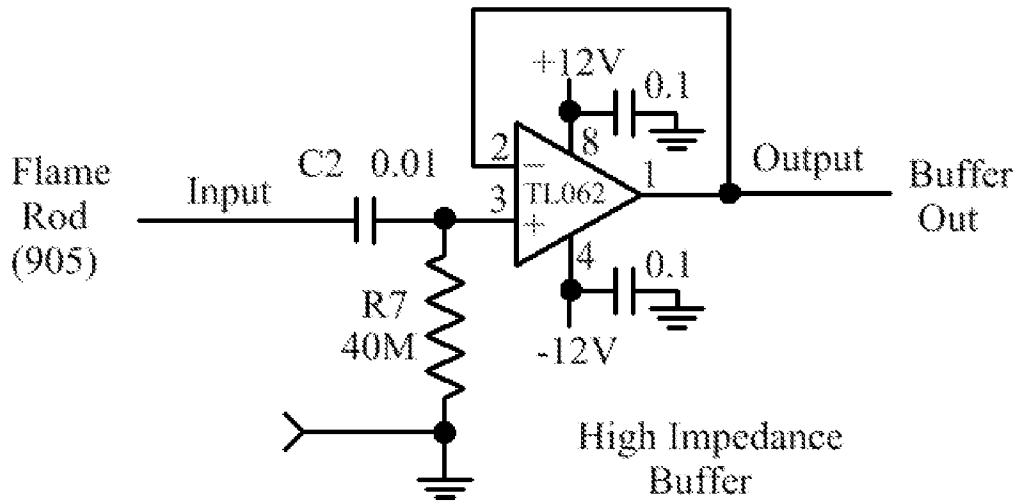
Figure 13

Figure 14

Figure 15

ABSTRACT OF THE DISCLOSURE

Flames exhibit the properties of both resistance and what can best be described as capacitance. The flame capacitance and flame resistance are both affected by the temperature of the flame. Both flame resistance and flame capacitance decrease as the flame temperature increases and increase as the flame temperature decreases. The flame capacitance and flame resistance cause a time delay in an applied signal. When flame rectification is used to heterodyne two signals and quadrature synchronous detection is used for the resulting sum and/or difference signals this time delay causes a phase delay between the detected in-phase and quadrature-phase signals. The temperature of a flame is affected by the fuel/air mixture, reaching a maximum at stoichiometric. Thus this method can be used to determine the optimum desired fuel/air mixture of a premixed flame.