FLAMES AUGMENTED BY ELECTRICAL POWER

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INTRODUCTION

The subject of this paper is a new type of high temperature flame which is produced by the superimposition of electrical power over a combustion flame. The temperature obtainable by this flame ranges from ordinary flame temperatures up to the temperature of the electric arc column, that is, the flame temperature may be anywhere from 2000 to 5000°K. This is a modest temperature range as compared with other sources of high temperature heat, for example the plasma jet, but technically a very important one. All chemical and metallurgical processes which require large quantities of heat at high temperatures can be carried out within this temperature range. The fuel for the flame may be gaseous, for example natural gas, or atomized liquid, or solid, like powdered coal. The oxidizer may be air, oxygen-enriched air or oxygen. The cost of the high temperature heat compares very favourably with any other source of high temperature heat, because only the top portion is supplied by electrical power, the rest by combustion heat. The temperature of the flame is independent of the composition of the combustion products and, therefore, strongly reducing or oxidizing flames can be produced at high temperatures.

The combination of electrical energy with the combustion heat of a flame is not new in itself. The combination of an electric arc with a flame has been used repeatedly in the past, most predominantly by Southgate in the 1920's. New is the mode of application of electrical power to the flame, which leads to important technical advantages. In all earlier work, either very weak power or an electric arc was used in conjunction with the flame. We propose to disperse a strong electrical discharge over the entire flame by utilizing the electrical and mechanical properties of turbulent flames. The dispersion of the discharge throughout the flame permits the use of higher voltages than are possible with an arc column. In consequence of this the currents, even at high power input, remain comparatively small. The dispersed discharge heats the stream of combustion products uniformly, the electrically augmented flame appears like a flame and can be applied like a flame.

TURBULENT FLAMES

The structure and properties of turbulent flames play an important rôle in the dispersion of the electrical discharge over the flame. It is known that in a turbulent flame combustion is accomplished in a thin combustion wave, which is wrinkled and moved about at random by the turbulent motion. Turbulent flames themselves generate turbulence which can be much stronger than the turbulence of the approach stream. This flame-generated turbulence enhances the heat release rate of turbulent flames. It also increases the permissible electrical power input density. Numerical data on the flame generated turbulence will be given below.

FLAME CONFIGURATION FOR ELECTRICAL POWER INPUT

The density of the combustion gas is approximately one-sixth of the unburned gas for ordinary air–fuel flames. It is even less for hotter flames. The combustion products of an ordinary air–fuel flame contain approximately 10^{10} to 10^{11} ion–electron pairs per cm^3. The ion–electron concentration may be readily increased by several magnitudes by introducing alkali atoms into the flame. The low gas density and the free electron concentration give a substantial electrical conductivity to the combustion gas. The flame may be used as an electrical resistance to absorb electrical power and thereby to heat the gas. *Figure 1* shows one possible arrangement of the flame and electrodes. The flame is anchored on the central electrode and on the rim of the burner tube. The electrodes are separated by the cold gas flow and they are connected by the conducting flame. The path of the discharge is the shortest, and, consequently, the voltage gradient highest, at the upstream edge of the flame where the flame temperature and the gas conductivity are the lowest. The length of the discharge path increases farther up along the flame where flame temperature and conductivity are higher. The total conductivity of the flame is, thereby, kept within bounds and uniform heating of the flame by electrical power becomes possible, if concentration of the discharge into a narrow highly conductive arc column is prevented. The requirements for this will be described below.

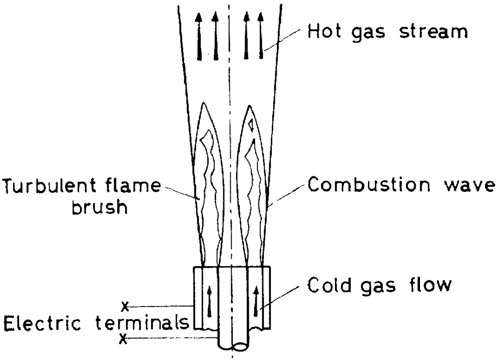

Figure 1. Open turbulent flame with distribution electric discharge

One other arrangement of the flame is shown in *Figure 2.* The flame is anchored on the central electrode and burns in a duct. Again the electrical power connections are to the central electrode and to the wall of the duct. This type of flame is a very powerful turbulence generator, and well suited for the production of concentrated, high velocity flame jets. The flame may be anchored in a combustion chamber from which the hot combustion products escape through a Laval nozzle and produce a supersonic jet. (*Figure 3.*)

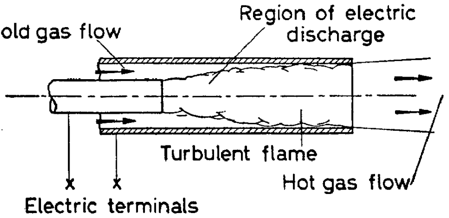

Figure 2. Turbulent flame in duct with distributed electric discharge

It is not necessary to use pre-mixed gases. The flame may be a diffusion flame produced by a fuel jet issuing from a flameholder electrode into an air stream. The only essentials are the initial conductivity of the flame and the presence of strong turbulence.

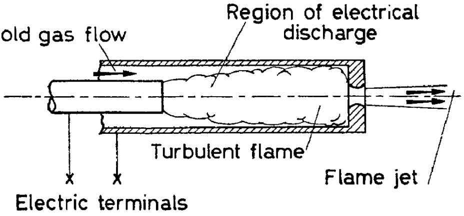

Figure 3. High pressure burner with distributed electric discharge

POWER INPUT AND IONIZATION DENSITY

The electrical power input density into the flame is given by

$$W = \epsilon N_e k_e E^2 \qquad \mathrm{W/cm^3}$$

where:

ϵ	charge of the electron	$1{\cdot}59 \times 10^{-19}$ coulomb
N_e	electron concentration	$\mathrm{cm^{-3}}$
k_e	electron mobility	$\dfrac{\mathrm{cm/sec}}{\mathrm{volt/cm}}$
E	voltage gradient	volt/cm

The power input density is controlled by the voltage gradient E. The electron concentration is dependent on the flame temperature and, therefore, on the power input, and on the composition of the combustion products, particularly on the concentration of components with low ionization potential such as sodium or potassium atoms and NO molecules. The equilibrium concentration of the positive ions, free electrons and negative ions can be calculated together with the equilibrium composition of the combustion products as a function of the gas temperature. In the lower temperature range, 2000 to 3000°K, only the constituents with very low ionization potential will contribute noticeably to the ion–electron concentration of the gas. In this temperature range it is, therefore, possible to estimate the ion–electron concentration from Saha's equation for the one or two significant constituents. As an example, *Table 1* shows the ion–electron concentration as a function of the gas temperature for the case of 10^{13} potassium atoms per cm^3 present. This small amount of potassium, which amounts to only a few parts per million, produces significant ion–electron concentration already at 2,000°K. Above 3,000°K the ionization produced by the small concentration of potassium additive approaches saturation. This example shows that both the absolute ion–electron concentration and its rate of increase with temperature can be very effectively controlled by the addition of a few parts per million of an ionizing agent to the combustible mixture.

Table 1. Thermal ionization in a flame containing 10^{13} potassium atoms per cm^3

Temperature (°K)	*Fraction of ionized potassium atoms* $\times 10^2$	*Ion–electron concentration* (per $\text{cm}^3 \times 10^{-12}$)	$\frac{\mathrm{d}N}{\mathrm{d}T}$ ($\text{cm}^{-3}\,{}^\circ\text{K}^{-1} \times 10^{-10}$)
2,000	1·8	0·18	0·16
2,100	3·4	0·34	0·25
2,200	5·9	0·59	0·41
2,300	10·0	1·00	0·61
2,400	16·1	1·61	0·89
2,500	25·0	2·50	1·10
2,600	36·0	3·60	1·20
2,700	48·0	4·80	1·40
2,800	62·0	6·20	1·25
2,900	74·5	7·45	0·70
3,000	81·5	8·15	

DISPERSION OF THE DISCHARGE IN THE FLAME

The combustion products of a flame possess electrical conductivity and, therefore, if a voltage is applied to the electrodes, the entire flame at first will carry an electric current. However, the ion–electron concentration increases with increasing gas temperature and, therefore, the possibility exists that with increasing power input the discharge current will concentrate into a filament which is, incidentally, hotter than its surroundings. Such a filament will be heated more rapidly by the increased current density than the rest of the flame, and, therefore, its temperature and electrical conductivity will increase further. Unless checked by some other process this thermal instability will concentrate the entire discharge current into a rather narrow, high temperature, highly conducting arc column. Such an arc column requires only a small voltage for its maintenance and therefore acts like a short circuit and reduces the power input for a given current to a small fraction of its original value.

The concentration of the discharge into an arc column is a thermal process. The time required for the overheating of a filament is determined by the power input rate and the heat capacity of the gas column. The electrical power input rate is proportional to the square of the voltage gradient. Therefore, the critical time interval can be controlled by the voltage gradient applied to the column. At values of the voltage gradient which are of interest here the critical time interval is in the order of a millisecond.

The overheating of a gas filament by electrical power input can be prevented if the filament is stretched and dispersed by strong turbulent motion. The time interval required to exchange a small volume of gas of the filament with the surrounding is given by the characteristic time of turbulence:

$$t = \frac{l}{u'} \quad \text{seconds}$$

where l is the scale

u' is the intensity of turbulence.

For strongly turbulent flames this characteristic time is a fraction of a millisecond, therefore comparable to the time interval required for the development of an arc column.

The ratio of the time required for the turbulent dispersion of a hot filament to the time required for overheating of the filament is a dimensionless number:

$$D = \left(\frac{\mathrm{d}\,N_e}{\mathrm{d}\,T}\right)\left(\frac{l}{u'}\right)\left(\frac{0{\cdot}24\ \epsilon k_e}{C_p \rho}\right) E^2$$

where N_e = ion–electron concentration cm^{-3}

T = gas temperature °K

l = scale of turbulence cm

u' = intensity of turbulence cm/sec

ϵ = elementary charge $1{\cdot}59 \times 10^{-19}$ coulomb

k_e = mobility of the electron $\dfrac{\text{cm/sec}}{\text{volt/cm}}$

C_p = heat capacity of the gas cal/g

ρ = density of the gas $\mathrm{g/cm^3}$

E = voltage gradient volt/cm

If $D < 1$, then less time is required for dispersal of the overheated filament than for the development of the arc filament, and the discharge will remain dispersed over the flame.

If $D > 1$, then turbulent dispersal requires more time than the transition into an arc, therefore a dispersed discharge cannot be maintained.

The value of the characteristic number D can be influenced by several means. We can exercise some control over the rate of rise of ion–electron concentration with temperature by judicious amounts of ionizing additives. The characteristic time of turbulence in the flame can be controlled within limits, but it is always possible to keep the dispersion number D smaller than one by keeping the voltage gradient below a critical value E_{crit}. It is interesting to calculate this critical voltage gradient and the corresponding critical power input density for a few typical flames. In these calculations we will assume 10^{13} potassium atoms per $\mathrm{cm^3}$ to be present in the flame gases.

The ion–electron concentration and its rate of rise with temperature are taken from *Table 1.*

Open turbulent flame

Measured data are available for both the scale and the intensity of turbulence. For medium sized flames $\frac{l}{u'} = 10^{-3}$ sec. With this value at $T = 2500°\text{K}$ the critical voltage gradient is calculated to be

$$E_{\text{crit}} = 100 \text{ V/cm}$$

and the critical power input density

$$W_{\text{crit}} = 60 \text{ W/cm}^3$$

Turbulent flame in constant area duct

The characteristic time of turbulence is calculated to be in the order of $\frac{l}{u'} = 10^{-4}$ sec. With this value at $T = 2500°\text{K}$ the critical voltage gradient is

$$E_{\text{crit}} = 310 \text{ V/cm}$$

and the critical power input density

$$W_{\text{crit}} = 500 \text{ W/cm}^3$$

These power input rates may be compared with the heat release rates of turbulent flames and combustion systems.

Turbulent flame brush	250 W/cm³
Turbo-jet main burner	25 W/cm³

It appears that the permissible electrical power input rate is comparable to the heat release rate of high intensity flames.

VOLT–AMPERE CHARACTERISTIC OF THE DISCHARGE

Due to the thermal ionization of the combustion gases the flame has an electrical conductivity even in the absence of an electrical discharge. At low power input levels this conductivity increases only slightly, and, therefore, at the lower power levels the volt–ampere characteristic of the discharge is rising. With increasing power input the conductivity starts to rise and the characteristic reaches its highest point when the conductivity of the flame starts to rise faster than linearly with the discharge current. The calculation of the electrical conductivity of the flame, and of its dependence on the electrical power input, is rendered very difficult, if not impossible, by the fact that the total conductivity is composed of parallel discharge columns of different temperature and voltage gradient, which are strongly interconnected by turbulent mixing. Simple analysis shows, nevertheless, that

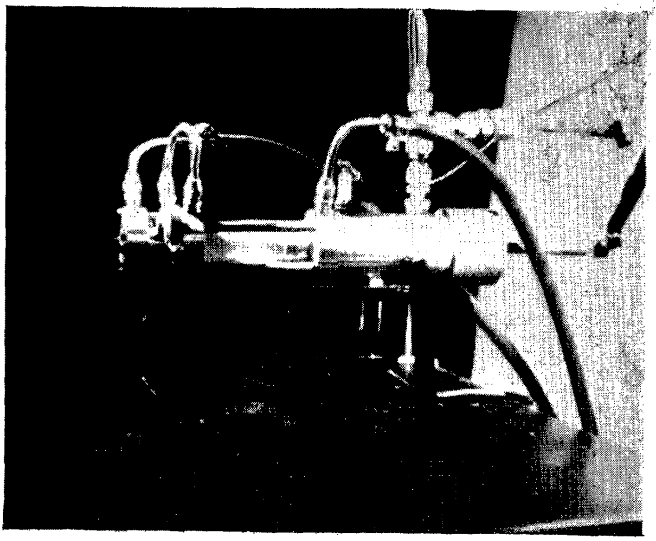

Figure 4. Experimental burner; natural gas–air flame, without electrical power

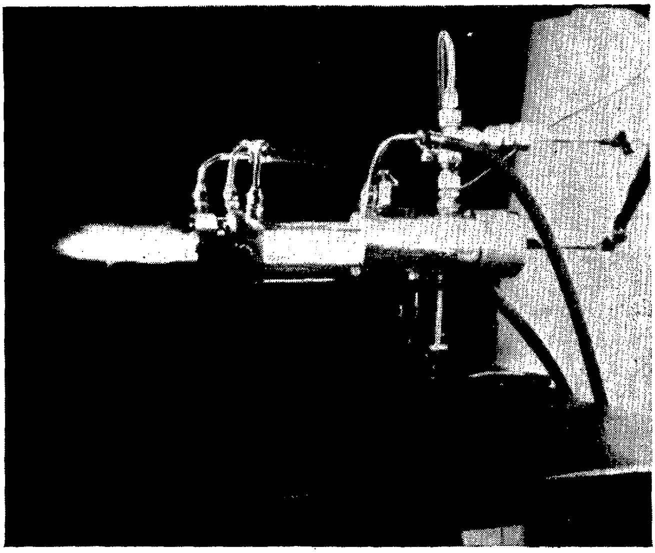

Figure 5. Experimental burner; natural gas–air flame with electrical power

for flames of initially high temperature the positive branch of the characteristic will reach high power input levels, while for initially low temperature flames the peak of the characteristic will be reached at low power input levels.

At high power input levels the volt–ampere characteristic is negative. Under static conditions a negative volt–ampere characteristic would inevitably lead to concentration of the discharge into a narrow column, but due to the continual renewal of the gas in the flame it is possible to maintain a dispersed discharge in the flame even on the negative branch of the characteristic.

EXPERIMENTS

Experiments to test the predicted performance of electrically augmented flames were carried out in co-operation with Arthur D. Little, Inc., Cambridge, Massachusetts, on natural gas–air and propane–air flames burning in a constant area duct. The heat produced by combustion was in the order of 10 kW and the electrical power input in the same order. Typical results are given in *Table 2.* The burner tube was 1 in. in diameter, the electrical power input into the flame was measured with a wattmeter, and the heat output of the flame in a water-cooled calorimeter. A more detailed account of these experiments will be published separately by the experimenters.

Table 2. Natural gas–air flame with superimposed electrical power

Pressure		1 at abs.
Air flow rate		310 cu. ft./h
Natural gas flow rate		33 cu. ft./h
Total flow rate		343 cu. ft./h
Combustion heat input	32,000 BTU/h	9·3 kW
Ionizing additive—KCl		0·3 g/h
Discharge voltage		1800 V
Discharge current		4·7 amp
Power input	15,700 BTU/h	4·6 kW
Total heat and power input	47,700 BTU/h	13·9 kW
Heat output of flame	45,000 BTU/h	13·1 kW
Efficiency		94 per cent

The discharge voltage in these experiments ranged between 1000 and 2000 volts. The length of the discharge path was 10 cm and the voltage gradient 100 to 200 V/cm. The dispersion criterion was fulfilled and the discharge dispersed over the entire flame. *Figure 4* shows the flame without electrical power input and *Figure 5* with electrical power approximately equal to the calculated heat.

No measurements have yet been carried out to establish the exact conditions of transition into an arc, but in all cases when the discharge did break down into an arc the voltage gradient exceeded the critical gradient several fold.

The experiments were carried out with stainless steel and copper electrodes, cooled only by the combustible mixture flow. The steel electrodes were consumed quite rapidly; the copper electrodes showed very little wear.

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APPLICATION OF FLAMES AUGMENTED BY ELECTRIC POWER

Electrically augmented flames offer technical and economic advantages whenever large quantities of heat or high heat transfer rates are required at high temperatures, such as in welding, cutting, melting and burning operations. A substantial further advantage arises from the fact that the flame temperature is independent from the composition of the combustion products and therefore strongly oxidizing and reducing flames can be produced at high temperatures. Chemical processes can be carried out in the flame which absorb heat while the flame temperature is maintained by electrical heating. Utilizing the turbulent transport properties of such flames it appears entirely feasible to entrain the constituents into a flame, carry out the desired reaction and quench the products within a few milliseconds time. It is to be expected, therefore, that in certain fields deep going technological advances will be initiated by the use of these high temperature flames.