AN INVESTIGATION INTO SUITABILITY OF NATURAL GAS AS SUBSTITUTE GAS FOR DOMESTIC BURNERS

DR. D.P.S. ABAM
Department of Mechanical Engineering
University of Port-Harcourt
River State Nigeria.

ABSTRACT:

This paper describes the study of the combustion characteristics of natural gas to determine its suitability as substitute gas for domestic burners in place of liquified petroleum gas (lpg).

The burning characteristics of a gas of given composition are described by burner aeration, thermal effects, flame stability and combustion quality. These are functions of either the Wobbe Number or the Combustion Potential.

The Wobbe Number and Combustion Potential are calculated for both liquified petroleum gas and various compositions representative of associated low pressure and non-associated high pressure natural gas. These are then graphically presented as an area enclose by lines representing limits of flashback, lifting and incomplete combustion.

The result for Nigerian natural gas compositions show that these can be interchanged on domestic burners designed for liquified petroleum gas without design modifications.

It is also shown that the quality of combustion for the associated natural gas is enhanced when it is fed into the burner above the hydrocarbon and water dewpoints of the gas, and at twice the pressure at which bottle liquified petroleum gas is usually supplied to the burners.

1. INTRODUCTION

Gases are generally classified according to "families". The first family comprises the manufactured town gases containing considerable amounts of hydrogen and with calorific values of about 1.672 x 10^7 - 1.881 x 10^7 J/m^3. The second family covers natural gas with calorific value of about 3.762 x 10^7 J/m^3, and the third family covers petroleum gases such as propane, butane and their mixtures. The paper concerns the interchangeability of the last two families of gases on domestic burners.

Nigeria's Proven natural gas reserves are estimated to be approximately 3.2 x$10^9 m^3$. However, less than 5% of the natural gas produced is economically utilized. The bulk of the produced gas is flared to waste. The quantity of associated natural gas flared in a standard 30 thousand barrels per day (30MBD) oil station is estimated at 800 metric-tons with energy equivalent of 450 MW. The associated gas is co-produced with crude oil from oil wells, separated-off in the oil stations and burned as flared gas. There are over 100 of such oil stations in Nigeria's oil fields, with energy equivalent of over 45 GW.

A conservative estimate of approximately 10 million Nigerian households utilize liquified petroleum gas as cooking gas in domestic appliances. This approximates to domestic energy demand equivalent of 25 GW, representing over 50% of energy currently wasted in gas flaring.

Liquified petroleum gas (lpg) is produced in Nigerian Refineries by expensive energy extraction process. This process is not a primary refinery function but an add-on process designed to meet short term local energy demands for cooking gas. The cost of producing a unit energy of lpg is by far in excess of the cost of producing the same unit energy of the premium refinery products such as motor spirit and related fuels. The implication of co-producing lpg with the primary refinery products is a substantial loss of refining capacity and efficiency. Where attractive options exist for viable substitute fuel, the current use of lpg as domestic fuel gas in the midst of abundant natural gas does not urgur well for sound management of an energy intensive economy.

The abundant natural gas provides this option for meeting Nigeria's domestic energy demands. The option provides two major advantages. Firstly, it would release lpg to more economically profitable use as industrial feedstock for production of important chemicals such as butane and propane which command high prices in international markets. Secondly, natural gas would take on more economic and commercial values, thereby attracting greater public and private investments. A case in point is the recent multilateral Agreement for the proposed Trans ECOWAS gas pipeline from Nigerian oil fields to Ghana, Togo and Benin.

Even when the Liquified Natural Gas LNG takes off in 1998/1999 there would still be abundance of associated natural gas to meet Nigeria's domestic and industrial energy demand.

However, the difference in composition between natural gas and lpg and indeed between natural gas from various producer oil fields does not make the substitution a simple process. For example, irrespective of the composition of the substitute gas, the thermal input to the burner should be equivalent. The flame should stay alight on the burner over the usual range of burner turn down, that is to say, the flame should neither flash back, lift-off nor blow-off the burners; dangerous or obnoxious gases should not be formed, that is to say, a high quality of combustion determined by a low degree of soot formation and the amount of carbon monoxide produced should be achieved.

A typical domestic gas burner is similar in design to a low pressure premixed burner. The primary air required for combustion is entrained by injection and mixes with the gas prior to combustion. The secondary air is supplied by diffusion at the burner month. These two processes result in a flame defined by an inner premixed zone, with a diffusion zone enveloping it.

The combustion properties attached to compositional variations are not well understood, and this has made the design modification of substitute gas burners a difficult process.

This paper describes a study to predict the behaviour of natural gas as substitute fuel for domestic burners designed for lpg and sets out the variational limits of these characteristics by which substitution of natural gas for lpg becomes permissible.

THE AERATED ATMOSPHERIC BURNER

A schematic drawing of a domestic burner is shown in Figure 1. Low pressure gas flows through the injector "a" at a fairly high velocity. The stream of gas leaving the injector draws air in through the air inlet "b" into the mixing tube "c" Gas and air are mixed in this mixing tube and the gas-air mixture passes through the burner ports "d" on the burner head, where it burns upon ignition. A theoretical analysis of the system is given elsewhere by the author (1) for a gas flare stack which operates on a similar principle.

The amount of air entrained by the gas is known as primary aeration and comprises between 45% and 65% of the total amount of air necessary to achieve complete combustion of the gas. The remaining air requirement, that is the secondary aeration is supplied from the air around the flame.

THERMAL CONSIDERATIONS

The heat input to the burner is governed by the amount of gas supplied to the burner and the heating value of the gas. For low Reynolds number flows at relatively low pressures and at small pressure differences over the nozzle, typical of domestic gas burners (Re < 500), Dobelin (2) suggests the use of the equation:

$$P_F = {}^1/_2 C d_g V_g 2 \quad \ldots\ldots\ldots\

From equation (1), the injector jet velocity is obtained as:

$$V_g = \left(\frac{2P_f}{Cd_g}\right)^{\frac{1}{2}} \quad \text{----------(2)}$$

The corresponding gas discharge rate is:

$$Q_g = A_o V_g = A_o \left(\frac{2P_f}{Cd_g}\right)^{\frac{1}{2}} \quad \text{----------(3)}$$

The thermal input for a given burner, corresponding to an amount of gas of heating value H discharging through an injector of area A_o is therefore given by:

$$Q_{th} = A_o H \left(\frac{2P_f}{Cd_g}\right)^{\frac{1}{2}} \quad \text{----------(4i)}$$

In operational situations, the pressure in the gas system is regulated to a constant domestic supply pressure. Consequently, the pressure difference (P_f) is independent of changes in the temperature of the gas, and may be taken as constant. Equation (4_i) may be re-written in the form:

$$Q_{th} = A_o H \left(\frac{2P_f}{Cd_a}\right)^{\frac{1}{2}} \left(\frac{d_g}{d_a}\right)^{-\frac{1}{2}} \quad \text{----------(4ii)}$$

Denoting the constant $A_o\left(\frac{2P_f}{Cd_a}\right)^{\frac{1}{2}}$ =K; and the specific gravity of the gas $\frac{d_g}{d_a}$ = S, equation (4i) takes the final form:

$$Q_{th} = KHS^{-\frac{1}{2}} \quad \text{----------(4iii)}$$

Equation (4iii) states that if the heating value of the gas or its density or both are changed, the thermal input of the burner remains constant as long as the ratio $HS^{1/2}$ remains constant. This ratio is known as the Wobbe Number (W). Thus, the Wobbe Number depends only on the gas composition.

However, it does not necessarily mean that the burner will perform satisfactorily on all gases with the same Wobbe Number since other characteristics for a particular gas composition may be different from the characteristics of other gas compositions.

The Wobbe Numbers of pure hydro-carbon gases are presented in Table 1. The Wobbe Number of natural gas of a given composition of N constituent gases (i) may be determined from the relationship:

$$W = HS^{-\frac{1}{2}} = \frac{\sum_{i}^{N} x_i H_i}{\left[\frac{1}{M_a}\sum x_i M_i\right]^{\frac{1}{2}}} \quad \text{----------(5)}$$

where: M_i is the molecular weight of constituent (i); H_i is the heating value of constituent (i); x_i is the volume fraction or mole fraction and M_a is the molecular weight of air.

COMBUSTION CHARACTERISTICS

3.1 FLAME STABILITY

The most important combustion characteristic of a gas is its burning velocity (U_b) or flame speed. The design of domestic gas burners is based on the principle that the gas-air mixture emerges from the burner port with a speed that matches closely with the speed of propagation of the flame towards the burner port. Thus, where differences in flame speed occur by virtue of variations in gas composition flash back of the flame into the mixing tube of the burner would occur if the flame speed is higher than that for which the burner was designed, where as if the flame speed is lower, the flame would lift-off or blow-off the burner.

The burning velocities of a number of pure flammable gases are presented in Table 2. It shows that hydrogen has a far higher flame speed than hydrocabon gases. Comparing hydrogen (W=11570) and methane (W=12790), it is seen that the difference in Wobbe Number is not large, but the burning velocities of hydrogen ($U_b = 280 \frac{cm}{sec}$) and methane ($U_b = 40 \frac{cm}{sec}$) differ greatly. Thus, natural gas consisting mainly of methane would cause blow-off on a burner designed for hydrogen. On the other hand, the flame speeds of propane and n-butane (W = 22170; $U_b = 39 \frac{cm}{sec}$) which are the main constituents of liquified petroleum gas are not too different from methane (W = 12790; $U_b = \frac{cm}{sec}$) which is the main constituent of natural gas. Consequently, natural gas would give a stable flame on a burner originally designed for use with lpg.

However, natural gases containing substantial proportions of inert gases such as nitrogen and carbon dioxide have lower burning velocities and could show tendency for unstable flame on converted lpg burners.

BURNER AERATION

A gas suitable for domestic appliance should burn safely and satisfactorily, without formation of dangerously poisonous gases such as carbon monoxide and without sooting. To achieve this requires adequate mixing of the gas with the right amount of air.

The aerated burner works on the principle of primary air aspiration by injection. Thus only part of the air necessary for complete combustion of the gas is entrained by the gas as primary air. The ratio between primary air and total amount of air required for complete combustion is called aeration factor (e). To a first approximation, the injector theory by Kentfield and Barnes (4) gives the primary $\frac{air}{gas}$ ratio (n) independent of the gas pressure:

$$n = \frac{K_1 S^{1}/_{2}}{r} \qquad (6)$$

where: K_1 is constant and r is the radius of the injector bore.

Malee (5), in his analysis of compound gaseous fuels established that on volume basis, the theoretical $\frac{air}{gas}$ ratio (m) is roughly proportional to the heating value (H) of the gas. Thus:

$$m = K_2 H \text{ ----------} \qquad (7)$$

where: K_2 is constant.

Combination of equations (6) and (7) yields:

$$e = \frac{n}{m} = \left(\frac{K1}{K2}\right)\frac{S^{\frac{1}{2}}}{rH} \qquad (8)$$

From equation (8) it can be seen that the aeration factor (e) is inversely proportional to the Wobbe Number of the gas, as long as the same injector jet bore is used.

Figure 2 shows the plot of burning velocities of methane-air mixtures as a function of aeration factor. The graph marks out the range relevant to domestic burners. Examination of the graph reveals that a lower aeration factor (high Wobbe Number) would give a lower burning velocity and thus a longer flame. When the inner cone of the flame gets so long that it touches a relatively cold surface such as the bottom of a cooking pan, combustion becomes partially arrested and the carbon monoxide content of the exhaust gases rises sharply. On the other hand, a lower aeration factor also implies that additional (secondary) air is required to fan the flame. For burners installed in confined spaces, it may well be that even the secondary air supply to the flame is restricted and could result in incomplete combustion and thus further increase in carbon monoxide and soot formation.

PREDICTION OF INTERCHANGEABILITY OF GASES

In the foregoing sections, the effects of variations in gas composition on the performance of a domestic burner were discussed. In this section, an empirical method for predicting the interchangeability between gases of different compositions shall be determined in terms of the tolerable limits of variations of the relevant gas properties. The empirical method combines the Wobbe Number, corrected for CO, CO_2 and O_2 in the gas, with the Combustion Potential. The capability of a burner of given design to deal with the various characteristics of burning gases is then expressed graphically as an area enclosed by lines representing the stability limits for flash back, lifting and blow-off and incomplete combustion.

Before proceeding to examine these limits of variations as they apply to natural gas and lpg, the empirical methods for calculating the various interchangeability characteristics of the gas shall be outlined.

COMBUSTION POTENTIAL

The combustion potential (C) of the gas of given composition is calculated from a modified version of the original equation by Delbourg (6) in the form:

$$C = \sum x_{ic} C_i \left(\frac{S_i}{S_c}\right)^{\frac{1}{2}} \qquad (9)$$

where: C_i and S_i are the combustion potential and specific gravity respectively of pure hydrocarbon constituent (i) in the gas; S_c is the specific gravity of the gas, corrected for CO, CO_2 and O_{2i} X_{ic} is the mole fraction of hydrocarbon constituent (i) in the gas corrected for CO, CO_2 and O_2.

Denoting the volume fractions of CO, CO_2 and O_2 by X_{co}, X_{co2} and X_{02} respectively, the corrected volume fraction (x_{ic}) of the pure hydrocarbon constituent (i) is then given by:

$$x_{ic} = \frac{x_i}{(1 - x_{co} - x_{co2} - x_{o2})}$$

Hence: $S_c = \frac{1}{M_a}\sum x_{ic}M_i$

The combustion potential (C_i) for constituent (i) is determined from the empirical relation:

$$C_i = \frac{a_i \times 100}{S_i^{1/2}}$$

For methane (CH_4), ai=0.3; while for the other pure saturated hydrocarbons (alkanes), a_i is corrected with M according to the expression:

$$a_i = 1.46 - \frac{21.3}{M_i}$$

Values of C_i for some pure hydrocarbons are presented in Table 1.

The combustion potentials computed with the aid of the above expressions are 72.5, 46.2 and 48 for LPG, high pressure natural gas and low pressure natural gas respectively.

Schneck and Brunet (7) carried out extensive tests with natural gases fed at pressures ranging from 1.227 bar to 1.307 bar, and observed that a combustion potential lower than 40.3 (the value for pure methane), which is the limit for blow-off can occur when appreciable amounts of inerts such as N_2 and CO_2 are present in the gas. On the other hand, the combustion potential can be increased considerably when H_2 is present in quantities not exceeding 10% in the gas, without risk of flashback.

COMBUSTION QUALITY

The corrected Wobbe Number (Wc) is given by:

$$Wc = \frac{H_c}{S_c^{1/2}} \text{ ----------(10)}$$

where: H_c is the heating value of the gas corrected for the presence of CO, CO_2 and O_2 in the gas.

According to Schneck and Brunet (7), when the Wobbe Number increases considerably, the limit of carbon monoxide which can be tolerated in the flue gas is exceeded. This limit is $0.01 \leq \frac{CO}{CO_2} \leq 0.02$

Computed values of the corrected Wobbe Number are 18748, 12759 and 13304 for LPG, high pressure natural gas and low pressure natural gas respectively.

YELLOW - TIP - INDEX

The Yellow-Tip-Index is a characteristic of interchangeability and shows the tendency of a gas to cause sooting upon combustion and its value increases with the higher hydrocarbons.

The Yellow - Tip - Index (i) is calculated from the modified Delbourg equation in the form:

$$I = \sum x_{ic} I_i \left(\frac{S_i}{S_c}\right)^{\frac{1}{2}} \text{ ----------(11)}$$

where: I, is the Yellow - Tip - Index of constituent (i) and is given by:

$$I_i = \frac{J_i \times 100}{S_i^{1/2}}$$

where: $103 \times J_i = 142.45M_i - 1342.73$

The computed yellow - tip - index for LPG is 431 and the corresponding values for low pressure natural gas and high pressure natural gas are 189 and 216 respectively. Based on results of tests carried out, Schneck and Brunet (7) prescribe that the value of the Index should not exceed 230 and preferably remain below 210 for aerated burners.

GENERALIZED CORRELATIONS

A general correlation between the corrected Wobbe Number and the Combustion Potential covering a wide range of natural gas compositions is presented in Figure 3. The diagram is bounded by lines representing stability limits for flash back, blow-off and flame lifting.

The diagram shows the wide interchangeability envelop for natural gas of various compositions. With reference to Figure 3, the combustion characteristics of natural gas produced from the high pressure and low pressure separators in Nigerian oil fields, are indicated by points x and y respectively, on the diagram. It can be seen that these points lie close to each other and fall within the interchangeability band for domestic appliances. This means that the combustion characteristics of Nigerian natural gas from low and high pressure oil wells permit interchangeability on a given burner, after treatment of the gases for dew point and removal of contaminants.

Computed values of the combustion characteris-

Computed values of the combustion characteristics of LPG are shown side by side with those of low pressure and high pressure natural gases in Table 3. It is noted that the values for LPG are higher than the corresponding values for natural gas. In particular, the Wobbe Number for LPG falls outside the range of the general correlation. If the pressure dependence of the heat input is taken into consideration according to Equation (4i), and in order to achieve the same thermal effects on a given burner, as a condition for interchangeability of LPG and natural gas, then the supply pressure of the natural gas must be regulated to about twice that to which LPG is normally supplied to the burners.

It is also to be noted that the lower values of combustion characteristics of natural gas fall within acceptable limits of interchangeability compared to LPG and is indicative that natural gas has superior and higher quality combustion performance to LPG.

CONCLUSION

This paper describes the development of criteria for the determination of interchangeability of natural gas with liquified petroleum gas on domestic burners from their burning characteristics.

From the analysis of the composition of natural gases produced from Nigerian oil wells, the paper establishes that the margin of interchangeability for these gases is wide, when the results are presented on a global correlation of Wobbe Number to the combustion potential.

Although the Wobbe Number for LPG falls outside the scope of the generalized correlation, it is found that when the Wobbe Number for LPG is scaled by the pressure dependence of the heat input to the burner, interchangeability between LPG and natural gas is achieved. The scaling Factor is twice the regulated pressure at which LPG is normally fed to the domestic burners.

These results broaden the potential of natural gas as substitute gas for domestic burners in place of LPG. The practical realization of this potential depends on the degree of treatment of the natural gas to enhance its use as domestic fuel.

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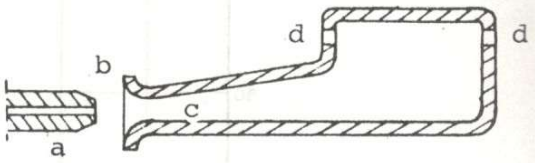
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TABLE 3

COMPARISON OF INTERCHANGEABILITY CHARACTERISTICS OF NATURAL GAS AND LIQUIFIED PETROLEUM GAS LPG

	LPG $M_0$1%	Natural Gas (Bonny F/S HP Seperator)	Natural Gas (Bonny F/S LP Separator)
Methane ($C H_4$)		84.74	79.29
Ethane ($C_2 H_6$)		5.85	6.21
Propane ($C_3 H_8$)	50	4.15	5.31
Butane-n ($C_4 H_{10}$)		1.39	2.44
Butane-i ($C_4 H_{10}$)	50	1.47	2.27
Pentane-n ($C_5 H_{12}$)		0.40	0.80
Pentane-i ($C_5 H_{12}$)		0.59	1.17
Hexane ($C_6 H_{14}$)		0.36	0.80
Heptane ($C_7 H_{16}$)		0.23	0.44
Octane ($C_8 H_{18}$)		0.18	0.31
Nitrogen (N_2)		0.04	0.05
Carbon Dioxide (CO_2)		0.60	0.91
Hydrogen Sulphide (H_2S)		Trace	Trace
Molecular Weight	51	20.531	22.919
Specific Gravity (Air=1)	1.768	0.7119	0.7947
Heat Content kCal/m^3 @ 298K and 76cm Hg	24928	10665	11698
Water Dew Point		292K(19OC)	291K(18.3OC)
Wobbe Number	18748	12640	13122
Corrected Wobbe Number		12759	13304
Combustion Potential	72.5	46.2	48.0
Yellow-Tip-Index	431.0	189.0	216.0
Corrected Specific Gravity		0.7070	0.7884



Sketch of a domestic burner

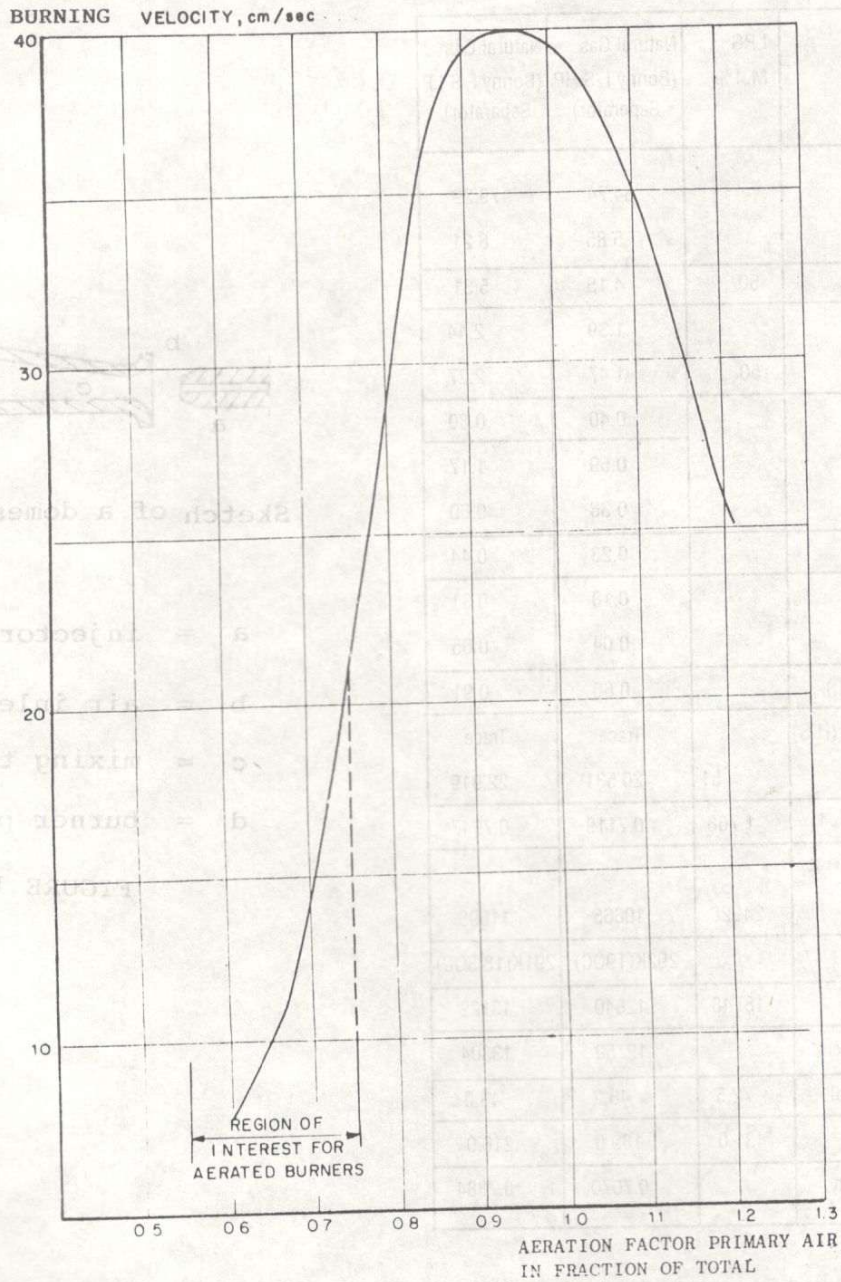
a = injector jet or nozzle

b = air inlet

c = mixing tube

d = burner ports

FIGURE 1



BURNING VELOCITY OF METHANE/AIR IN RELATION TO AERATION FACTOR

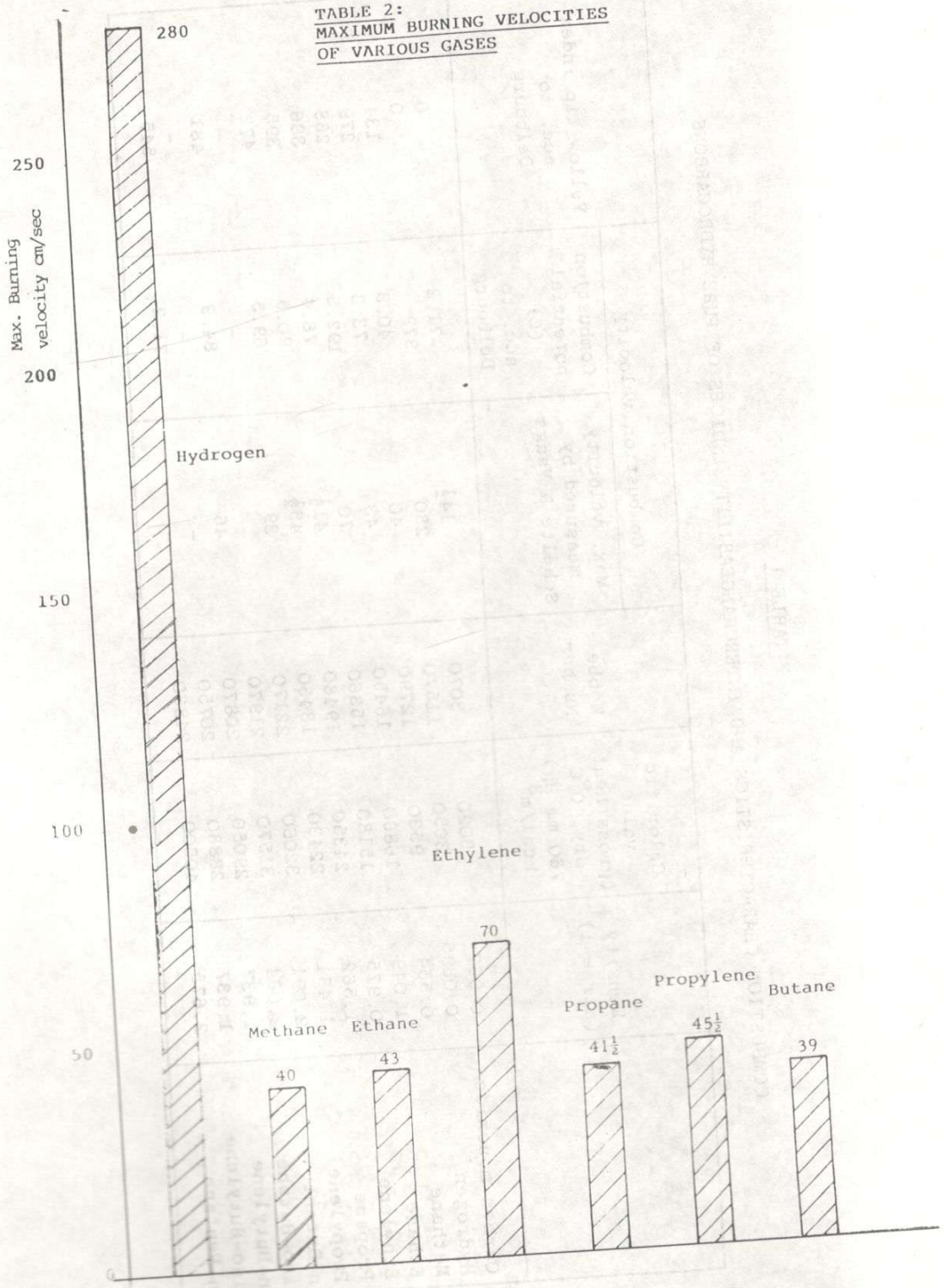
FIGURE 2

TABLE I

COMBUSTION CHARACTERISTICS AND INTERCHANGEABILITY INDICES OF PURE HYDROCARBONS

	Density (air = 1)	Calorific value (gross heat dry, 0°C 760 mm Hg) kcal/m³	Wobbe Number	Combustion velocity		Yellow tip index acc. to Delbourg
				Max. velocity measured by Schelte & Vaags	Combustion potential (C) acc. to Delbourg	
Carbon monoxide	0.967	3020	3070	14½	71.2	0
Hydrogen	0.0695	3050	11570	280	379	0
Methane	0.554	9530	12790	40	40.3	134
Ethane	1.049	16860	16450	43	73.3	279
Ethylene	0.975	15180	15360	70	192.5	268
Propane	1.562	24350	19480	41½	76.4	386
Propylene	1.481	22430	18430	45½	90.5	395
n-Butane	2.091	32060	22170	39	69.5	472
iso-Butane	2.064	31570	21970	-	-	-
n-Butylene	1.937	29050	20870	46	84.9	481
iso-Butylene	1.937	28880	20750	-	-	-
n-Pentane	2.675	40600	24830	-	71.2	545

TABLE 2:
MAXIMUM BURNING VELOCITIES
OF VARIOUS GASES



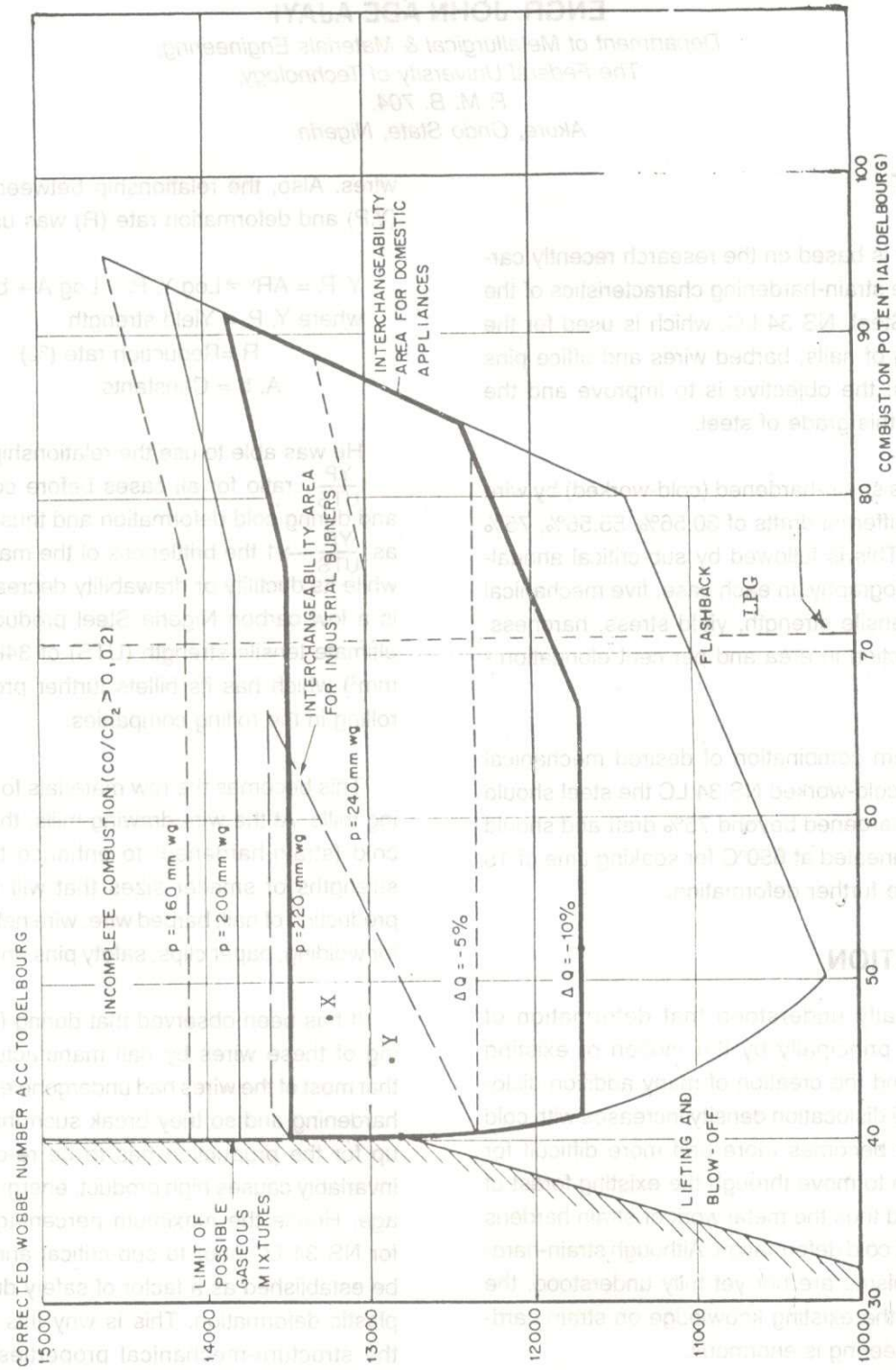

AREA OF INTERCHANGEABILITY OF GASES
CORRECTED WOBBE NUMBER ACC TO DELBOURG
15000
14000
13000
12000
11000
10000
30
40
50
60
70
80
90
100
COMBUSTION POTENTIAL (DELBOURG)
INCOMPLETE COMBUSTION ($CO/CO_2 > 0,02$)
p = 160 mm wg
p = 200 mm wg
p = 220 mm wg
p = 240 mm wg
INTERCHANGEABILITY AREA FOR INDUSTRIAL BURNERS
INTERCHANGEABILITY AREA FOR DOMESTIC APPLIANCES
ΔQ = -5%
ΔQ = -10%
X
Y
LIMIT OF POSSIBLE GASEOUS MIXTURES
LIFTING AND BLOW-OFF
FLASHBACK
LPG

FIGURE 3