GASIFICATION OF LIQUID FUELS

BY

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DECLARATION

I hereby declare that this thesis has been composed by myself and that it is a record of my own research work. It has not been presented in any previous application for a higher degree. All quotations are distinguished by quotation marks and the sources of information are specifically acknowledged by means of references.

AUDU, Yusuf Buba

December 4, 1995

CERTIFICATION

This project report entitled "Gasification of Liquid Fuels" by AUDU, Yusuf Buba meets the regulation governing the award of Master of Science in Chemical Engineering of Ahmadu Bello University and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

This piece is dedicated to my parents, who love me in every way, and to Miss Zulai, for her continuing patience and understanding.

ACKNOWLEDGEMENT

I am grateful to Almighty Allah for His guidance and protection.

I am deeply indebted to my supervisor Professor S.S. Adefila, who proved to be a great tutelar. His unceasing interest helped maintain the initial tempo, despite the rising resistance to academic activities: the working relationship brought about by this work is probably second only to that shared by Father and Son. Prof., since I can't thank you enough, I pray God rewards you, abundantly, in His special way.

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Sincere appreciation to my parents, guardian and close associates who stand the test of time.

Forever, I will remain grateful.

ABSTRACT

Analysis of the results of the simulation for the production of gaseous fuel by gasification of kerosene was made. Also treated, were the possible methods of actualizing this principle.

Simulation results showed that at ambient conditions, kerosene (DPK) can not support a flammable vapor and a liquid booster in form of petrol (PMS) was employed to increase the total combustibles. Flammability range of the mixture at different bottled pressure using air as filler were determined. It was observed that a minimum of 3.5 mol% PMS in the DPK-PMS liquid mixture is required to form a combustible gas, herein called the Vaporised Liquid Fuel (VLF) gas.

At 5 bar, the domestic supply pressure of LPG, a liquid mix of 70 mol% DPK produced a VLF gas of calorific value 3.7 MJ/m^3. This, however, improved to 12.7 MJ/m^3 upon the reduction of operating pressure to 1.5 bar. Wobbe index evaluated for both cases fall short of that for LPG. Hence, the modification of LPG burners is necessary to help it burn the VLF.

Of the two actualization methods suggested -batch and continuous-, the former method produced VLF gas of constant calorific value arising from its uniform composition. However, a 12.5kg bottle of VLF gas was evaluated to contain

one-sixth, as much energy as for LPG. On the other hand, the latter method can be domesticated though, with relatively increased risk. Also, periodic topping of PMS is required to produce VLF gas of fairly constant calorific value.

Typical laboratory burner produced a stable VLF gas flame, and combustion was essentially complete as shown by its deep blue colouration. Thus, the gasification of kerosene favours healthier environment.

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Abbreviations and symbols

A	area, m^2
C	*discharge coefficient*
CP	heat capacity at constant pressure, J/kg K
CV	net calorific value, MJ/m^3 or MJ/kg
CV'	net calorific value, MJ/kmol
d	diameter, m
DPK	dual purpose kerosene
f	fugacity, N/m^2
k	parameter (CP/CV) = 1.33
L	lower inflammability limit (vol %)
m	mass per mass of fuel
M	*mass, kg*
N_{wb}	Wobbe index
P	pressure, N/m^2 or bar
PMS	premium motor spirit (petrol)
r	parameter, P_0/P_s
R	*gas constant, J/mol. K*
SG	specific gravity
t	temperature, ^0C
T	temperature, K
u	velocity, m/s
U	upper inflammability limit (vol %)
V	volumetric flow rate, m^3/s
VLF	vaporised liquid fuel
x	liquid phase mole fraction
y	vapour phase mole fraction

γ vapour phase mole fraction based on total combustibles

β parameter, d_0/d_s

ρ density, kg/m^3

μ viscosity, Ns/m^2

v specific volume, m^3/mol

Ω parameters for Antoine equation

Subscripts

a adiabatic or air

m mixtures

N_2 nitrogen

o orifice

pdts products

r reference

rxts reactants

s supply

Superscripts

L liquid

o saturated property

ss excess

v vapor

T total

CHAPTER ONE

INTRODUCTION

Heat is a, major and a most important, form of transient energy harnessed by man for his activities and general well-being. The burning process that characterizes the generation of heat and often light is essentially a fuel combustion application, i.e the chemical reaction between a fuel and oxygen. The fuel mostly used for this purpose is a carbonaceous material that takes any form of matter such as coal, gas oil and natural gas.

Oil and natural gas form about 70% of today's energy supply *[Hafelle, 1981]*. Oil and natural gas are clean, versatile and relatively easy to use fuels. Further, the drive has been strongly towards oil. The reasons being its high specific energy content (ca 10^4 kcal/kg) and physical properties of a liquid, permit easy storage and transportation at low cost. Technological progresses tend to decrease energy demand. These lead to improved efficiencies in energy conversions, and of recent, to environmentally safe conversions.

1.1 ENERGY TRANSFORMATION THROUGH COMBUSTION AND ENVIRONMENTAL CONSIDERATIONS

It is conclusive that combustion has been outstanding in providing the bulk of the energy needed by man. The combustion of fossil fuels necessarily result in the release of CO_2. While emissions of sulphur and nitrogen oxides can in practice be reduced and in theory eliminated, the same can not be true for CO_2.

In complex steps of combustion mechanism, the fuel must change phase to gas so as to mix properly with oxidant before it can burn. Therefore gaseous fuel (e.g., natural gas) burns easily, cleanly and relatively more efficient, and all other combustion processes try to simulate this burning state.

Combustion of fuels with high ash content and objectionable amounts of sulphur often do produce particulates and SO_2 which result in environmental pollution in form of acid rains, etc. When incomplete (inefficient) combustion occurs, among the products are CO, soot and unburned hydrocarbons. Apart from being a loss as they are fuels themselves, CO is highly poisonous. Soot contaminates products in direct-fired process, and in the case of indoor burning, produces gauche impression.

1.2 THESIS MOTIVATION, AIMS AND OBJECTIVES

Introduction of fossil fuel necessitated the need to have a safe, simple and efficient mechanism for burning it. In urban Nigerian homes today, one finds burner types either for LPG or kerosene. The extent to which rural dwellers embraced the use of fossil fuel is poor: it could not compete with fuel wood because of price and limitation of supply. And since efficiency holds no meaning to them, an added advantage is that fuel wood needs no special apparatus to burn.

Gaseous fuel burns more efficiently and is least prone to polluting the environment, therefore, the fuel of preference whenever available. In Nigeria today, gaseous fuel use is being hampered by undeveloped domestic supply system. Absence of proper infrastructure to support the costly handling and storage of such fuel, limited its availability to source regions only. Though government policy on this necessitates a safe and continuous supply nationwide, there are doubts as to its actualization in the near future. Another important cost feature in the comparison of domestic fuel supply systems is the maintenance expenses. This is relatively high for gaseous fuel.

The scarcity and price of this commodity has made some users turn to kerosene not as a backup but as an alternative source of domestic energy. This is distinctive to consumers far from the source, especially, the Northern part of Nigeria. Though, energy price is subject to upwards reviewal now and then, as part of government's deliberate policy, the price of kerosene shall always rank relatively low. Full and efficient utilization of liquid fuel supply facilities on ground can lead to large distribution coverage. This will smoothen the erratic supplies currently being experienced. Most homes use kerosene oil burner and in the face of ever increasing price of energy, the issue of efficient burning (leading to larger cost savings) becomes more relevant. Presently, domestic burning of kerosene results in slow heat generation rate and in an incomplete combustion as higher rates are approached.

This work is an attempt to produce a clean and cheap gaseous fuel from kerosene, usable under conditions similar to that operating for domestic gas fuel. Strong emphasis will be laid on adapting the available technologies, including gas burners, storage and maintenance facilities to this new fuel. This system can be built-in to Vapor absorption heat pumps, for space heating, for use in rural hospitals, storage of agricultural products, etc. This can effectively replace solar energy system being contemplated or in use, because of its lower fixed cost and round-the-clock application. It is expected that in the course of this work, a lot of theories in thermodynamics will be thoroughly explored, thereby leading to greater understanding of the subject and the guiding principles of burner technology.

The project aims and objectives, importance and scope of work are summarized below.

Project Aim: ▲ To produce clean fuel for domestic use

Importance:
- ▲ Replace inefficient domestic burning of liquid fuel
- ▲ Produce readily available, portable gaseous fuel

Scope:
- ▲ Produce gaseous fuel from liquid fuel
- ▲ Evaluate compatibility with existing infrastructure
- ▲ Determine its burning characteristics
- ▲ Suggest possible actualization methods

CHAPTER TWO

SURVEY OF LITERATURE

2.1 FUELS

It was seen from the preceding chapter that a fuel is any material that is capable of burning to provide energy. The essential constituents, the combustible parts, mostly are carbon and hydrogen. These could be present in free state, but are usually found combined (in most instances together) in most fuels. Most fuels originate directly or indirectly from the plant kingdom, either of the present or of the past that lived millions of years ago. Such fuels are classified respectively as renewable and non-renewable. Generally, *fuels are classified into gas, liquid and solid, depending on* their physical form under normal atmospheric condition. This classification is of paramount practical significance because, equipments for handling and burning fuels differ greatly from one class to the other. The first two classes are of concern in this work and are briefly discussed below.

2.1.1 Gaseous fuels

The naturally occurring gaseous fuel, and hence generally known as natural gas, is methane (CH_4). The rest are referred to as *manufactured or synthetic gases*. Perhaps the most common are liquified petroleum gas (LPG) and acetylene.

Natural gas is obtained, mainly from underground reservoirs which may or may not be associated with crude oil. On the other hand, there are lots of processes that result in the production of manufactured gas. These processes may be collectively termed gasification. Table 2.1 gives composition ranges of some gaseous fuels at 288 K and 1.013 bar *[NNPC, 1994; Jessen, 1977; Spalding, 1973; Cremer, 1960]*.

TABLE 2.1 COMPOSITION RANGE OF SOME GASEOUS FUELS AT 288 K 1.013 Bar (VOL %)

	Liquified Petroleum Gas	Natural Gas	Biogas	Refinery Gas	Coal Gas	Carburated Water Gas	Producer Gas
Higher Homologues		10-15	-	0-4	2-4	7	-
C_5H_{12}	(0.1)	-					
C_4H_{10}	0-99(80.6)	(2.4)					
C_3H_8	0-99(19.3)	(3.6)					
C_2H_6	-	(7.0)					
Others	0-1						
CH_4	-	80-99 (82.4)	55-75	0-32	20-30	14	0-3
CO	-	-	-	12-17	8-18	30	29
H_2	-	0-1	1-5	48-65	49-52	37	11-12
CO_2	-	0-2 (0.2)	25-45	3-9	2-4	6	5
N_2	-	0-2 (4.4)	-	0-5	4-6	5	52-55
O_2	-	-	-	-	1	1	-
Net Calorific Value MJ/m^3	(105.9)	(42.2)	23	18	18	18	6

(): For typical Nigerian Gas

Gaseous fuels are stored and transported under pressure and in many cases, in liquified form. Pipeline distribution network with boosters, are used for continuous transportation to depots. Such networks extend to local consumers in advanced countries. Small pressure container trucks and large vessels are used for land and sea transport respectively. Large quantities are stored in gas holders or in spherical and oblong containers called hartonspheres constructed with stainless steel. Domestic storage systems are pressure vessels in varying sizes.

2.1.2 Liquid Fuels

Naturally occurring liquid fuels can not be used directly without some form of treatment to alter its character. Liquid fuels are broadly divided into petroleum and non-petroleum fuels. Petroleum fuels are derived from crude oil and/or natural gas, and are essentially hydrocarbons. Non-petroleum liquid fuels are synthesized from a variety of materials (natural gas and petroleum fractions inclusive), such as alcohols from sugar fermentation. Liquid fuels that are basically obtained from crude oil are sometimes referred to as non-renewable. Table 2.2 lists average characteristics of some liquid fuels *[Othmer, 1992; Jessen, 1977; Spalding, 1973; Cremer, 1960]*.

TABLE 2.2 PROPERTIES OF SOME LIQUID FUELS

Property	Ethanol	Petrol	Kerosine	Gas oil	LPFO
Composition, %mass					
Carbon	52.2	86.5	85.8	86.1	85.6
Hydrogen	13	13.4	14.1	13.2	11.7
Sulphur	-	<0.1	<0.1	0.7	<2.7
Oxygen	34.8	-	-	-	-
Ash	-	-	-	-	0.03
Sediment	-	-	-	-	0.2
Water Content, %Vol	-	-	-	-	0.1
Min. Handling Temperature, K (if not ambient)	-	-	-	-	283
Flash Point, K	289	228	>318	343	368
Density, kg/m^3	785	745	780	830	930
Vapor Pressure, Bar	0.08	0.33	0.0017	0.0013	0.0009
at 318 K	0.27	0.67	0.0051	0.0033	0.0023
Critical Parameters:					
Pressure, Bar	63.8	63.8	33.4	15.2	-
Temperature, K	516	543	700	711	-
Gross Calorific value, MJ/kg	29.7	46	46.5	46	44

Properties at 288 K and/or 1.013 bar

The same main transport and distribution methods do exist here as for gaseous fuels. Large quantities are stored in surface and, as well as underground reservoirs. Additional heating may be required for some liquid fuels to maintain their physical properties. However, it is important to keep vapor pressures outside explosive limits to prevent fire hazards during handling.

2.2 GASIFICATION: HISTORICAL

Gasification refers to the gaseous change of substance from the original phase. The process involved may be physical or chemical in nature. Due to the wide range in product composition, gases generated are categorized based on their heating values as either low heat-value (<5.6 MJ/m^3), medium heat-value (up to 20 MJ/m^3), or high heat-value (>22.5 MJ/m^3) *[Othmer, 1980]*

The conversion of fossil fuels to gas dates back to 1800 [*US DOE Survey, 1978*], when "Manufactured gas" was first produced by heating coal to liberate volatile constituents. A maximum of 20% coal conversion was obtained along with a medium heat-value (ca 20.5 MJ/m^3) gas. Subsequently, "Blue water gas" appeared in the late 19th century and since then, variety of synthetic gases were produced through many processes.

Liquid fuels were first gasified by bubbling hot blue water gas through oil. This increased the heating value of the gas from a low 10.2 MJ/m^3 to a value above that of manufactured gas. Thermal cracking of oil was an important method for producing gas following its use for carburetion of water gas. The catalytic cracking process developed in 1940, is essentially for producing lighter, and not, necessarily, gaseous petroleum fractions from the higher homologues.

In the 1940's, the British Gas Council, which had been working on coal hydrogasification, experimented with the hydrogasification of oil. This yielded a rather low heating capacity gas. In 1964, the Council found that light distillates having end boiling points below 455 K could be catalytically reformed into essentially pure methane (heating value of ca. 40 MJ/m^3). This method was extensively used in the UK (and other parts of the world) until the North Sea gas came on stream.

In the recent past, there have been concerted efforts in using distillate petroleum fractions for domestic gas production. Such processes more often than not use distillates in the specific gravity range 0.68 to 0.72. The distillate is vaporized in a stream of flowing air and, the air-vapor mixture compressed for delivery into a tank. The gas obtained has heating value between 10 to 15 MJ/m^3 *[Aerogen bulletin]*

While the above general definition of gasification presupposes a change in concentration, it does not impose any chemical reaction. In fact some physical gasification processes border pseudo-gasification, in that the product may not be wholly gas. Carburetion and atomization, naturally fall into this category. Most of the processes mentioned above, are explored on industrial scale (for obvious reasons of economics and complexities). The physical methods are easily domesticated. This work is limited to physical gasification of liquid fuels. However, a brief overview of entire spectrum of gasification processes is given below.

2.2.1 Common Gasification Processes

The degradative process of cracking, necessarily, results in molecular carbon-carbon bond cleavage. Thus it is an endothermic reaction. This could be carried out solely by heating, sometimes, in combination with a catalyst. Thermal methods are essentially high pressure (2-27 bar) and temperature (673-773 K) operations *[Jack, 1980]*, depending on the nature of feed stock and product distribution desired. The calorific value of the gas varies from 26.1 to 59.6 MJ/m^3 *[Linden and PettyJohn, 1952]* according to the severity of the process conditions and residence time of the fluids. The yield of gas over liquid obtained shows a rather strong dependence on feed stock characteristics. Further, the composition of gas produced from a wide variety of feed stock depends on the severity of cracking much more than on the feed stock type. Yield based on feed input varies from 78.8 wt% for naphtha cracking to 28.7 wt% for residuum oils *[Ward, 1965 & 1972 Bannett, 1962]*.

In contrast, the primary aim of catalytic cracking process is to increase the gasoline yield and the octane number. To prevent transitional metals vanadium and nickel, from poisoning cracking catalyst, the feed is often cut at about 773-823 K. Though heavier fractions are used, these must be treated to remove potential poisons. Catalysts usually employed include silica gel, activated with 15-60% Al_2O_3, molecular zeolites, etc. In this process, the operating conditions vary from 773 to 833 K and 1.5 to 2 bar *[Rheaume & Maggee, 1979; Luckenbach, 1976]*. Catalytic cracking, generally, produces low heat value gas. There is appreciable contribution of CO and H_2 from the gasification process in the regeneration cycle. The yield of gas based on oil feed is between 5 to 6.5 wt% *[Luckenbach, 1976]*.

2.2.2 Pseudo-Gasification Processes

This refers to processes that do not change the molecular constitution of the liquid fuel and product is not entirely gaseous. Being wholly physical in nature, they are not temperature intensive, and rarely are moderate pressures exceeded. The choice of atomization or carburetion in physical gasification of liquid fuels is entirely dependent on the physical properties of the fuel and the required output capacity. Relative cost implications and mechanical complexities are also weighed when the options exist.

2.2.2.1 Atomization

This is the shearing of the condensed liquid phase into "small particles", by the application of pressure energy. Particle sizes vary from droplet diameters of few tenths of millimeters to a few hundred microns. Efficiencies of conventional atomization processes are generally low: the energy required to produce the increase in surface area is usually less than 1% of the total energy consumption *[Perry, 1973]*. The bulk energy is consumed in preparing the liquid fuel and or, an atomizing agent. The efficiency drops even further as the droplet sizes decrease.

Conventional processes are carried out using nozzles. A purely mechanical atomization process utilizes the fuel pressure only e.g., impinging jet. The two fluid method engages the use of atomizing agents such as air and steam e.g., in venturi atomizers. The air is supplied by a fan or compressor and, varies from 25-30% of stoichiometric requirement for low pressures to 2-3% for high pressure processes. Steam pressure is between 50-100 psig (3.45-6.9 bar) *[Cremer, 1960]*. Mechanically aided processes utilize an input mechanical energy in form of rotary mechanism in which liquid is swirled either at or prior to atomizing point e.g., rotating disk atomizers.

Droplet sizes are difficult to estimate. Literature search reveals a functional relation to geometry, velocity and liquid properties. Although there is no general all-purpose equation, viscosity effects are known to be most prominent

[Perry, 1973; Cremer, 1960]. And since this property is strongly temperature dependent, temperature is normally varied for the kinematic viscosity to fall within 15 to 36 cS (0.15 to 0.36 m^2/s) *[Van, 1951]*, though a value of 25 cS (0.25 m^2/s) is recommended for most conventional atomizers *[Joyce, 1953]*.

Droplets size is better described with a statistically defined dimension, the volume median diameter, obtained from population plots. Smaller sizes resulting from good atomization usually lead to complete combustion, and by virtue of liquid fuels high calorific value, produces a high-heat value "gas".

2.2.2.2 Carburetion

This method is particularly good for volatile liquid fuels. The process is simple and is based on the phenomenon of phase equilibria, governed by thermodynamic principles.

Liquids at a given temperature are normally associated with a quantity of vapor, in equilibrium. Vaporization of the liquid can be achieved if the quantity of vapor is kept below equilibrium conditions. A mechanism is developed in which the vapor is evacuated, for compression or direct use. In gas-liquid saturators, some carrier gas is introduced into the system to cart away the equilibrium vapor *[Doolittle, 1963]*. The physical properties of the carrier gas and calorific value requirement of resultant mixture dictate the quantity of the carrier gas needed. Continuous saturation methods of carrier gas are increasingly being domesticated [*Aerogen Bulletin*]. Extent of saturation depends on the contact time which, is determined by mass transfer characteristics of the contacting scheme.

Calorific value of the resultant gaseous mixture is a function of relative quantities of the components present in the gas. Often, combustion of such fuel is complete and, considerable heating is obtained even at low concentrations of combustibles. This, however, may be at low temperature.

2.3 PRINCIPLE OF GASIFICATION

The principle of gasification, and indeed any phase change process, is best appreciated through a phase diagram. In fact the method of gasification could be adopted from the diagram. Referring to a typical Pressure-Volume (*P-V*) diagram (with temperature as a parameter), presented in Figure 2.1, it can be seen that the physical condition of a given material is determined by the values of any of the two properties *P, V, T*. In the diagram, lines *EF, DG* and *BCA* are boundaries demarcating different phases of a material. Consequently, phase change can occur only by crossing these boundaries. It is noteworthy that the gas region is characterized by larger specific volume. Therefore, gasification necessarily results in increased specific volume. Depending on the physical state of the material, isothermal or isobaric (or even a combination of both) methods may be adopted.

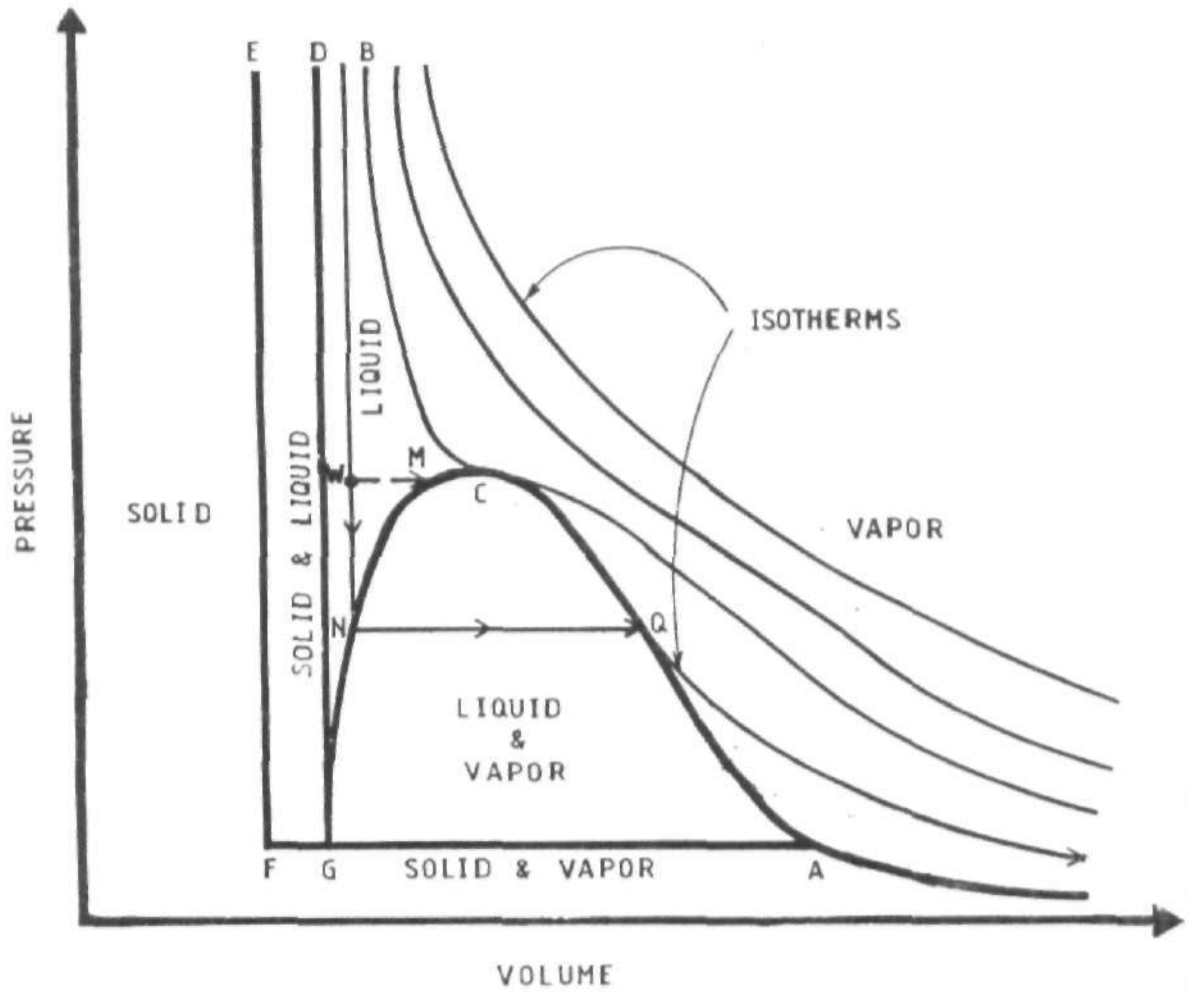

Fig. 2.1. Typical P-V Diagram for Substances.

Phase change by heating can be effected for most materials, but there are some, that degrade upon excessive heating, yielding undesirable gaseous products. Such processes operate at above normal temperatures.

Isothermal processes imply moving along an isotherm, such as route ***WN*** shown for liquid **W**. As the pressure is reduced, a point *N* is reached where the total pressure equals the saturation pressure of the liquid. This equilibrium state is maintained until all the liquid is vaporized at *Q*, while the *specific* volume *for* the *system* is observed to be increasing. Thereafter, the pressure-volume variation is as described by an equation of state.

Domestic applications of isothermal methods operate at ambient temperature. A suitable example is the cooking gas, supplied as bottled LPG. The physical properties of LPG (which is mainly butane) at ambient conditions show that it exists as super-heated vapor. On a *PV*-diagram for LPG (as adapted from *MacPhee, 1977*) shown in Figure 2.2, it is located in the **Liquid-Vapor** region along an isotherm corresponding to ambient temperature at bottled condition. As the contents of this bottle is depleted by withdrawing gaseous LPG, the total pressure remains constant (at the saturation pressure), but the net specific volume increases. This continues until all liquid is exhausted and thereafter, the system pressure drops, sharply. A refill is required when the pressure drops close to atmospheric.

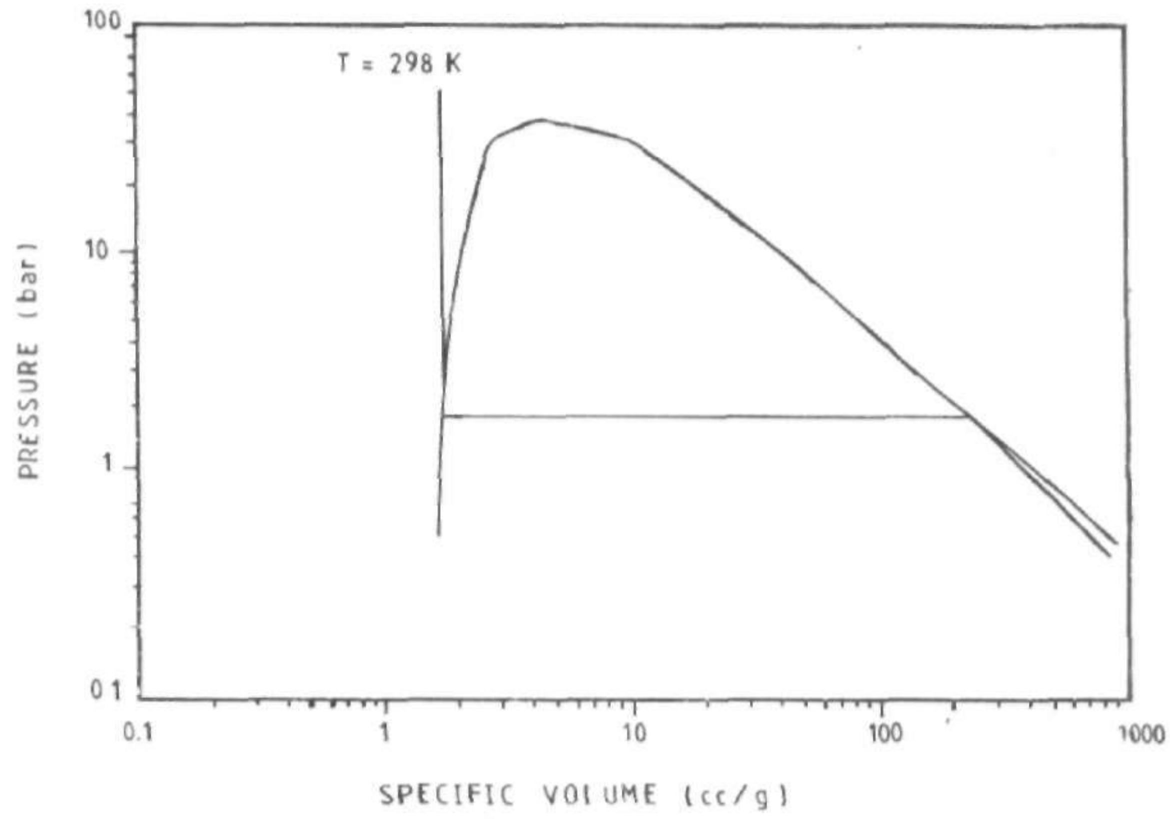

Fig. 2.2: P-V Diagram for LPG (mainly butane)

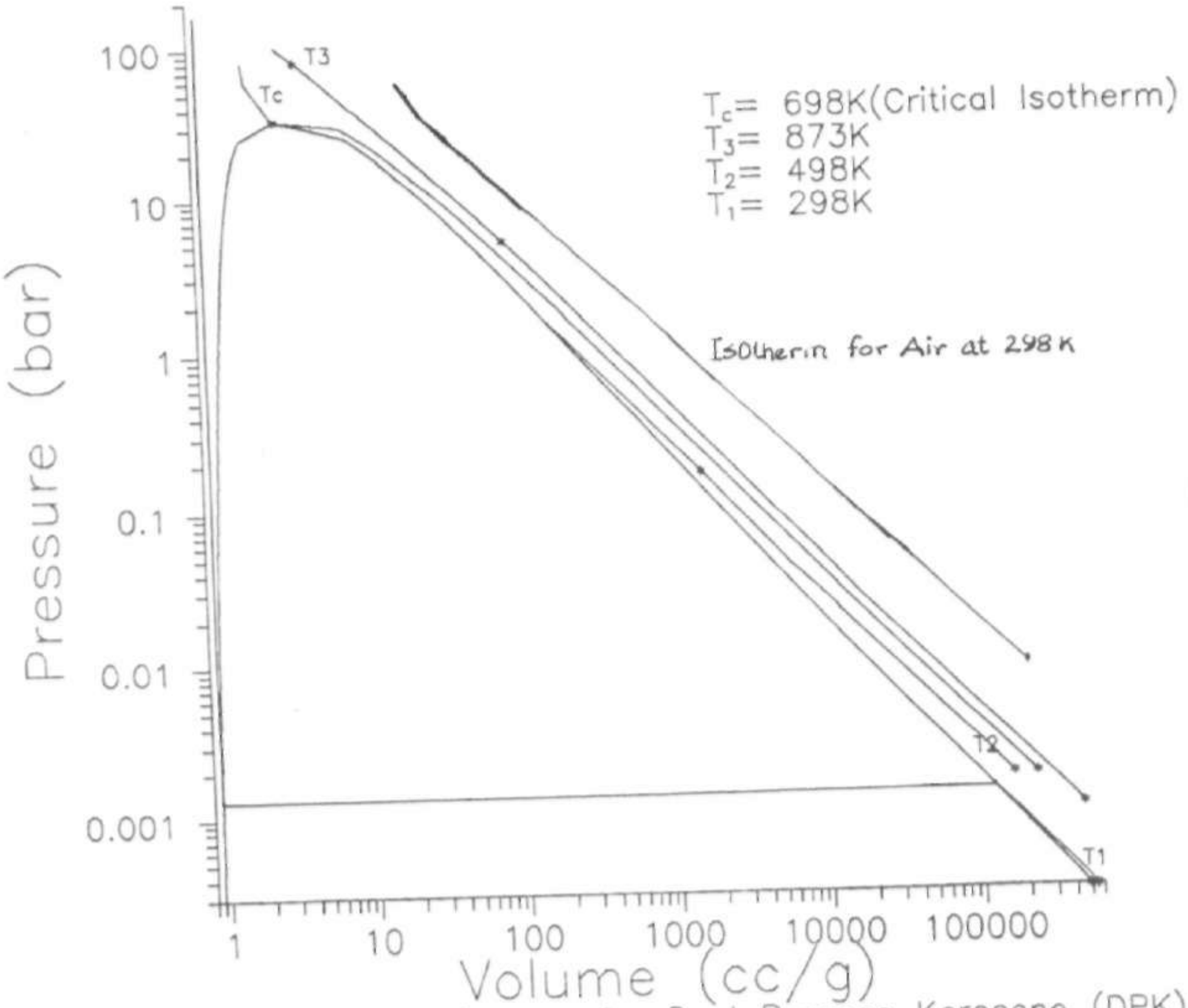

Figure 2.3: P–V Diagram for Dual Purpose Kerosene (DPK)

At ambient condition, kerosene (as shown in Figure 2.3 -see Appendix I for details) has low specific volume and is liquid. The type of isothermal method, described above, results in gasification only at sub-atmospheric pressure. This means that the gaseous product will not be available for use at ambient conditions.

Materials that exist in super-heated regions at ambient conditions, can be admixed with kerosene to increase the **total pressure** of the gaseous product to super-atmospheric. Such materials could be referred to as fillers. Air is a good example (see Figure 2.3), and it is widely used, also, because of its oxidative properties. Therefore, a mixture of air and the gasified kerosene can exist at super-atmospheric, total, pressure. This essentially means it could be bottled like LPG. This is the basis for this exercise.

2.4 ELEMENTS OF GASEOUS COMBUSTION

Safety measure requires for combustible gases to be handled, at least, below the auto ignition point. A flammable mixture must be formed before it burns (and once such a mixture is ignited, combustion will continue). The mixture or part of it must then be raised to a temperature at which ignition occurs. If the combustion that ensues is to be safe and controllable, it is important to know the propagating speed of combustion in the mixture. The energy delivery ability of the mixture per unit measure, upon which its economics lie, finally determines the acceptability of the gas as fuel. The following are relevant factors in combustion of fuels, with particular emphasis on gaseous fuel. Table 2.3 previews these properties for some fuels of interest.

TABLE 2.3 SELECTED COMBUSTION PROPERTIES OF SOME FUELS AT 298 K, 1.013 Bar

	Natural Gas▸	Liquified petroleum Gas▸	Ethanol	Petrol◂	Kerosene◂
Specific Gravity (Air=1)	0.63	1.92	1.6	2.9	5.3
Specific Gravity (Water=1)	–	0.56■	0.78	0.75	0.78
Flammabilty, Vol% Upper	15.00	8.50	19.00	7.60	5.60
Flammabilty, Vol% Lower	5.30	1.90	3.30	1.40	0.67
Auto Ignition Temp, K	*850*	*800*	*680*	535	525
Stoichiometric Air, vol ratio	10.6	29.7	14.3	56	78.5
Flame speed, m/s	0.34	0.38	–	–	–
Net Calorific value, MJ/kg	50.7	48.3	27.1	43	43.5
Wobbe Index, kJ/m^3	52200	78700	40300	85500	118200

▸ Nigerian gas composition as given in Table 2.1
◂ Average values only, from literature earlier cited.
■ Estimate based on literature [Jessen, 1977], using the Gunn Yamada method [Reid, 1977] at 5 bar

2.4.1 Inflammability Limits

A combustible mixture, like one described above cannot be ignited if there is too little or too much combustible component present. The minimum fraction of combustible component(s), required for combustion to proceed is called the lower limit of inflammability. And the maximum fraction that can sustain burning, is the upper inflammability limit. If a combustible mixture is divided mentally into "pockets" of gas, the limits demarcate the composition range, within which, the heat generated by the combustion of a pocket is great enough to raise the adjacent pocket to ignition point. Therefore, once begun, the combustion becomes self-propagating. Synonyms widely in use are, the lean/rich inflammability limits, and the lower/upper explosive limits.

Inflammability limits are affected by gas composition, temperature, pressure and direction of flame propagation. They decrease with increasing molecular weight of gas, while diluents generally raise the lower limit and, to lesser extent, reduce the upper limit. Expectedly, the range becomes wider as air is replaced with oxygen. The limits for mixtures of gaseous fuels are obtained by applying the Lé Chateliérs' rule *[Jessen, 1977]*. The lower and upper limits L_m and U_m, are evaluated from the following equations:

$$L_m = \frac{1}{\sum \frac{Y_i}{L_i}} \qquad (2.1)$$

$$U_m = \frac{1}{\sum \frac{Y_i}{U_i}} \qquad (2.2)$$

where mole fractions are based on the net combustibles only.

Temperature increases result in widening of inflammability range because, less heat is now required to raise adjacent pockets to ignition point. The Burgess-Wheeler law predicts, reasonably, with minimum data requirement, inflammabilities of many fuels over extended temperatures *[Jessen, 1977]*.

$$L_T = L_r - \frac{3.14}{CV'} [T - T_r] \qquad (2.3)$$

$$U_T = U_r + \frac{3.14}{CV'} [T - T_r] \qquad (2.4)$$

However, inflammability ranges are found to be less sensitive to pressure changes *[Cremer, 1960]*. The range is affected by direction in that it is greatest when the flame propagates upwards and least when downward. It has an intermediary value for horizontal propagation.

2.4.2 Ignition and Auto Ignition Temperatures

The ignition temperature of a combustible mixture is the lowest temperature at which combustion becomes self-propagating. Similarly, auto ignition temperature designates a point where the combustible mixture spontaneously ignites in the absence of local source. Both temperatures decrease with increasing molecular weight of gaseous fuel *[ABUCONS, 1993; Cremer, 1960]*. The effect of pressure is complex, but generally an inverse relationship is observed, and the temperatures are low for oxygen mixtures than that of air.

Reported auto ignition (at times called spontaneous ignition) temperatures are generally taken to refer to stoichiometric mixtures. This may not necessarily be the least ignitable. Presence of combustion promoters (e.g nitrogen dioxide) or inhibitors (e.g tetraethyl lead), even in traces and, the rate of temperature rise greatly (and often unpredictably) affect auto ignition temperatures.

2.4.3 Stoichiometric Air

This is the least amount of air theoretically required for complete combustion of fuel. This can be envisaged as a well mixed stage where adjacent to each molecule of fuel, is just enough oxidant. Stoichiometric quantities are *established from balanced chemical equations:*

$$C + O_2 \rightarrow CO_2$$
$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O \tag{2.5}$$

And for combustion in air (volume composition 21% O_2, 79% N_2),

$$C + 4.76\,[air] \rightarrow CO_2 + 3.76N_2$$
$$H_2 + 2.88\,[air] \rightarrow H_2O + 2.38N_2 \tag{2.6}$$

Complete combustion is usually achieved with excess oxidant, to make up for the imperfect mixing that always exist. As much as 8% excess air, is, at times utilized in combustion of gaseous fuels *[Othmer, 1979; Hicks, 1972]*. Higher values are adopted for other forms of fuel. Excess oxidant in a mixture is evaluated as follows:

$$\frac{[amt.\ of\ oxidant\ in\ mixture] - [stoichiometric\ amt.]}{stoichiometric\ amt.} X100\% \tag{2.7}$$

The inflammability limits lie on either side of stoichiometric composition. Any excess in a non-stoichiometric mixture, and inerts, such as the nitrogen of air, which does not participate in the combustion process are diluents; they will absorb heat without contributing any, and thus, will lower the flame temperature.

2.4.4 Flame speed

A flame is a combustion reaction which propagates through combustible mixtures, often accompanied by visible radiation.

It travels at a definite speed, measurable by suitable experimental techniques.

The flame speed has a minimum value of about 0.2 m/s for hydrogen and most hydrocarbon fuels at either inflammability limit. Maximum velocities are observed roughly half way between the limits. This may not necessarily be at the stoichiometric composition or, the most easily ignitable mixture. The flame speed is seen to increase from C_1 hydrocarbon to C_2 hydrocarbon, but decreases thereafter *[Ogunsola, 1987; Cremer, 1960]*. For most hydrocarbon fuels, the maximum flame speed lies between 0.6 to 1.9 m/s *[Perry, 1973; Cremer, 1960]*. The flame speed in fuel mixtures has an intermediate value that can be estimated based on individual fuel characteristics.

2.4.5 Flame Temperature

Essentially, this is the exit flue gas temperature. Strictly, this is applicable only to the combustion of stoichiometric mixtures. The flame temperature depends largely on the lower calorific value of fuel, quantity and specific heat of combustion products.

The flame temperature is estimated through energy balance, through a trial-and-error process, as there is significant variation of the specific heats. (Effects of excess oxidant and presence of inerts, together referred to as diluents, have been discussed earlier). This can be visualized in the following relationship of calculating flame temperature.

$$T = \frac{CV}{[\sum mCp]_{pdts} + [mCp]_a y_a^{ss} + [mCp]_{N_2}} + T_{rxts} \qquad (2.8)$$

Here the Σ sign sums stoichiometric quantities, and m refers to respective mass per unit mass of fuel. The variation of Cp's with temperature for the combustion products could be approximated with a linear relation

$$Cp = \omega_1 t + \omega_o \qquad (2.9)$$

where ω_0 and ω_1 are constants for specific temperature range

2.4.6 Calorific Value

The calorific value of a fuel is the heat evolved per unit quantity in a complete combustion process. In most instances, the latent heat of vaporization is not recovered as the water produced leaves in form of steam. This differentiates the two calorific values, and all calculations, including energy price comparisons are based on the lower calorific value (LCV).

Another good indicator of heating ability of gaseous fuel is the Wobbe index defined as

$$N_{Wb} = \frac{CV}{\sqrt{SG}} \qquad (2.10)$$

This implies that, even fuels of equal calorific value may have unequal heating rate, if operated under the same condition. The number finds great use in burners of interchanging fuels.

CHAPTER THREE

DOMESTIC UTILIZATION OF GASEOUS FUEL

Field and literature surveys revealed an almost absolute dependence on a particular type of fuel gas in Nigerian homes and indeed in most part of the world. The liquified petroleum gas among gaseous fuels, probably enjoys the most universal patronage as domestic fuel gas *[Williams & Lom, 1982; Hafelle, 1981]*.

An economically or technically more attractive substitute gaseous fuel will be most welcome if available appliances are able to use it efficiently, with little or no modification necessary. In achieving this, the modelling of the operations of a typical domestic burner would be most useful. This chapter presents a requiem for any fuel thought to complement or as acceptable alternative to domestic gaseous fuel currently in use. Theories and relationships employed here are simple and are universally applicable; these give thorough analysis of the combustion mechanism found in today's domestic applications of gaseous fuels.

3.1 LOCAL STORAGE

LPG for domestic use is usually supplied in pressure cylinders popularly referred to as bottled gas. The bottled gas comes in varying sizes, the most common being the 12.5 kg cylinder. The cylinders are made from carbon steel and tested up to working pressures of about 31 bar *[ABUCONS 1993;*

Williams & Lom, 1982; Salisbury, 1950]. Since the gas is traditionally supplied in liquified form, the maximum loading pressure of LPG encountered in summer temperatures hardly exceeds 11 bar. For Nigerian LPG (composition as given in Table 2.1), this pressure is about 5 bar.

Pressurized LPG in cylinders are let down to almost atmospheric pressure before use in domestic combustion equipment. This is achieved in one or two pressure-reduction steps by means of simple valves or excess flow valves. Cylinder valves by design are such that a single pressure regulator is capable of reducing the emergent LPG to 10 to 20 in. w.g. (0.026 to 0.051 bar gauge) *[Williams & Lom, 1982]*. Characteristically, the regulators do maintain essentially constant delivery pressure despite large upstream variations.

In countries where two brands of the LPG are marketed as commercial propane and commercial butane, the cylinders and regulators are distinguished, usually, by color. The regulator delivery pressure is set at 10 and 14 in. w.g. (0.026 and 0.034 bar gauge) for butane and propane respectively *[Williams & Lom, 1982]*. Molar composition is used to estimate delivery pressure for mixtures, which invariably lies in between the quoted boundaries. The reported value of 11 in. w.g. (0.028 bar) for Nigerian LPG *[Gas Division, NNPC]* is a fair approximation of this rule.

3.2 DOMESTIC GAS BURNER

Domestic gas burners come in various shapes and sizes. Technically, they are not different and are perfectly described by the common Bunsen burner (invented in 1855 by a German scientist) *[Williams & Lom, 1982; Lewis & von Elbe, 1961]*. The burners operate in the neighborhood of atmospheric pressure, and as a result, are collectively referred to as low pressure premixed burners or simply, atmospheric burners.

The basic concept in the operation of typical bunsen burner has not changed much since creation: a gas issues from an orifice as a jet, entrains some air and, homogenizes as the mixture proceeds (almost, always turbulently) to the burning area. To a large extent, it gives premixed flames. The homogenizer could be a special chamber or any ordinary tube leading to the burner mouth. Modern domestic gas burners are fitted with venturis to aid homogenization and to build up enough pressure for transport of mixture to combustion area. The usual blown size of burner mouths instill laminar flow identity to mixtures, necessary for a stable flame.

Burner control is achieved by regulating individual flows, more often, independently. In the domestic LPG burner, unlike the Bunsen burner, the gas flow is controlled. This control is achieved by varying the orifice size.

3.2.1 Modelling of Air Entrainment in Domestic Burners

A domestic burner setup could be broken into 3 units as shown schematically in Figure 3.1. Unit I encompasses the orifice and the air entrainment zone, which upon analysis would yield orifice conditions leading to estimation of entrainment data. Unit II is purposely for pressure build up and homogenization of gas-air mixture. The pressure developed must be sufficient to drive the mixture against the resistances of turbulence, friction, tube fittings, and flame thrust back-pressure. Substantial velocity loss is encountered in Unit III where additional mixing is also achieved. The mixture exit velocity here must conform with the flame speed range.

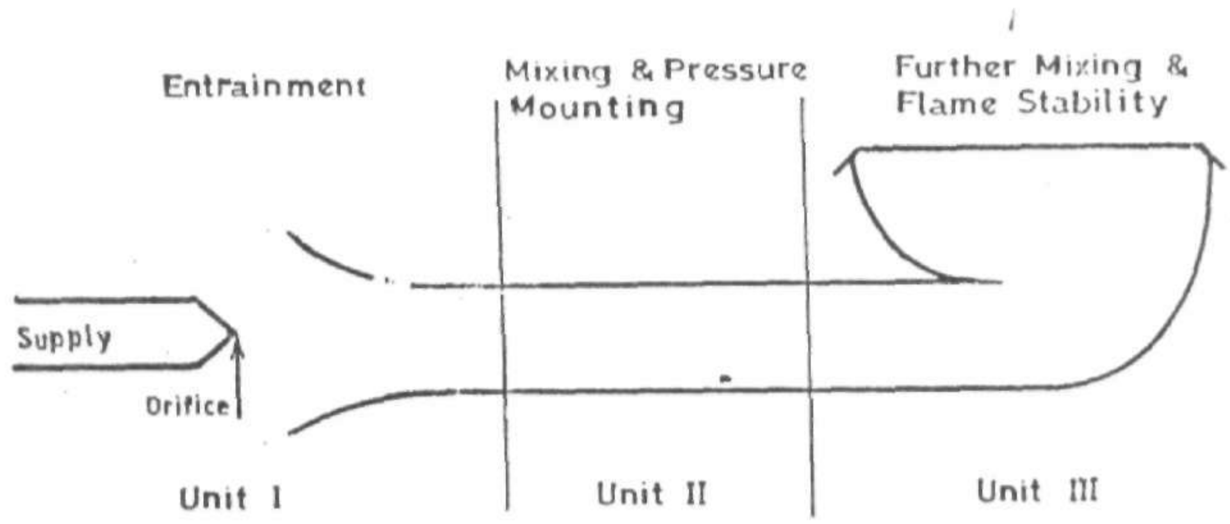

Fig. 3.1 Schematic Diagram of Typical Domestic Burner.

The following presents some observations and assumptions used in the course of simulation.

Unit	Observation	Assumption
I	Orifice size is very small compared to upstream tube diameter	Negligible approach velocity of flow upstream. No pressure gradient.
II	Long, smooth (high surface finish) transport tube with initial venturi shape	Maximum pressure build up and minimum head loss, in addition to flat velocity profile with extensive mixing.
III	Gas mixture issues out as sub-divided mini jets at burner mouth	Further air entrainment reduce tendencies of incomplete combustion and results in additional flame cooling.

The continuity equation of flow through nozzles/orifices gives the exit velocity of compressible fluid as *[Perry, 1973]*:

$$U_o = C\Gamma\sqrt{\frac{2\,[P_s - P_o]}{\rho_s\,[1-\beta^4]}} \tag{3.1}$$

where the expansion factor γ is evaluated from

$$\Gamma = \sqrt{r^{2/k}\,\frac{k}{k-1}\,\frac{1-r^{[k-1]/k}}{1-r}\,\frac{1-\beta^4}{1-\beta^4 r^{2/k}}} \tag{3.2}$$

U_0 becomes substantially insensitive to small changes in burner orifice sizes because

$$\beta^4 = [d_o/d_s]^4 \ll 1 \quad \text{and} \quad r = P_o/P_s < 1 \tag{3.3}$$

therefore the equations reduce to

$$U_o = CY\sqrt{2\,[P_s - P_o]\,/\,\rho_s} \tag{3.4}$$

and

$$Y = \sqrt{r^{2/k}\,\frac{k}{k-1}\,\frac{1-r^{[k-1]/k}}{1-r}} \tag{3.5}$$

Lewis and von Elbe derived relationships from momentum balance of unit I *[Gaydon & Wolfhard, 1972]*. These approximate well, air entrainment in bunsen burners. A simplified version gives a relation independent of gas flow *[Lewis & von Elbe, 1961]*:

$$[V/V_o]^2 = \rho_o A/\rho A_o \tag{3.6}$$

where

$$\begin{aligned} \rho &= \rho_a[1 - V_o/V] + \rho_o V_o/V \\ \mu &= \mu_a[1 - V_o/V] + \mu_o V_o/V \end{aligned} \tag{3.7}$$

Combining the above equations and combustion relations given in the preceeding chapter, a computer program for use with MS-DOS Qbasic compiler is developed for LPG. The program is presented in Appendix I. This is simulated for the following conditions which appear to be most common:

▲ Orifice Diameter, d_o:	up to 0.0006 m
▲ Burner Tube Diameter, d_t:	up to 0.025 m
▲ Burner mouth Diameter:	2.25 times d_t

Results are quite within similar predictions for other gaseous fuels *[Lewis & von Elbe, 1961]*. Below are the range values of some parameters obtained from the simulation results.

▲ Delivered calorific value, MJ/m^3	1.99 to 3.60
▲ Excess air, %	up to 78
▲ Burner duty, kW	0.5 to 2.0
▲ Flame temperature, K	1400 to 2000

CHAPTER FOUR

VAPORISED LIQUID FUEL

4.1 INTRODUCTION

It has been noted in Section 2.2 and 2.3 that the physical gasification of a relatively less volatile liquid fuel, almost entirely, means saturation of some filler gas in contact with the condensed phase of the fuel. The three possible ways of achieving this condition are by

- producing fine liquid droplets, specifically mists, to complement its low vapor pressure. This is carried out mechanically, through strong agitation of the liquid mass; or

- using gaseous fuel as the filler to increase total combustibles in the gas phase. This is traditionally used to enrich lean gaseous fuels, especially the low-heat value gases; or

- gasifying appropriate mixtures with another liquid fuel of high enough volatility to supplement the lean gas produced.

A combination of these techniques is sometimes used, but primarily to raise a gas calorific value. Mechanism of the first method utilizes the principles of atomization.

Secondary fuels employed in later methods are referred to as ***Boosters***, because, they increase the calorific value of the resultant gas. Generally, the handling and storage cost of a fuel gas is far in excess of that for a corresponding liquid fuel. Therefore, unless for a deliberate policy, for forseable future in Nigeria, petroleum-based liquid boosters will continue to enjoy favourable price edge compared to the gaseous counterpart. To this end, the third option would be explored further for the gasification of less volatile liquid fuels.

4.2 CHOICE OF FUEL COMPONENTS

4.2.1 Liquid Fuel

The basis for the choice of kerosene has been discussed extensively in Chapter 1. This centered around the following points:

- established fuel for domestic use
- availability
- relatively cheap

4.2.2 Liquid Booster

It is known that the volatility of kerosene at ambient temperature is relatively low. As a result, it is necessary to adopt the recommendation given before to increase the vapor phase density of the fuel. This will enable the vapor support a flame with high calorific value at ambient conditions.

A basic requirement of a liquid booster is to have high enough volatility at ambient conditions, as to form vapor mixtures with the primary liquid fuel above the lean limit. Other properties of importance for typical boosters are listed in Table 4.1. Final selection is based on availability and price.

TABLE 4.1 IMPORTANT PROPERTIES OF COMMON LIQUID BOOSTERS

Property	Acetone	Ethanol	Hexane	Benzene	Petrol
Inflammability Range Vol%	2.6 - 13.0	3.3 - 19.0	1.2 - 7.4	1.4 - 8.0	1.4 - 7.6
Net Calorific Value MJ/kg	36.3	27.1	45.1	40.6	43.8
Combustion Air Fuel Ratio, v/v	14.3	14.3	45.2	35.7	55
Average Retail Price, ₦/litre	500	100	1,500	50	11
Source	Foreign	Foreign/ Local	Foreign	Local/ Foreign	Local

Acetone, hexane and benzene are essentially petroleum-based products. They are non-domestic, largely utilized in industrial processes as feed stocks and solvents. Given the haphazard nature of Nigerian policies on importation, there could be neither reliable projections of availability nor of price, to encourage the intended use. In addition, these could precipitate unfavorable competition in the event of local application for domestic purposes.

The price of petrol is regulated and still enjoys government's subsidy. By virtue of its social significance, this may continue to be so. Conventionally, ethanol is manufactured from cellulosic materials or low level polysacharrides, which are largely of renewable source. Accordingly, ethanol is universally seen as one of the potential replacements to domestic/commercial fossil fuels in the near future. However, the local production of ethanol is still below the national requirement. Moreover, government does not consider it being of any social importance. Thus, its current retail price makes it uncompetitive for use as booster against petrol.

4.2.3 Filler Gas

Air has been established as an appropriate filler for kerosene vapor fuel in Section 2.3. It is useful to note that normal air (volume composition 79% N_2 and 21% O_2) could be partially or wholly replaced with oxygen, within the inflammability range of the fuel mixture

In summary, the components of the fuel are as follow

Component	Role
▲ Kerosene	*Liquid Fuel*
▲ Petrol	*Liquid Booster*
▲ Air	*Filler Gas*

4.3 GASIFICATION AS AN EQUILIBRIUM PROCESS

It has been established that the mechanism of gasification is essentially an equilibrium process. Fugacity, *f*, is a property used in describing vapor-liquid equilibrium through the fundamental relation

$$f^L = f^V \tag{4.1}$$

where

$$\begin{aligned} f^L &= \gamma x P_T \\ f^V &= \phi y P_T \end{aligned} \tag{4.2}$$

Rigorous procedure for obtaining equilibrium composition by the use of fugacity equations and volumetric data is available in literature *[Ohe, 1990]*. Even at moderate pressures, Raoult's equation serves most engineering requirements *[Reid et al, 1977]*, and is therefore applied here.

$$P^o x = P_T y \tag{4.3}$$

Equations relating the pure liquid vapor pressure P^0, to absolute temperature T are listed by Reid et al. Any of the modified Antoine equations, such as

$$Log_{10}\,[P^o] = \Omega A - \frac{\Omega B}{T-\Omega D} \tag{4.4}$$

represents well, this relationship over appreciable temperature range *[Holland et al, 1970]*. Conversely, vapor pressure is generally insensitive to external pressures commonly encountered in most operations *[Moore, 1962; Paauwe et al, 1977]*. The temperature and pressure dependence of the density of vapor, υ, supported by liquid is given by an equation of state,

$$P\mathbf{v} = RT \tag{4.5}$$

4.4 PRELIMINARY CALCULATIONS OF FUEL COMPOSITION

Equations relating the basic requirements of a gaseous fuel to relevant properties were highlighted in Section 2.4. Essentially, the equations do give the combustion characteristics of the fuel gas.

For mixtures of kerosene and petrol gasified using air, the resultant gas must be of certain composition if it is to burn. Therefore, it becomes imperative to determine the boundary, which now encompasses a domain for this work. Application of Equations 4.3 to 4.5 would yield equilibrium properties of the subject, necessary as an input to Equations 2.1, 2.2, 2.7 to 2.10 for evaluating the characteristics of the gas produced.

The properties of some components for use in the listed equations are summarised in Table 4.2. The exact constituents of kerosene, petrol and indeed all other petroleum fractions are difficult to establish. Moreover, the effort required is hardly justified as their properties can be fairly represented by an appropriately chosen compound. The following is compiled after extensive literature search *[KRPC, NNPC, 1994; Othmer, 1, 4(1992); Rodgers and Mayhew, 1981; Shell Petroleum Hbk, 1980; Weast, 1978; Jessen, 1977; Glushko, 1974; Spalding, 1973; Cremer, 1960; Salisbury, 1950]*

	Kerosene	Petrol	Air
Empirical Formula	$C\ H_{1.98}$	$C\ H_{1.87}$	$[O_2]:3.76[N_2]$
Representative Formula	$C_{11}\ H_{22}$	$C_8\ H_{15}$	$0.21[O_2]:0.79[N_2]$
Relative Molecular Weight	154	111	29

Procedure

- *Specify liquid phase composition and operating pressure*
- *Determine the mole fraction of kerosene and petrol in vapor phase at operating temperature using Eqs. 4.4 and 4.3*
- *Estimate the upper and lower limits of inflammability from Eqs. 2.1 and 2.2 respectively*
- *Check if the total fraction of combustibles just balances either limit. Otherwise, vary the liquid phase relative quantities of kerosene and petrol until this condition is attained*
- *At this condition, determine, for the resultant gas (referred to as Vaporised Liquid Fuel, VLF, gas), the following combustion properties: density, calorific value, excess air, flame temperature and Wobbe Index from Eqs. 4.5 and 2.7 to 2.10*
- *Repeat the procedure for other pressures*

TABLE 4.2 SUMMARY LIST OF PARAMETERS REQUIRED FOR CALCULATING FUEL COMPOSITION

Parameter	Kerosene		Petrol	
Inflammability, vol% (Eqs. 2.1 & 2.2) L U	 0.67 5.60		 1.3 7.6	
Stoichiometric Requirement, vol% (Eq. 2.7) Oxygen Air	 16.5 78.5		 11.7 56.0	
Net Calorific Value, MJ/kg (Eqs. 2.8 & 2.10) LCV	 43.5		 43.8	
Antoine Equation (Eq. 4.4) OA OB OD	 7.63 2259 0.0		 7.48 1523 0.0	
Specific Heat (Eq. 2.8)	Air	Nitrogen	Carbon dioxide	Water
For 850 < t ≤ 1350 °C a_0 a_1	 989 0.1506	 997 0.1694	 1054 0.1882	 1588 0.7026
For 1350 < t < 2200 °C a_0 a_1	 1086 0.0803	 1126 0.0753	 1190 0.0900	 1967 0.4266

A computer program for use with MS-DOS Qbasic Compiler developed to run at various filler concentrations is presented in Appendix-II. A summary of the results is shown in Table 4.3.

The results show that up to a pressure of 4 bar there exit a maximum composition and a minimum composition of kerosene-petrol mixture that can support a combustible gas. Thereafter, no maximum is observed, while the minimum limit extended to 10 bar. It is noteworthy that a minimum of 3.5 mol% petrol is required to make kerosene support a combustible gas at atmospheric condition. It is also seen that the properties become constant even at low liquid fractions of petrol. This is however expected, by virtue of its dominating volatility.

TABLE 4.3 SUMMARY OF SIMULATION RESULTS

A. Results for Minimum Flammability (Lower Boundary)

Operating Pressure	Liquid phase Composition		Vaporised Combus-tibles	Liquid Fuel Gas Calorific Value		Excess Air	Flame Temp
	DPK	PMS					
[Bar]	[Mol %]		[Mol %]	[MJ/m^3]	[MJ/kg]	[%]	[K]
1.00	96.50	3.50	1.25	2.58	2.10	35.40	1880
1.50	94.21	5.79	1.30	2.65	2.16	32.10	1907
2.00	91.90	8.10	1.33	2.69	2.19	30.30	1920
3.00	87.40	12.60	1.35	2.72	2.21	28.70	1940
4.00	82.90	17.10	1.37	2.74	2.23	27.80	1950
5.00	78.30	21.70	1.37	2.75	2.24	27.40	1950
6.00	73.80	26.20	1.38	2.76	2.24	27.00	1960
7.00	69.30	30.70	1.38	2.76	2.24	26.80	1960
8.00	64.70	35.30	1.39	2.77	2.25	26.60	1960
9.00	60.20	39.80	1.39	2.77	2.25	26.50	1960
10.00	55.70	44.30	1.39	2.77	2.25	26.40	1960

B. Results for Maximum Flammability (Upper Boundary)

1.00	76.10	23.90	7.56	15.12	10.50	-78.30	2280*
2.00	51.60	48.40	7.59	15.11	10.50	-78.30	2280
3.00	27.10	72.90	7.60	15.11	10.50	-78.30	2280
4.00	2.60	97.40	7.60	15.11	10.50	-78.30	2280

* Temperature calculated based on stoichiometric combustion.

4.5 DETERMINATION OF FUEL COMPOSITION

Further analysis of the results is carried out to investigate variation of some important properties within the boundaries observed. Amongst these, is the calorific value which has a direct relationship with the net combustibles present in the resultant gas. Figure 4.1 shows how this increases, through either decrease in operating pressure (i.e. effective reduction in filler gas concentration) at constant liquid composition, or increase in liquid fraction of petrol at fixed operating pressure. However, either can not be varied indefinitely.

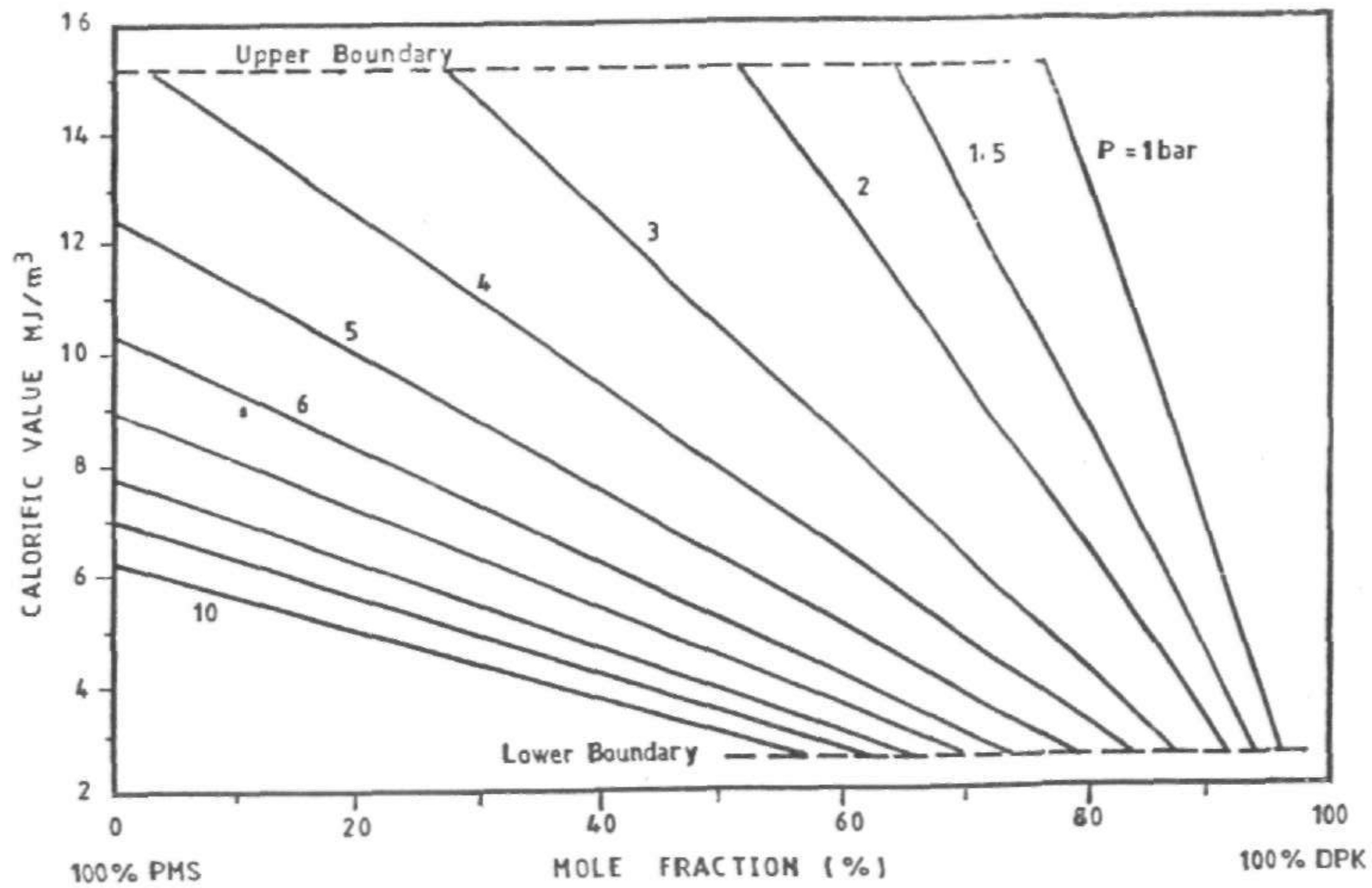

Fig. 4.1 VLF Gas Calorific Value Dependance on DPK-PMS Mixture Composition.

At the pressure of 5 bar, normally quoted for domestic LPG systems, calorific value range, from the figure, is 2.75 - 12.41 MJ/m^3. Although this is far below that of LPG (105 MJ/m^3) and other conventional gaseous fuels, like natural gas (42 MJ/m^3) and acetylene (55 MJ/m^3), the range borders that delivered in domestic burners (up to 4 MJ/m^3) as simulated in Chapter 3. Moreover, in order not to shift emphasis away from the main component of gasification, at the suggested pressure, it is observed that the VLF gas has a calorific value of 3.7 MJ/m^3 at about 70 mol% kerosene.

It has been established that reduction in total pressure, increases the calorific value of VLF gas, and it is known (from Chapter 3) that downstream regulator pressure is essentially independent of the upstream superatmospheric pressure. Therefore, it is advantageous to operate at low pressures, but enough to overcome downstream resistances. At 1.5 bar (see Fig. 4.1), the VLF gas calorific value improved from 3.7 MJ/m^3(at 5 bar) to 12.7 MJ/m^3. For both cases, the Wobbe Index range (from Appendix II) is 53 to 57 MJ/m^3 which falls short of that of LPG, 79 MJ/m^3 (see Table 2.3). This, necessarily, implies the need to modify present LPG burners, if it is to be used to deliver the same power.

Evaluating other parameters at 298 K, given that

System Pressure, P_T = 1.5 bar

Liquid phase composition,

$$X_{DPK} = 70\%$$

$$X_{PMS} = 30\%$$

Saturation pressure (Table 2.2)

$$P^0_{DPK} = 0.0017 \text{ bar}$$

$$P^0_{PMS} = 0.33 \text{ bar}$$

Therefore, partial pressure,

$$P_{DPK} = X_{DPK} * P^0_{DPK} = 0.0012 \text{ bar}$$

$$P_{PMS} = X_{PMS} * P^0_{PMS} = 0.0990 \text{ bar}$$

and composition of VLF gas,

$$y_{DPK} = P_{DPK}/P_T = 8*10^{-4}$$

$$y_{PMS} = P_{PMS}/P_T = 6.6*10^{-2}$$

4.6 PRODUCTION OF VLF GAS

In principle, the methods highlighted here could be made continuous. Presently, in Nigeria domestic utilization of LPG is batchwise; in which case a user goes to designated outlets for a refill. In this light, the VLF gas production methods can be categorised into batch and continuous.

4.6.1 The Batch Method

The following are required

- a cylinder containing kerosene
- a cylinder containing petrol
- an empty cylinder
- vacuum pump and compressor
- pressure pipings and valves

With reference to Figure 4.2, the batch process can be divided into 3 stages

- evacuating air from cylinders
- charging gas into the VLF gas cylinder
- pressurizing the VLF gas cylinder

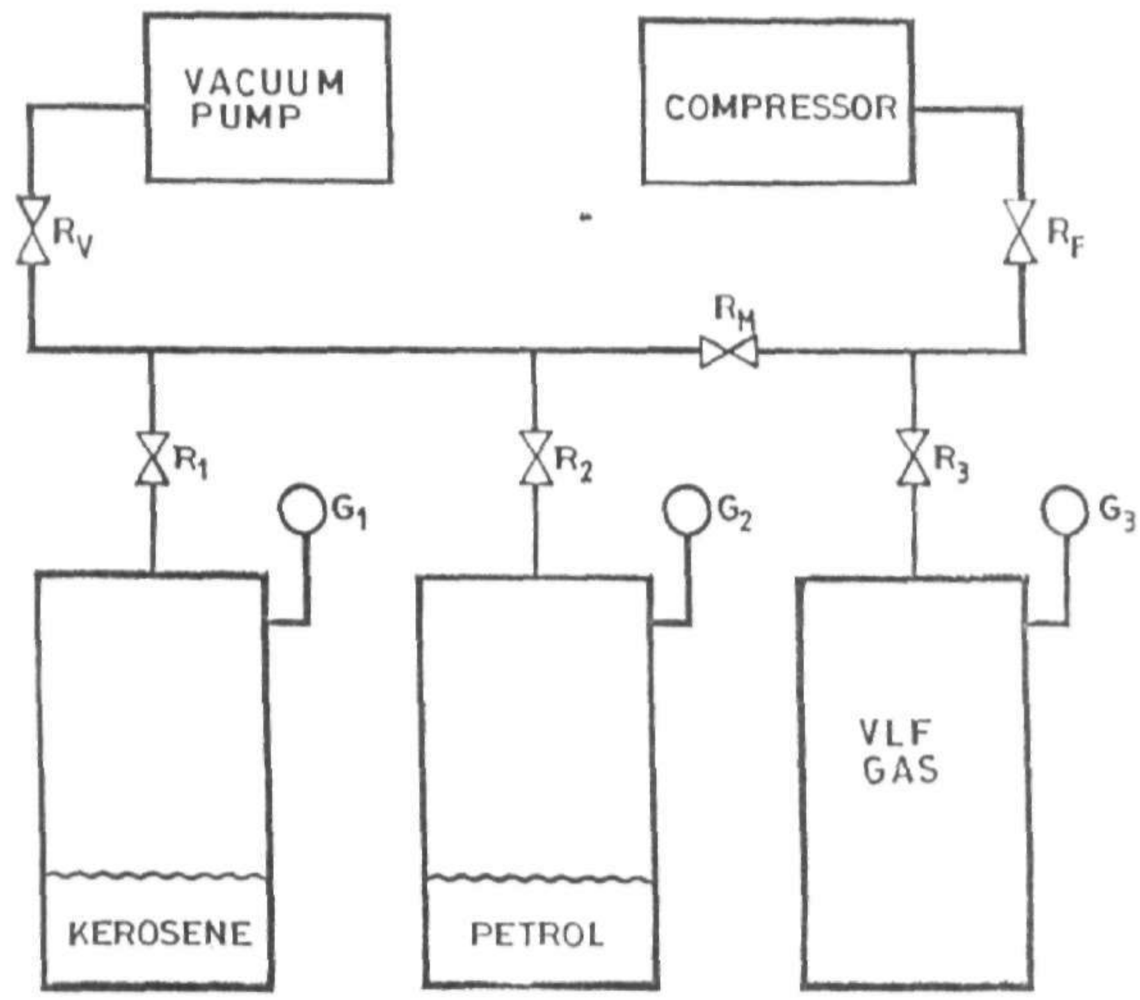

Fig. 4.2: Proposed Setup for Batch Gasification of Kerosene.

This process can be carried out through the following procedure presented in Table 4.4:

TABLE 4.4 PROCEDURE FOR BATCH PRODUCTION OF VLF GAS

Step	Action	Remarks
A.	Evacuation of air from the cylinders	
1.	Open R_V & R_1 and start Vacuum Pump	to evacuate both atmospheric and dissolved air in DPK
2.	*Close* R_1 *when* $G_1 = P^0_{DPK}$. constant	all air out, *leaving kerosene at* saturation; P^0_{DPK} . 0.0017 bar
3.	Open R_2	to evacuate both atmospheric and dissolved air in PMS
4.	Close R_2 when $G_2 = P^0_{PMS}$. constant	all air out and petrol at saturation P^0_{PMS} . 0.33 bar
5.	Open R_M & R_3	to evacuate air
6.	Close R_3 when G_3 . 0 absolute pressure	empty vessel
7.	Close R_M & R_V and stop Vacuum pump	
B.	Charging gas into the VLF gas cylinder	
1.	Open R_M	
2.	Open R_1 & R_3	charging in kerosene vapor
3.	Close R_1 when $G_3 = P_{DPK}$	required partial pressure of DPK in VLF gas $P_{DPK} = 0.0012$ bar
4.	Open R_2	charging in petrol vapor
5.	Close R_2 when $G_3 = P$	where P, is the pressure of total combustibles, $= P_{DPK} + P_{PMS}$
6.	Close R_3 & R_M	
C.	Pressurizing the VLF gas cylinder	
1.	Open R_T & R_3 & Start compressor	charging in air
2.	Close R_3 when $G_3 = P_T$	required system pressure $P_T = P_{DPK} + P_{PMS} + P_a = 1.5$ bar
3.	Close R_T and Stop Compressor	
4.	Isolate Bottle #3	VLF gas ready for use

For a 12.5 kg bottle, approximate capacity of $0.03m^3$, it would contain 0.03m^3 VLF gas of calorific value 12.7 MJ/m^3 at 1.5 bar. This gives an energy content of 0.381 MJ per bottle. On the other hand, the same cylinder takes 12.5 kg of LPG, essentially in liquified form, whose density is 550 kg/m^3 (at 298K & 5bar) and gas calorific value of 105.8 MJ/m^3. Then, the computed energy content of LPG bottle is 2.4 MJ, which is over six folds compared to VLF gas.

4.6.2 Continuous Method

This method is aimed for domestication since, the gasification is performed at the point of usage. Figure 4.3 is a simplified diagram of the continuous in which the following materials are required:

- gasifier (pressure vessel equipped with gas disperser and pressure indicator)
- compressed air (at a pressure > 1.5 bar)
- valves

The process is carried out by opening R_1 and, subsequently R_2 when system pressure, P, is about 1.5 bar. R_1 is continuously manipulated to maintain this condition as R_2 is adjusted according to demand.

The source of compressed air could be a low pressure compressor or a blower. Alternatively, reservoir of compressed air, at a pressure greater than 1.5 bar, can also be used. Moderate liquid level is required to facilitate proper saturation. Adequate room above the liquid is essential, both for gas homogenization and, disengagement of entrained droplets. A requirement, even at minimum liquid level, jets produced by the disperser should not survive beyond the liquid mass to ensure proper saturation, and eliminate mist formation or entrainment to greater heights.

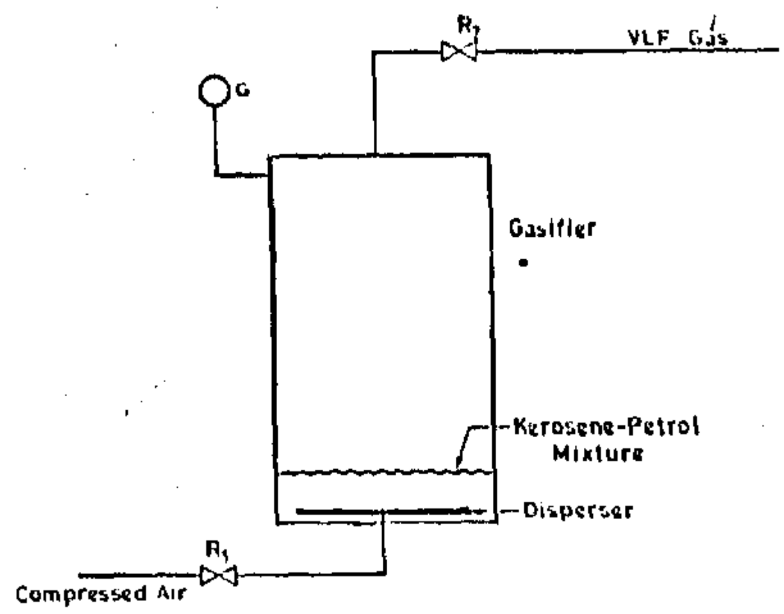

Fig. 4.3: Proposed Setup for Continuous Gasification of Kerosene.

As the process progresses, the liquid mass becomes richer in DPK because of net stripping of PMS. The shift in liquid phase composition results in lower caloric value of VLF gas as can be seen from Figure 4.1, where also the slope amplifies the rate of the shift. This necessitates periodic topping of PMS to maintain VLF gas of fairly constant energy content.

Practical setup of this method is shown in Plate 4.1. A stable, deep blue flame is obtained, thus implying an efficient combustion. However, the flame is unable to appear in the photograph.

Plate 4.1: Practical Setup for Continuous Gasification of Kerosene (in operation)

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

In the study of the gasification of kerosene carried out, it is established that,

1 a booster is needed to produce a combustible gas, herein called VLF gas. For the case studied, a minimum of 3.5 mol% petrol is required at atmospheric conditions

2 the VLF gas can be bottled like LPG, using air as a filler

3 at 5 bar, the normal domestic supply pressure of LPG, the VLF gas has a calorific value of 3.7 MJ/m^3 at 70 mol% kerosene. The calorific value improved to 12.7 MJ/m^3 when system pressure was let down to 1.5 bar

4 modification of present domestic burners is necessary

5 a constant calorific value VLF gas is obtained from the batch method of gasification. On the other hand, regular topping of petrol is required to maintain an average calorific value of VLF gas in the continuous method.

6 from the demonstration of the continuous method, gasification of kerosene leads to environmentally friendly combustion.

5.2 RECOMMENDATIONS

1 Characteristics of the VLF gas should be determined experimentally so as to permit actual comparison with the LPG.

2 Thorough analysis of the gasifier in the continuous method, is required to establish design and scale up parameters, in addition to its economics.

3 The work can be used as a framework for the gasification of different materials. For example, by replacing PMS with ethanol (being a renewable energy source and presently, thought as a future replacement to fossil fuels) as a booster.

4 Biogas, which is an unlimited source of local energy, could be enriched to march the calorific value of LPG when employed to replace air, as the filler.

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APPENDIX I

PVT DATA GENERATION FOR KEROSENE

The data generation for the *PV*-diagram of DPK (kerosene)shown in Figure 2.3 is done in 2 stages:

- *generation of saturation data*
- *generation of Isotherms in the superheat region*

Below is the list of equations utilized for the saturation curve.

$$Log_{10} PV = 7.63 - \frac{2259}{T} \tag{I.1}$$

$$\omega = -Log_{10} P_r - 1 \tag{I.2}$$

$$v_g = \frac{10^6 Z_g T R}{P} \tag{I.3}$$

$$\begin{aligned} Z_g &= \frac{1}{1-h} - \frac{a'h}{b'(1+h)} \\ a' &= \frac{0.4278\, T_c^{2.5}}{P_c T^{2.5}} \\ b' &= \frac{0.0867\, T_c}{P_c T} \\ h &= \frac{b'P}{Z_g} \end{aligned} \tag{I.4}$$

$$\begin{aligned} \frac{V}{V_{sc}} &= V_r^{\,o}(1-\omega\Gamma) \\ V_{sc} &= \frac{RT_c(0.292-0.0967\,\omega)}{P_c} \end{aligned} \tag{I.5}$$

$$For\ 0.2 \le T_r \le 0.8$$
$$V_r^0 = 0.33593 - 0.33953\,T_r + 1.51941\,T_r^2 - 2.02512\,T_r^3 + 1.11422\,T_r^4$$

$$For\ 0.8 < T_r < 1.0$$
$$V_r^0 = 1.0 + 1.3\,(1-T_r)^{1/2} Ln(1-T_r) - 0.50879\,(1-T_r) - 0.91534\,(1-T_r)^2 \qquad (I.6)$$

$$\Gamma = 0.29607 - 0.09045\,T_r - 0.04842\,T_r^2 \qquad (I.7)$$

$$Z_c = 0.2918 - 0.0928\,\omega \qquad (I.8)$$

$$V_c = \frac{Z_c R T_c}{P_c} \qquad (I.9)$$

where $[P_v]$ = mmHg

$[P]$, $[P_c]$ = N/m^2

$[T]$, $[T_c]$ = K

$[V_g]$, $[V_{sc}]$ = cc/mol

P_r at T_r = 0.7

R = 8.31 J/mol K

The isotherms for kerosene and that for air are obtained using the equation of state (Equation I.3). As usual, the set in Equation I.4 provided the correction for non-ideality.

Computer programs for these purposes, written for use with MS-DOS Qbasic Compiler are presented herewith. Characteristically, these programs could be used for substances with similar properties, by substituting appropriate physical constants.

```
'Saturation Curve for Dual Purpose Kerosene (DPK)
'
CLS : PRINT " PROGRAMME RUNNING   --*** please wait ***--"
OPEN "b:\programs\rsckero.bas" FOR OUTPUT AS 1
BEEP
mw = 154
pc = 25000 / 760 * 101325   'N/m2
tc = 698                    'K
r = 8.312                   'J/mol K
PRINT #1, "****Saturation Curve for Dual Purpose Kerosene (DPK) ***"
PRINT #1, " T (K)", "P (bar)", "    Zg", "Vg (cc/g)"
FOR t1 = 273 TO tc - 1 STEP 25: t = t1
PRINT #1, t;
GOSUB Vapvol: p1 = p: GOSUB Liqvol: p = p1
PRINT #1, USING "########.####"; p / 10 ^ 5; zg; vg; vl
NEXT t1
GOSUB Critical: PRINT #1, "Tc(K)= "; tc, "Pc(bar)= "; pc / 10 ^ 5, "Zc= ";
zc, "Vc(cc/g)= "; vc
CLS : BEEP: END


pmtvr0: IF (tr < .8) THEN vr0 = .33593 * (1 - tr) + 1.51941 * tr ^ 2 -
2.02512 * tr ^ 3 + 1.11422 * tr ^ 4: GOTO 10
        ttr = 1 - tr: vr0 = 1 + 1.3 * ttr ^ .5 * 1 / 2.303 * LOG(ttr) -
.50879 * ttr - .91534 * ttr ^ 2
10      gmm = .29607 - .09045 * tr - .0482 * tr ^ 2
        RETURN

Liqvol:     GOSUB Pmtvsc: GOSUB pmtvr0: vl = vsc * vr0 * (1 - w * gmm) / mw
            RETURN

Pmtvsc:     tr = t / tc: GOSUB Accfac
            vsc = r * tc * (.292 - .0967 * w) / pc * 10 ^ 6
            RETURN

Accfac:     t = .7 * tc: GOSUB Coxant: pr = p / pc
            w = -1 / 2.303 * LOG(pr) - 1
            RETURN

Vapvol:     GOSUB Coxant: GOSUB Comfac
            vg = zg * t * r / (p * mw) * 10 ^ 6
            RETURN

Comfac:     zg = 10: DO: a1 = .4278 * (tc ^ 2.5) / (pc * t ^ 2.5)
            b1 = .0867 * tc / (pc * t)
            h1 = b1 * p / zg
            zg0 = zg
            zg = 1 / (1 - h1) - a1 * h1 / (b1 * (1 + h1))
            LOOP WHILE ABS(zg - zg0) >= .001
```

```
            RETURN

Coxant:        pp = 10 ^ (7.63 - 2259 / t)
               p = pp / 760 * 101325
               RETURN

Critical:      zc = .2918 - .0928 * w
               vc = zc * r * tc / (pc * mw) * 10 ^ 6
               RETURN
```

```
'Isotherms for Superheated DPK
'
CLS : BEEP: OPEN "b:\programs\reshdpk.bas" FOR OUTPUT AS 1
PRINT #1, "**********  RESULTS FOR SUPERHEATED DPK  **********"
mw = 154
pc = 25000 / 760 * 101325                'N/m2
tc = 698                                 'K
r = 8.312                                'J/mol K
FOR t1 = 773 TO 873 STEP 50: t = t1
PRINT #1, "For Isotherm...  "; t; "K"
PRINT #1, "          P (bar)", " zg", "vg (cc/g)"
FOR p1 = 10 ^ -5 TO 40 STEP 1: p = p1 * 101325: GOSUB Vapvol
PRINT #1, USING "########.####"; p / 10 ^ 5; zg; vg
NEXT p1: BEEP: NEXT t1: END

Vapvol:        GOSUB Comfac
               vg = zg * t * r / (p * mw) * 10 ^ 6
               RETURN

Comfac:        zg = 10: DO: a1 = .4278 * (tc ^ 2.5) / (pc * t ^ 2.5)
               b1 = .0867 * tc / (pc * t)
               h1 = b1 * p / zg
               zg0 = zg
               zg = 1 / (1 - h1) - a1 * h1 / (b1 * (1 + h1))
               LOOP WHILE ABS(zg - zg0) >= .001
               RETURN
```

APPENDIX II

MS-DOS QBASIC PROGRAM FOR SIMULATING THE AIR ENTRAINMENT IN DOMESTIC GAS BURNERS

```
'PROGRAM TO SIMULATE THE AIR INSPIRATION IN TYPICAL DOMESTIC GAS BURNERS
DIM cp(7), d0(10)
HtCaps: cpa(3, 1) = .1694: cpb(3, 1) = 997: cpa(3, 2) = .0753: cpb(3, 2) =
1126
        cpa(4, 1) = .1506: cpb(4, 1) = 989: cpa(4, 2) = .0803: cpb(4, 2) =
1086
        cpa(5, 1) = .1882: cpb(5, 1) = 1054: cpa(5, 2) = .09: cpb(5, 2) =
1190
        cpa(6, 1) = .7026: cpb(6, 1) = 1588: cpa(6, 2) = .4266: cpb(6, 2) =
1967
mwg = 55.34: visg = .0000905: cpg = 1.64: oxys = 6.22: lcv = 105'mj/m3 gas
mwa = 28.95: visa = .0000185: aocf = 100 / 21: nocf = 79 / 21
mwn = 28: mww = 18: mwc = 44: wfcf = 5: cfcf = 4
ccf = .98: rk = 1.33
pcf = 101325: tcf = 273
p0 = 1: ti = 25: t = ti + tcf
vm = .022414
dss = .0155
CLS : OPEN "sirest.bas" FOR OUTPUT AS #1
FOR dt = .015 TO .025 STEP .005: da = dt: dt2 = dt / SQR(.14): BEEP
PRINT #1, "SIMULATION OF AIR INSPIRATION IN DOMESTIC BURNERS"
PRINT #1, "For Burner tube diameter of   "; 1000 * dt; "mm"
PRINT #1, "    Supply "; "     Orifice     Conditions"; "    Tube Conds";
"   Burner "
PRINT #1, "  Press"; "   Dens"; "    Vel"; "     V/Rate"; "    Duty"; " Nre";
"   Vel"; "  Nre"; "   Exit vel"
PRINT #1, "  mBar"; "     kg/m3"; "  m/s"; "  [xE-6]m3/s"; "  kW "; "
m/s"; "          m/s"
FOR i = 0 TO 6 STEP 1: d0 = .0004 + i * .00005
PRINT #1, "For Orifice diameter of   "; 1000 * d0; "mm"
FOR ps = 1.02 TO 1.031 STEP .0025
GOSUB NozVel
PRINT #1, USING "####.##"; (ps - p0) * 1013.25; dens; u0;
rd = d0 / dss
GOSUB Frate:  GOSUB CalVal: GOSUB Stoich: GOSUB Ittmp
d0(i) = d0: rv(i) = rv: cvv(i) = cvv: cvm(i) = cvm: xssair(i) = xssair: tt(i)
= tt
PRINT #1, USING "#####.##"; f0 * 1000000!; pwr;
PRINT #1, USING "#####"; nre0;
PRINT #1, USING "####.##"; ut;
PRINT #1, USING "######"; nret;
PRINT #1, USING "###.##"; ut1
NEXT ps: NEXT i:
```

```
PRINT #1, "Orifice "; "   Gas"; "   Cal Value"; "    Excess"; "   Flame"
PRINT #1, "Dim., mm"; "  Vol %"; "  MJ/m3  MJ/kg"; "  Air %"; "  Temp [K]"
FOR j = 0 TO i - 1 STEP 1
PRINT #1, USING "####.##"; 1000 * d0(j); rv(j) * 100; cvv(j); cvm(j); 100 *
xssair(j);
PRINT #1, USING "########"; tt(j)
NEXT j: NEXT dt: END

Dnsty:          v = t / 273 * 1 / p * vm          'm^3/mol
                den = mw / (1000 * v)
                RETURN

Area:           a = 3.142 * d ^ 2 / 4: RETURN

Pmtery:         rr = p0 / ps: rrk = (rk - 1) / rk
                y = SQR(rr ^ (2 / rk) * 1 / rrk * (1 - rr ^ rrk) / (1 - rr))
                RETURN

NozVel: GOSUB Pmtery: p = ps: mw = mwg: GOSUB Dnsty: dens = den
        u0 = ccf * y * SQR(2 * (ps - p0) * 101325 / (dens))
        RETURN

Itrv:           p = p0: mw = mwg: GOSUB Dnsty: den0 = den
                mw = mwa: GOSUB Dnsty: dena = den: dden = den0 - dena
                d = d0: GOSUB Area: a0 = a: d = da: GOSUB Area: aa = a
                aaa = den0 * aa / a0: ddd = SQR(dden ^ 2 + 4 * aaa * dena)
                rv1 = (dden + ddd) / (2 * aaa)
                rv2 = (dden - ddd) / (2 * aaa)
                IF rv1 < 0 THEN rv = rv2: RETURN
                rv = rv1: RETURN

mixpty:         denm = dena * (1 - rv) + den0 * rv
                vism = visa * (1 - rv) + visg * rv
                RETURN

Frate:  GOSUB Itrv: f0 = a0 * u0: nre0 = den0 * u0 * d0 / visg: pwr = f0 *
lcv * 1000
        d = dt: GOSUB Area: at = a: ft = f0 / rv
        ut = ft / at: GOSUB mixpty: nret = denm * ut * dt / vism
        ut1 = (dt / dt2) ^ 2 * ut
        RETURN

CalVal: cvv = lcv * rv
        cvm = cvv / denm
        RETURN

Stoich: stair = oxys * aocf
        rstga = 1 / stair
        xssair = (1 / rv) / (stair) - 1
```

```
        RETURN

cp:             IF tt < 1370 THEN j = 1: GOTO cont1
                j = 2
cont1:          FOR ii = 3 TO 6: cp(ii) = cpa(ii, j) * tt + cpb(ii, j): NEXT
ii
                cpn = cp(3): cpa = cp(4): cpc = cp(5): cpw = cp(6)
                RETURN

FTemp:          GOSUB cp
                IF xssair <= 0 THEN zzz = 0
                f1st = lcv / den0 * 1000000 / (mw * cpw + mc * cpc + ma * cpa
* zzz + mn * cpn)
                tt1 = f1st + t: RETURN

Mss:            ma = stair * mwa / mwg: mn = oxys * nocf * mwn / mwg
                mw = wfcf * mww / mwg: mc = cfcf * mwc / mwg: RETURN

Ittmp:  tt = 100: zzz = xssair: GOSUB Mss: DO: tt = (tt + tt1) / 2: GOSUB
FTemp
        LOOP WHILE ABS(tt - tt1) >= 10: RETURN
```

SIMULATION OF AIR INSPIRATION IN DOMESTIC BURNERS

For Burner tube diameter of 15 mm

Supply		Orifice	Conditions			Tube Conds		Burner
Press	Dens	Vel	V/Rate	Duty	Nre	Vel	Nre	Exit vel
mBar	kg/m3	m/s	[xE-6]m3/s	kW		m/s		m/s
For Orifice diameter of .4 mm								
20.26	2.31	40.62	5.10	0.54	406	1.48	1347	0.21
22.80	2.31	42.97	5.40	0.57	430	1.57	1425	0.22
25.33	2.32	45.18	5.68	0.60	452	1.65	1499	0.23
27.86	2.32	47.26	5.94	0.62	472	1.73	1568	0.24
30.40	2.33	49.23	6.19	0.65	492	1.80	1633	0.25
For Orifice diameter of .45 mm								
20.26	2.31	40.62	6.46	0.68	457	1.67	1504	0.23
22.80	2.31	42.97	6.84	0.72	483	1.76	1591	0.25
25.33	2.32	45.18	7.19	0.75	508	1.86	1673	0.26
27.86	2.32	47.26	7.52	0.79	532	1.94	1750	0.27
30.40	2.33	49.23	7.83	0.82	554	2.02	1823	0.28
For Orifice diameter of .5 mm								
20.26	2.31	40.62	7.98	0.84	508	1.85	1658	0.26
22.80	2.31	42.97	8.44	0.89	537	1.96	1754	0.27
25.33	2.32	45.18	8.87	0.93	565	2.06	1845	0.29
27.86	2.32	47.26	9.28	0.97	591	2.15	1930	0.30
30.40	2.33	49.23	9.67	1.02	615	2.24	2010	0.31
For Orifice diameter of .55 mm								

20.26	2.31	40.62	9.65	1.01	558	2.03	1810	0.28
22.80	2.31	42.97	10.21	1.07	591	2.15	1915	0.30
25.33	2.32	45.18	10.73	1.13	621	2.26	2014	0.32
27.86	2.32	47.26	11.23	1.18	650	2.37	2106	0.33
30.40	2.33	49.23	11.70	1.23	677	2.47	2194	0.35
For Orifice diameter of .6 mm								
20.26	2.31	40.62	11.49	1.21	609	2.22	1960	0.31
22.80	2.31	42.97	12.15	1.28	644	2.35	2074	0.33
25.33	2.32	45.18	12.78	1.34	677	2.47	2180	0.35
27.86	2.32	47.26	13.36	1.40	709	2.58	2281	0.36
30.40	2.33	49.23	13.92	1.46	738	2.69	2376	0.38
For Orifice diameter of .65 mm								
20.26	2.31	40.62	13.48	1.42	660	2.40	2108	0.34
22.80	2.31	42.97	14.26	1.50	698	2.54	2230	0.36
25.33	2.32	45.18	14.99	1.57	734	2.67	2344	0.37
27.86	2.32	47.26	15.68	1.65	768	2.79	2452	0.39
30.40	2.33	49.23	16.34	1.72	800	2.91	2555	0.41
For Orifice diameter of .7 mm								
20.26	2.31	40.62	15.63	1.64	711	2.58	2253	0.36
22.80	2.31	42.97	16.54	1.74	752	2.73	2383	0.38
25.33	2.32	45.18	17.39	1.83	790	2.87	2506	0.40
27.86	2.32	47.26	18.19	1.91	827	3.00	2621	0.42
30.40	2.33	49.23	18.95	1.99	861	3.13	2731	0.44

Orifice Dim., mm	Gas Vol %	Cal Value MJ/m3	MJ/kg	Excess Air %	Flame Temp [K]
0.40	1.95	2.04	1.70	73.52	1547
0.45	2.19	2.30	1.91	54.07	1671
0.50	2.44	2.56	2.12	38.51	1789
0.55	2.68	2.82	2.33	25.78	1902
0.60	2.93	3.08	2.53	15.17	2010
0.65	3.18	3.34	2.74	6.19	2113
0.70	3.43	3.60	2.95	-1.50	2192

SIMULATION OF AIR INSPIRATION IN DOMESTIC BURNERS

For Burner tube diameter of 20 mm

Supply Press mBar	Dens kg/m3	Orifice Vel m/s	V/Rate [xE-6]m3/s	Conditions Duty kW	Nre	Tube Conds Vel m/s	Nre	Burner Exit vel m/s
For Orifice diameter of .4 mm								
20.26	2.31	40.62	5.10	0.54	406	1.12	1369	0.16
22.80	2.31	42.97	5.40	0.57	430	1.18	1448	0.17
25.33	2.32	45.18	5.68	0.60	452	1.24	1522	0.17
27.86	2.32	47.26	5.94	0.62	472	1.30	1592	0.18
30.40	2.33	49.23	6.19	0.65	492	1.35	1659	0.19
For Orifice diameter of .45 mm								
20.26	2.31	40.62	6.46	0.68	457	1.25	1531	0.18

22.80	2.31	42.97	6.84	0.72	483	1.33	1619	0.19
25.33	2.32	45.18	7.19	0.75	508	1.40	1703	0.20
27.86	2.32	47.26	7.52	0.79	532	1.46	1781	0.20
30.40	2.33	49.23	7.83	0.82	554	1.52	1855	0.21
For Orifice diameter of			.5 mm					
20.26	2.31	40.62	7.98	0.84	508	1.39	1691	0.19
22.80	2.31	42.97	8.44	0.89	537	1.47	1789	0.21
25.33	2.32	45.18	8.87	0.93	565	1.55	1881	0.22
27.86	2.32	47.26	9.28	0.97	591	1.62	1967	0.23
30.40	2.33	49.23	9.67	1.02	615	1.69	2049	0.24
For Orifice diameter of			.55 mm					
20.26	2.31	40.62	9.65	1.01	558	1.53	1849	0.21
22.80	2.31	42.97	10.21	1.07	591	1.62	1956	0.23
25.33	2.32	45.18	10.73	1.13	621	1.70	2057	0.24
27.86	2.32	47.26	11.23	1.18	650	1.78	2151	0.25
30.40	2.33	49.23	11.70	1.23	677	1.86	2241	0.26
For Orifice diameter of			.6 mm					
20.26	2.31	40.62	11.49	1.21	609	1.67	2006	0.23
22.80	2.31	42.97	12.15	1.28	644	1.76	2122	0.25
25.33	2.32	45.18	12.78	1.34	677	1.86	2231	0.26
27.86	2.32	47.26	13.36	1.40	709	1.94	2333	0.27
30.40	2.33	49.23	13.92	1.46	738	2.02	2431	0.28
For Orifice diameter of			.65 mm					
20.26	2.31	40.62	13.48	1.42	660	1.81	2160	0.25
22.80	2.31	42.97	14.26	1.50	698	1.91	2285	0.27
25.33	2.32	45.18	14.99	1.57	734	2.01	2403	0.28
27.86	2.32	47.26	15.68	1.65	768	2.10	2513	0.29
30.40	2.33	49.23	16.34	1.72	800	2.19	2618	0.31
For Orifice diameter of			.7 mm					
20.26	2.31	40.62	15.63	1.64	711	1.94	2313	0.27
22.80	2.31	42.97	16.54	1.74	752	2.06	2447	0.29
25.33	2.32	45.18	17.39	1.83	790	2.16	2573	0.30
27.86	2.32	47.26	18.19	1.91	827	2.26	2691	0.32
30.40	2.33	49.23	18.95	1.99	861	2.36	2804	0.33

Orifice	Gas	Cal Value		Excess	Flame
Dim., mm	Vol %	MJ/m3	MJ/kg	Air %	Temp [K]
0.40	1.46	1.53	1.28	131.86	1283
0.45	1.64	1.72	1.43	105.93	1380
0.50	1.82	1.91	1.59	85.18	1483
0.55	2.01	2.11	1.75	68.21	1578
0.60	2.19	2.30	1.91	54.07	1671
0.65	2.38	2.49	2.06	42.10	1760
0.70	2.56	2.69	2.22	31.84	1846

SIMULATION OF AIR INSPIRATION IN DOMESTIC BURNERS

For Burner tube diameter of 25 mm

Supply	Orifice	Conditions	Tube Conds	Burner

Press mBar	Dens kg/m3	Vel m/s	V/Rate [xE-6]m3/s	Duty kW	Nre	Vel m/s	Nre	Exit vel m/s
For Orifice diameter of .4 mm								
20.26	2.31	40.62	5.10	0.54	406	0.89	1382	0.13
22.80	2.31	42.97	5.40	0.57	430	0.95	1462	0.13
25.33	2.32	45.18	5.68	0.60	452	0.99	1537	0.14
27.86	2.32	47.26	5.94	0.62	472	1.04	1608	0.15
30.40	2.33	49.23	6.19	0.65	492	1.08	1675	0.15
For Orifice diameter of .5 mm								
20.26	2.31	40.62	7.98	0.84	508	1.12	1711	0.16
22.80	2.31	42.97	8.44	0.89	537	1.18	1810	0.17
25.33	2.32	45.18	8.87	0.93	565	1.24	1903	0.17
27.86	2.32	47.26	9.28	0.97	591	1.30	1991	0.18
30.40	2.33	49.23	9.67	1.02	615	1.35	2074	0.19
For Orifice diameter of .55 mm								
20.26	2.31	40.62	9.65	1.01	558	1.23	1873	0.17
22.80	2.31	42.97	10.21	1.07	591	1.30	1982	0.18
25.33	2.32	45.18	10.73	1.13	621	1.36	2083	0.19
27.86	2.32	47.26	11.23	1.18	650	1.43	2179	0.20
30.40	2.33	49.23	11.70	1.23	677	1.49	2270	0.21
For Orifice diameter of .6 mm								
20.26	2.31	40.62	11.49	1.21	609	1.34	2034	0.19
22.80	2.31	42.97	12.15	1.28	644	1.41	2152	0.20
25.33	2.32	45.18	12.78	1.34	677	1.49	2262	0.21
27.86	2.32	47.26	13.36	1.40	709	1.56	2366	0.22
30.40	2.33	49.23	13.92	1.46	738	1.62	2465	0.23
For Orifice diameter of .65 mm								
20.26	2.31	40.62	13.48	1.42	660	1.45	2193	0.20
22.80	2.31	42.97	14.26	1.50	698	1.53	2320	0.21
25.33	2.32	45.18	14.99	1.57	734	1.61	2439	0.23
27.86	2.32	47.26	15.68	1.65	768	1.68	2552	0.24
30.40	2.33	49.23	16.34	1.72	800	1.75	2658	0.25
For Orifice diameter of .7 mm								
20.26	2.31	40.62	15.63	1.64	711	1.56	2351	0.22
22.80	2.31	42.97	16.54	1.74	752	1.65	2487	0.23
25.33	2.32	45.18	17.39	1.83	790	1.73	2614	0.24
27.86	2.32	47.26	18.19	1.91	827	1.81	2735	0.25
30.40	2.33	49.23	18.95	1.99	861	1.89	2849	0.26

Orifice Dim., mm	Gas Vol %	Cal Value MJ/m3	MJ/kg	Excess Air %	Flame Temp [K]
0.40	1.16	1.22	1.02	190.21	1117
0.45	1.31	1.38	1.15	157.80	1202
0.50	1.46	1.53	1.28	131.86	1283
0.55	1.60	1.68	1.40	110.65	1361
0.60	1.75	1.84	1.53	92.96	1444
0.65	1.90	1.99	1.65	78.00	1521
0.70	2.04	2.15	1.78	65.18	1597

APPENDIX III

MS-DOS QBASIC PROGRAM FOR SIMULATING CHARACTERISTICS OF THE VLF GAS

```
'Program to calculate relevant combustion parameters of vaporised liquid fuel
gas
DIM cp(10), x(3), y(3), yy(3), my(3), h(3)
Phys.Qties:          pcf = 101325 / 760: tcf = 273: vm0 = .0224

CombProps:           mwa = 28.95: mwn = 28: mwc = 44: mww = 18
                     aocf = 100 / 21: nacf = 79 / 100
                     ccf(1) = 11: wcf(1) = 11
                     ccf(2) = 8: wcf(2) = 7.5

HtCaps: cpa(3, 1) = .1694: cpb(3, 1) = 997: cpa(3, 2) = .0753: cpb(3, 2) =
1126
        cpa(4, 1) = .1506: cpb(4, 1) = 989: cpa(4, 2) = .0803: cpb(4, 2) =
1086
        cpa(5, 1) = .1882: cpb(5, 1) = 1054: cpa(5, 2) = .09: cpb(5, 2) =
1190
        cpa(6, 1) = .7026: cpb(6, 1) = 1588: cpa(6, 2) = .4266: cpb(5, 2) =
1967
a(1) = 7.63: b(1) = 2259: d(1) = 0: m(1) = 154: fl(1) = .67: fu(1) = 5.6:
cv(1) = 43.5: oxys(1) = 16.5  'MJ/kg DPK
a(2) = 7.48: b(2) = 1523: d(2) = 0: m(2) = 111: fl(2) = 1.4: fu(2) = 7.6:
cv(2) = 43.8: oxys(2) = 11.75    'MJ/kg PMS
ti = 25
t = ti + tcf
n = 2: dx = .00005
OPEN "fdrest.bas" FOR OUTPUT AS #1
BEEP: CLS : PRINT "      *************PROGRAMME RUNNING************"
PRINT #1, "         *******Results for Minimum Flammability*******"
FOR i = 1 TO n: h(i) = fl(i): NEXT i
Start:  x(1) = 1!: x(2) = 0!
        PRINT #1, "  Press"; " Liquid  mol%"; "  F/Mix"; "  C/ Value(M)";
" C/ Value(F)"; "  Excess"; " F/Temp"; " Nwb"
        PRINT #1, "  [Bar]"; "  DPK "; "    PMS "; "  mol%"; "   MJ/m3"; "
MJ/kg"; "  MJ/m3 "; " MJ/kg"; "  Air%"; "  [K]"; "  MJ/m3"
        pp = 1: DO: pp = pp + .5: p = pp * 760 / 1.013: GOSUB itery: GOSUB
Stoich
        GOSUB calval: cvv = cv / (1000 * vm): cvm = cv / mwcg
         'MJ/m3 & MJ/kg
        PRINT #1, USING "###.## "; pp; 100 * x(1); 100 * x(2); 100 * sy; cvv;
cvm;
        denf = dencg: mwf = mwcg: FOR i = 1 TO n: y(i) = yy(i) / 100: NEXT
i:
        GOSUB calval: cvv = cv / (1000 * vm): cvm = cv / my
        'MJ/m3 & MJ/kg
        GOSUB Ittmp: GOSUB WBBno
        PRINT #1, USING " ####"; cvv;
```

```
        PRINT #1, USING " ###.##"; cvm; xssair; ': BEEP
        PRINT #1, USING " #####"; tt + tcf; nwb
        LOOP WHILE x(1) > 0 AND pp < 10: IF h(1) > fl(1) THEN BEEP: END
        FOR i = 1 TO n: h(i) = fu(i): NEXT i: BEEP
        PRINT #1, "        *******Results for maximum flammability*******":
GOTO Start

itery:  vm = vm0 * t / 273: DO: x(1) = x(1) - dx: x(2) = x(2) + dx: sy = 0:
        FOR i = 1 TO n: GOSUB pvpp: y(i) = x(i) * p(i) / p: sy = sy + y(i):
NEXT i:
        FOR i = 1 TO n: yy(i) = 100 * y(i) / sy: NEXT i: GOSUB LIMTS
        LOOP WHILE x(1) > 0 AND 100 * sy <= hh: IF x(1) < 0 THEN BEEP: END
        RETURN

pvpp:           p(i) = 10 ^ (a(i) - b(i) / (t - d(i)))
                RETURN

LIMTS:          hhr = 0: FOR i = 1 TO n: hhr = hhr + yy(i) / h(i): NEXT i:
                hh = 100 / hhr
                RETURN

Stoich: oxys = 0: FOR i = 1 TO n: oxys = oxys + yy(i) / 100 * oxys(i): NEXT
i:
        sar = oxys * aocf                               'Stoichiometric air
required
        af = (1 - sy) / sy                              'mol air present/mol
fuel combined
        xssair = (af / sar - 1) * 100
        RETURN

calval: my = 0: cv = 0: FOR i = 1 TO n:
        my(i) = y(i) * m(i): my = my + my(i):
'kg/kmol
        cv = cv + cv(i) * my(i): NEXT i:                       'MJ/kMol
        mwcg = my + (1 - sy) * mwa: dencg = mwcg / (1000 * vm)     'kg/kmol
& kg/m3
        RETURN

cp:             IF tt < 1370 THEN j = 1: GOTO cont1
                j = 2
cont1:          FOR i = 3 TO 6: cp(i) = cpa(i, j) * tt + cpb(i, j): NEXT i
                cpn = cp(3): cpa = cp(4): cpc = cp(5): cpw = cp(6)
                RETURN

FTemp:          GOSUB cp
                IF xssair <= 0 THEN zzz = 0: GOTO Cont2
Cont2:           flst = lcv * 1000000! / (mw * cpw + mc * cpc + ma * cpa *
zzz / 100 + mn * cpn)
                tt1 = flst + 25:  RETURN

Mss:            cfcf = 0: wfcf = 0: mwg = 0: lcv = 0: FOR i = 1 TO n:
                mwg = mwg + m(i) * y(i): cfcf = y(i) * ccf(i) + cfcf
                wfcf = wcf(i) * y(i) + wfcf: lcv = cv(i) * y(i) + lcv: NEXT
```

```
i:                  ma = sar * mwa / mwg: mn = sar * nacf * mwn / mwg
                    mw = wfcf * mww / mwg: mc = cfcf * mwc / mwg: RETURN

Ittmp:  tt = 100: zzz = xssair: GOSUB Mss: DO: tt = (tt + tt1) / 2: GOSUB
FTemp        'tt in C
        LOOP WHILE ABS(tt - tt1) >= 1:   RETURN

WBBno:  dena = mwa / (1000 * vm): sg = denf / dena
        nwb = lcv * denf / SQR(sg)                   'MJ/m3
        RETURN
```

*******Results for Minimum Flammability*******

Press [Bar]	Liquid DPK	mol% PMS	F/Mix mol%	C/ Value(M) MJ/m3	C/ Value(M) MJ/kg	C/ Value(F) MJ/m3	C/ Value(F) MJ/kg	Excess Air%	F/Temp [K]	Nwb MJ/m3
1.50	94.20	5.80	1.30	2.66	2.16	204	43.77	31.85	1847	53
2.00	91.90	8.10	1.33	2.70	2.20	203	43.78	29.69	1864	53
2.50	89.60	10.40	1.35	2.73	2.22	202	43.78	28.43	1874	53
3.00	87.40	12.60	1.35	2.72	2.21	201	43.79	28.58	1873	53
3.50	85.10	14.90	1.36	2.74	2.23	201	43.79	27.84	1879	53
4.00	82.80	17.20	1.37	2.75	2.24	201	43.79	27.30	1884	53
4.50	80.60	19.40	1.37	2.75	2.23	200	43.79	27.52	1882	53
5.00	78.30	21.70	1.38	2.76	2.24	200	43.79	27.12	1885	53
5.50	76.00	24.00	1.38	2.76	2.25	200	43.79	26.79	1888	53
6.00	73.80	26.20	1.38	2.76	2.24	200	43.79	27.00	1886	53
6.50	71.50	28.50	1.38	2.76	2.25	200	43.80	26.73	1889	53
7.00	69.20	30.80	1.39	2.77	2.25	200	43.80	26.50	1890	53
7.50	67.00	33.00	1.39	2.77	2.25	200	43.80	26.68	1889	53
8.00	64.70	35.30	1.39	2.77	2.25	199	43.80	26.49	1891	53
8.50	62.40	37.60	1.39	2.77	2.25	199	43.80	26.31	1892	53
9.00	60.20	39.80	1.39	2.77	2.25	199	43.80	26.48	1891	53
9.50	57.90	42.10	1.39	2.77	2.25	199	43.80	26.32	1892	53
10.00	55.60	44.40	1.39	2.78	2.26	199	43.80	26.19	1893	53

*******Results for maximum flammability*******

Press [Bar]	Liquid DPK	mol% PMS	F/Mix mol%	C/ Value(M) MJ/m3	C/ Value(M) MJ/kg	C/ Value(F) MJ/m3	C/ Value(F) MJ/kg	Excess Air%	F/Temp [K]	Nwb MJ/m3
1.50	63.80	36.20	7.59	15.14	10.52	199	43.80	-78.32	2136	57
2.00	51.60	48.40	7.59	15.12	10.50	199	43.80	-78.28	2135	57
2.50	39.30	60.70	7.60	15.12	10.51	199	43.80	-78.29	2135	57
3.00	27.00	73.00	7.60	15.13	10.51	199	43.80	-78.30	2135	57
3.50	14.80	85.20	7.60	15.12	10.50	199	43.80	-78.28	2135	57
4.00	2.50	97.50	7.60	15.12	10.51	199	43.80	-78.28	2136	57