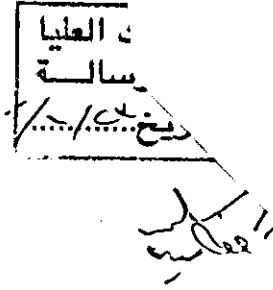# THE EFFECT OF PRESENCE OF WATER C
## COMBUSTION EFFICIENCY

By

Tareq Khalil Rady

Supervisor

Prof. Mohammed A. Hamdan

Co-Supervisor

Dr. Yahya H. Khraisha

Submitted in partial fulfillment of the requirements for the Degree of the
Master of Science in
Mechanical Engineering

Faculty of Graduate Studies

University of Jordan
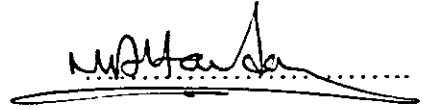
January 2000

This thesis was successfully defended and approved on 5/1/2000
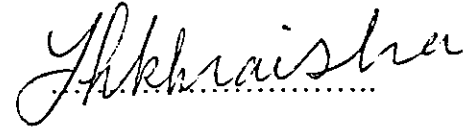
Examination Committee                                    Signature

Dr. Mohammed A. Hamdan, Chairman.
Prof. of Thermal Sciences.
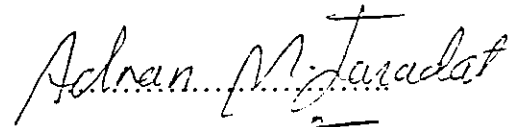
Dr. Yahya H. Khraisha, Co-Chairman.
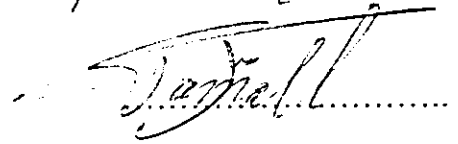Assoc. Prof. of Combustion Science.

Dr. Ali Badran, Member.
Assoc. Prof. of Thermal Sciences.

Dr. Adnan Jaradat, Member.
Assoc. Prof. of Thermal Sciences.

Dr. Jamal Nazzal, Member.
Asst. Prof. of Combustion Science.

# DEDICATION

To all beloved people,
my parents, family,
and fiancé, whom all
were there for me
when ever I needed
them.

Tareq...

# ACKNOWLEDGMENT

It is my pleasure to express my gratitude and thanks to all whom helped me to complete this work, specially my supervisors Prof. Mohammed Hamdan and Dr. Yahya Khraisha.

My thanks to the examination committee, Dr. Ali Badran, Dr. Adnan Jaradat, and Dr. Jamal Nazzal, for their help and guidance.

Special thanks for my family and my fiancé for their advice and encouragement all over the way.

Many thanks also to the staff of Chemical Engineering labs for their assistance and advice, especially Eng. Nabeel Al-Hajj Eid and Eng. Rushdi Nofal.

My greatest thank to my friends whom gave me all support and help to make my work a success, Eng. Alaa E. Abu Amarah, Eng. Majed Hassan, Eng. Mahmoud Khraisha.

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# NOMENCLATURE

| | |
|---|---|
| A/F | Mass Air fuel ratio (kg/kg). |
| $Cp_{a(in)}$ | Specific heat at constant pressure of the air inlet (kJ/kg.K). |
| $Cp_{a(out)}$ | Specific heat at constant pressure of the air outlet (kJ/kg.K). |
| $\overline{Cp}_a$ | Average Specific heat of the inlet and outlet air at constant pressure (kJ/kg.K). |
| $Cp_{w(in)}$ | Specific heat at constant pressure of the cooled water inlet (kJ/kg.K). |
| $Cp_{w(out)}$ | Specific heat at constant pressure of the cooled water outlet (kJ/kg.K). |
| $\overline{Cp}_w$ | Average Specific heat of the inlet and outlet cooled water at constant pressure (kJ/kg.K). |
| $CV_e$ | Calorific value of the emulsion (J/g). |
| $\dot{m}_a$ | Air mass flow rate (kg/hr). |
| $\dot{m}_{em}$ | Emulsion mass flow rate (g/s). |
| $\dot{m}_f$ | Pure gas oil mass flow rate (g/s). |
| $\dot{m}_w$ | Cooled Water mass flow rate (g/s). |
| o/w | Oil-in-water emulsion. |
| $Q_a$ | Energy of the inlet air (kJ/s). |
| $Q_{cv}$ | Energy of the fuel (Calorific value energy) (kJ/s). |
| $Q_{pro}$ | Products energy (kJ/s). |
| $Q_w$ | Energy transfer to the cooled water in the jacket of the chamber (kJ/s). |
| $T_{a(in)}$ | Inlet temperature of air (°C). |
| $T_{a(out)}$ | Outlet temperature of air (°C). |
| $T_{w(in)}$ | Inlet temperature of cooled water (°C). |
| $T_{w(out)}$ | Outlet temperature of cooled water (°C). |
| w/o | Water-in-oil emulsion. |
| $\eta_{comb}$ | Combustion efficiency (%). |
| $\eta_{th}$ | The thermal efficiency (%). |

# ABSTRACT

## THE EFFECT OF PRESENCE OF WATER ON GAS OIL COMBUSTION EFFICIENCY

By
Tareq Khalil Rady

Supervisor
Prof. Mohammed A. Hamdan

Co-Supervisor
Dr. Yahya H. Khraisha

The  main purpose of this work is to study the combustion process of water-in-oil (gas oil) emulsion using a small laboratory combustion unit.

Different ratios of water in  oil (w/o) emulsions, 1%, 2%, 5%, 7%, and 10% by weight, were investigated and compared with pure oil at various values of air fuel (A/F) ratios. The  stability  of the emulsion was insured by a mechanical mixing process using a stirrer inducing a high level of turbulence.

Combustion and thermal efficiencies,  temperature distribution along the flame, and flue gases analysis,  were studied.  Results have shown an increase in both combustion and thermal efficiencies with the  increase of w/o ratio, within the studied range.

# Chapter One

# INTRODUCTION

Most of the thermal energy used in our planet for practical purposes came from the combustion of fossil fuels. Equipment used to burn fuels generally have low efficiency and high air pollution emissions, which in return have a significant effect on the environment.

Combustion is the rapid, high temperature oxidation of. Since most fuels used at present consist almost entirely of carbon and hydrogen, burning involves the rapid oxidation of carbon to carbon dioxide and carbon monoxide, together with hydrogen to water vapor.

One of the methods used to improve the combustion process in liquid fuels is the addition of water to the fuel as an "Emulsion".

Emulsion is a system containing two liquid phases, one phase is dispersed as globules in the dispersion medium. The two phases are immiscible, so they can only be mixed by mechanical or chemical techniques, which guarantee the stability of the emulsion.

Emulsions combined of water and oil are either water-in-oil emulsions or oil-in-water emulsions. In this work water-in-oil emulsion was used, where water is the internal phase and the gas oil is the external phase.

The main objective of this work was studying the combustion efficiency at different operating conditions by using various values of air/fuel ratios, and various values of water-in-oil emulsions.

# Chapter Two

## LITERATURE REVIEW

Ballaster *et. al.* (1995) developed two comparisons between heavy oil and water-in-oil emulsions. It has been demonstrated that the use of water-in-oil emulsion produces some significant effects on the combustion of liquid fuels, especially the reduction of particulate emissions. Pure oil and an emulsion with 8 %wt. water were burnt in a large laboratory furnace (0.33 MW thermal input).

They concluded that addition of water had a dramatic effect on the flame, the visible flame length was about 1 m for pure oil and it changes to 0.6 m when water was added to oil as an emulsion. The addition of water increased the fuel viscosity and lead to coarser and narrow sprays. Temperature level was reduced by 65 K in the combustion of the oil-water emulsion, where the absorption of heat by the additional water caused an average decrease in temperature of about 25 K. The remaining 40 K can be attributed only to the greater loss of energy by radiation to the walls in the first part of the flame.

Ishida and Watanabe (1990) studied experimentally and in detail the suppression of spread of flame over heavy oil pool by w/o (water-in-oil) type emulsification. Water content ranging from 2% to10% by volume was prepared by mixing heavy oil with water without using surface active agent in gear pump type

emulsification apparatus. The effects of w/o emulsification on the flash point, the velocity of flame spread over the pool and on the development of preceding surface flow ahead of flame leading edge were investigated. Results were as follows:

1. The flash point rises 2 to 4 °C in the w/o emulsion comparing with pure oil.

2. The velocity of flame spread can be suppressed owing to the emulsification to about 1/2 to 2/3 of the pure oil.

A study of water-in-oil emulsion was conducted by Cook and Low (1978) using single cylinder diesel engine to investigate the effect of water emulsification on particulate emission, with the fuel-air ratio ranging from 0.02 to 0.07 by volume. The obtained results indicated that the optimum water content for particulate reduction seems to be between 10% and 20% by volume, also it was found that smoke emission decreased with increased water addition.

Aburas (1976) used gas oil and heavy oil to prepare water-in-oil and methanol-in-oil emulsions, the presence of 5 % and 10 % by weight of the internal phase (water or methane) was investigated. Results obtained showed that the presence of water or methanol in the fuel aids the atomization process and improves the spry characteristics. He concluded that the presence of water has a greater effect on the fuel oil than the gas oil.

Valdmanis and Wulfhorst (1970) investigated three water/fuel emulsions, the ratios of water-in-oil (w/o) were 20/80, 33/76 and 50/50 by volume. The

emulsifying agent was of the organic type with zero ash content with a percentage did not exceed 2% of the fuel volume. Authors concluded the following:

a) The effect of water addition on combustion process varies with the type of combustion system and method of water addition.

b) Introduced water was effective in reducing the NO levels.

c) Water addition reduced the CO and smoke slightly, but caused an increase in the unburned hydrocarbons.

# Chapter Three

## THEORY

### 3.1 Emulsion

### 3.1.1 Classification of Emulsions

In emulsions, one phase is dispersed throughout the second phase as "globules". An emulsion consist then, of a dispersed phase and a dispersion medium, a third component, known as emulsifying agent, can be used to aid the two phases mixing process (Becher, 1966).

When the dispersed phase is oil and the dispersion medium phase is water, the emulsion is known as an oil-in-water emulsion (o/w). When the dispersed phase is water and the dispersion medium is oil, the emulsion is of water-in-oil (w/o) kind, as shown in Figure (3.1).

Dispersion Medium (Oil)

Dispersion Medium (Water)

Dispersed Phase (Water)

Dispersed Phase (Oil)

a

b
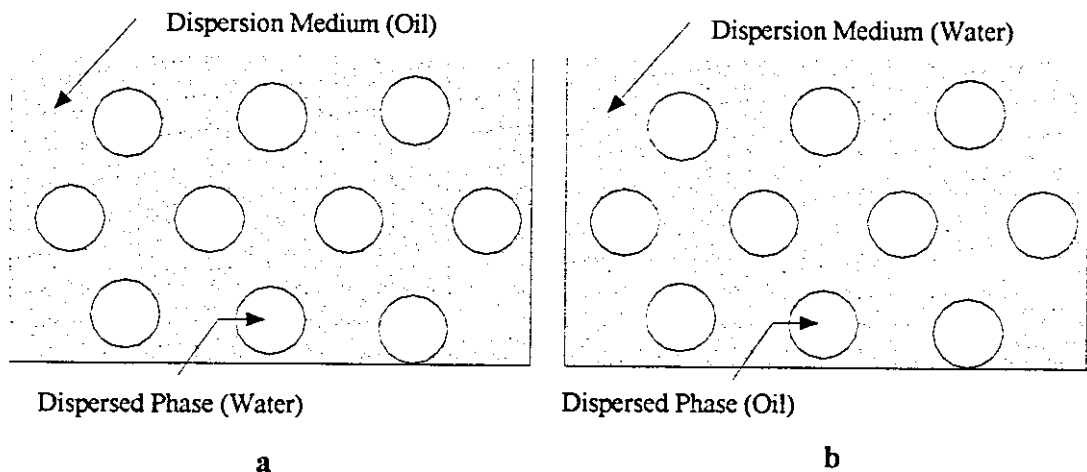
**Figure (3.1) a. Water-in-oil emulsion (w/o), b. Oil-in-water emulsion (o/w).**

## 3.1.2 Emulsion Stability

Emulsions are by nature, physically unstable, they tend to separate into two distinct phases or layers over time, Therefor there is a levels of instability such as creaming which occurs when dispersed oil droplets merge and rise to the top of an o/w emulsions, sedimentation that describes the same occurrence in w/o emulsions, when water droplets merge and settle to the bottom.

In both cases, the emulsion can be easily redispersed when water droflocculation occurs when dispersed droplets conglomerate into larger droplets, but do not fuse and can be redispersed by shaking. Coalescence is the complete and irreversible separation and fusion of the dispersed phase. (Aburas, 1976).

Generally, for some practical systems, emulsion stability may be required for only a few seconds, as in our study case; however, if the emulsion is to be stored and transported before use, then stability requirements become more demanding. The generation of stable emulsions is an empirical art for which emulsifying agent addition and method of manufacture are the major tools (Hartley *et. al*, 1975).

## 3.2 Combustion Process

### 3.2.1 Definition of Combustion

Combustion can be defined as the rapid oxidation of fuels generating heat or both heat and light (Turns, 1996), it can also be defined as the rapid, high temperature oxidation of fuels (Smith and Stinson, 1952).

Most of the currently used fuels contains carbon and hydrogen, burning involves the rapid oxidation of carbon to carbon dioxide, or carbon monoxide, and of hydrogen to water vapor.

The combustion process consists of the oxidation of constituents in the fuels that are capable of being oxidized, and can therefore be represented by a chemical equation.

### 3.2.2 Combustion Reactions

Carbon is one of the most important combustible elements and is essential part of any hydrocarbon compound. The oxidation of carbon is slower and more difficult than that of either hydrogen or sulfur.

In the theoretical combustion process it will be assumed that both, sulfur and hydrogen, burn completely before carbon burns. Furthermore, it will be assumed that all the carbon will be oxidized to carbon monoxide (CO) before any carbon is converted to carbon dioxide ($CO_2$), (Culp, 1979).

The chemical reactions are as following:

$$H_2 + 1/2 O_2 \rightarrow H_2O \qquad + \qquad 286,470 \text{ kJ/(kg.mol } H_2) \qquad (3.1)$$

$$C + 1/2 O_2 \rightarrow CO \qquad + \qquad 110,380 \text{ kJ/(kg.mol C)} \qquad (3.2)$$

$$CO + 1/2 O_2 \rightarrow CO_2 \qquad + \qquad 283,180 \text{ kJ/(kg.mol CO)} \qquad (3.3)$$

$$S + O_2 \rightarrow SO_2 \qquad + \qquad 296,774 \text{ kJ/(kg.mol S)} \qquad (3.4)$$
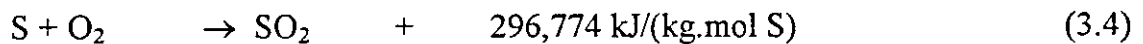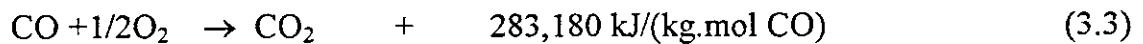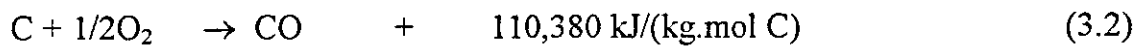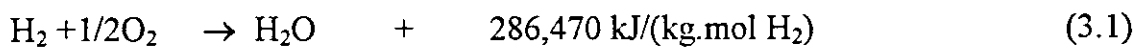
Each of the above reactions is considered as an exothermic chemical reaction.

## 3.2.3 Combustion with Air

In most applications of combustion, each element of the fuel needs a portion of oxygen in order to burn, therefore, the presence of air is essential since it is the most suitable source for oxygen; That means much nitrogen from the air must accompany the oxygen, which goes into the chemical reaction. However, the nitrogen, being inert, does not enter into the reaction.

The amount of air supplied to the fuel is important in the products percentages, since when the amount of air is not sufficient the combustion will not be

complete, which means that carbon monoxide (CO) will occur. For this reason it is important to calculate the minimum air required for the complete combustion of any specific amount of fuel. This concept is named as the stoichiometric or theoretical air to fuel ratio (A/F $_{st}$), which is the exact quantity of air required for the chemical reaction.

In the case of more than a stoichiometric quantity of oxidizer is supplied, the mixture is said to be fuel lean, or just lean; while supplying less than the stoichiometric oxidizer it is said to be fuel rich, or rich mixture.

Usually little excess air is present than what is actually needed to enter into the chemical reaction, the quantity of air present beyond the actual required is called excess air.

Stoichiometric (theoretical) air fuel ratio (A/F $_{st}$) can be calculated according to the following equation:

$$\left(\frac{A}{F}\right)_{st} = \frac{2.66C + 7.94H_2 + 0.998S - O_2}{0.232} \tag{3.5}$$

Where C, $H_2$, S, and $O_2$ are represented as percentage of each element by weight of the fuel.

### 3.2.4 Combustion and Thermal Efficiencies

Combustion efficiency is the total energy produced by the actual combustion of any fuel divided by the theoretical combustion energy can be given by such fuel. The combustion efficiency ($\eta_{comb}$) is expressed in the following equation (Toone, 1959).

$$\eta_{comb} = \frac{\left(\dot{m}_w \overline{Cp}_w \left(T_{w(out)} - T_{w(in)}\right) + \left(\dot{m}_a + \dot{m}_f\right)\overline{Cp}_a \left(T_{a(out)} - T_{a(in)}\right)\right)}{\dot{m}_f CV_f + \dot{m}_a \overline{Cp}_a \left(T_{a(in)} - T_{a(ref)}\right)} \tag{3.6}$$

The thermal efficiency is the useful energy taken from the combustion chamber of any specific fuel, divided by the theoretical combustion energy can be given by such fuel.

Thermal efficiency ($\eta_{th}$) is expressed in the following equation.

$$\eta_{th} = \frac{\dot{m}_w \overline{Cp}_w \left(T_{w(out)} - T_{w(in)}\right)}{\dot{m}_f CV_f + \dot{m}_a \overline{Cp}_a \left(T_{a(in)} - T_{a(ref)}\right)} \tag{3.7}$$

Where:

$\dot{m}_a$, $\dot{m}_w$, $\dot{m}_f$ : are the mass flow rates for air, water, fuel respectively.

$\overline{Cp}_w$, $\overline{Cp}_a$ : are the average specific heat of water and air respectively.

$T_w$, $T_a$ : are the temperatures for the water and air respectively.

$T_{ref}$ : is the reference temperature of the air, and is equal to 25 °C.

$CV_f$ : is the calorific value of the used fuel.

## 3.3 Effect of Water-in-Oil Emulsion on the Combustion Process

Combustion of pure fuels can produce an amount of unreacted fuel, which will be discharged with the flue gases, reducing the reacted amount of the fuel entering the reaction, leading to lower combustion efficiency.

Many methods are used in order to achieve the complete combustion of the fuel, by improving the combustion process in order to approach the heating value (calorific value) of the fuel.

Water-in-oil emulsion has a significant effect on improving the combustion process by increasing the surface area of the fuel, where the droplets are "broken up into small fuel particles, gaining more speed in relation to heating up, evaporation and ignition." (Hartley *et. al.*, 1975).

So as a result of using the emulsion, a better mixing with oxidant and therefore more complete combustion are achieved.

# Chapter Four

# EXPERIMENTAL APPARATUS, CONDITIONS AND

# TECHNIQUES

## 4.1 Introduction

Experiments were conducted using Hilton combustion chamber (Hilton, 1975), which consist of several instruments to measure and to give indication about the operation conditions at the combustor. Mass flow rates of air, fuel and water, temperatures of the inlet and outlet for air and water, and temperature of the flame inside the chamber along the axis of the nozzle tip were measured; In addition the produced flue gases were analyzed using a gas chromatograph analyzer apparatus. The combustion chamber is equipped with the necessary accessories required for the experiment.

## 4.2 Experimental Apparatus

## 4.2.1 Combustion Unit

Consists mainly of the combustion chamber, which is a cylindrical shaped horizontal container, surrounded by a water jacket for the absorption of heat produced during the combustion process. The combustion unit components can be seen in Figure (4.1).
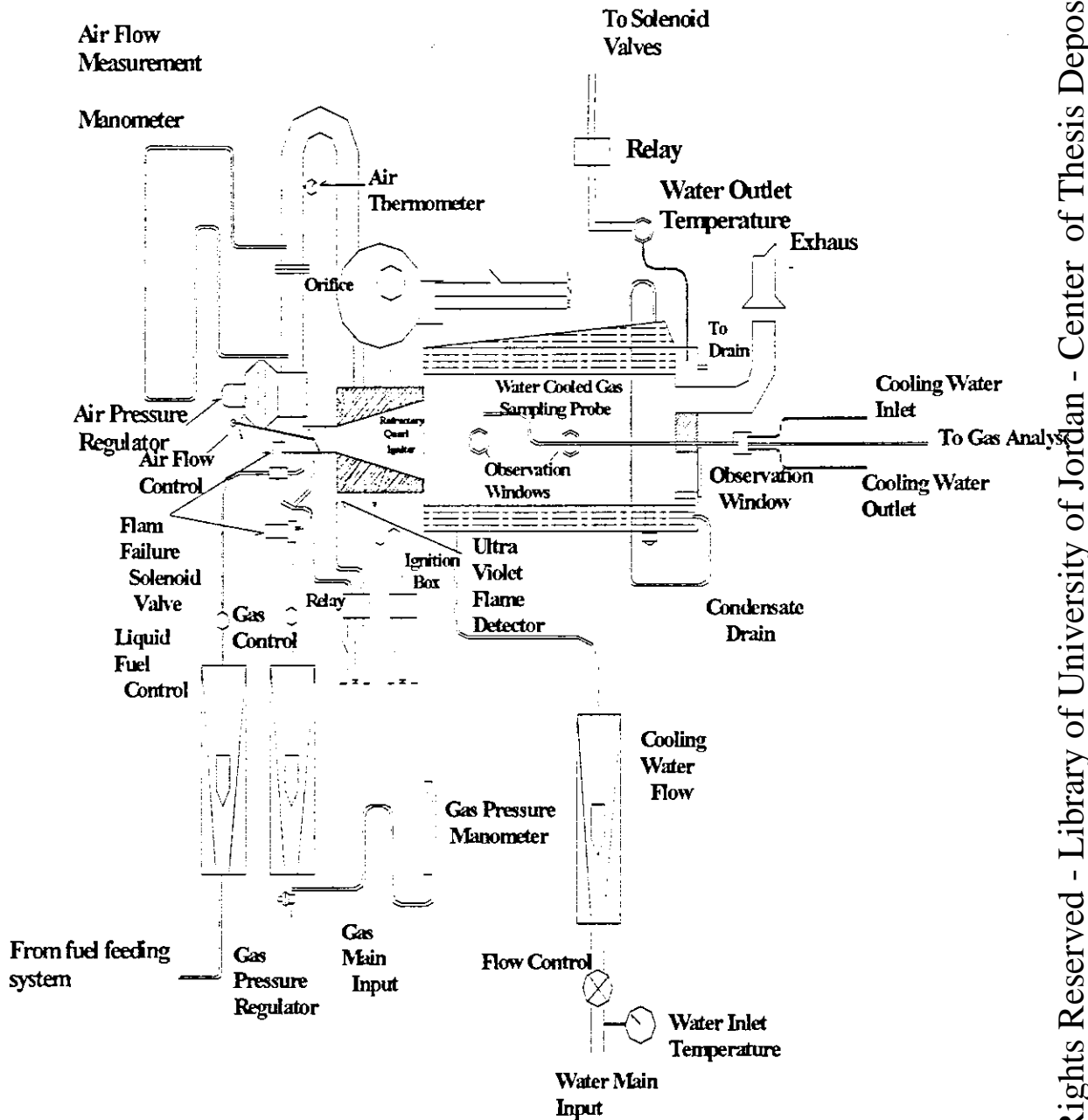
**Figure (4.1) Schematic diagram of the laboratory combustion unit (Hilton, 1975).**

## 4.2.2 Fuel Supplying System

The liquid fuel supplying system consists of the following:

- Main fuel tank

It's a cylindrical tank 30L capacity, with 31cm diameter and 40 cm height. It is mounted at 2.5m height above the combustion chamber.

The tank is equipped with baffles to enhance and stabilize the gas oil and water emulsion.

- Mixer

An electrical mixer is used to make the gas oil and water as a one phase, stable emulsion, where the stirring process keeps the emulsion in a state of high turbulence.

- Auxiliary fuel tank

The auxiliary fuel tank is used in circulating the w/o emulsion, where emulsion flowing from the main tank is divided into two lines, where the first line feeds the burner and the other line pours into the auxiliary tank (By-pass line), which return again to the main tank through a pump connecting the two tanks together.

- Pump

The aim of the pump is to circulate the emulsion from the auxiliary tank to the main tank.

The purpose of using two tanks is to keep the water and the gas oil in one phase, by increasing the mass flow rate through the pipe line, while the required flow to the burner is much less, so the extra flow is returned through the auxiliary tank and the pump connecting it with the main tank. The schematic diagram of the fuel supplying system can be seen in Figure (4.2).
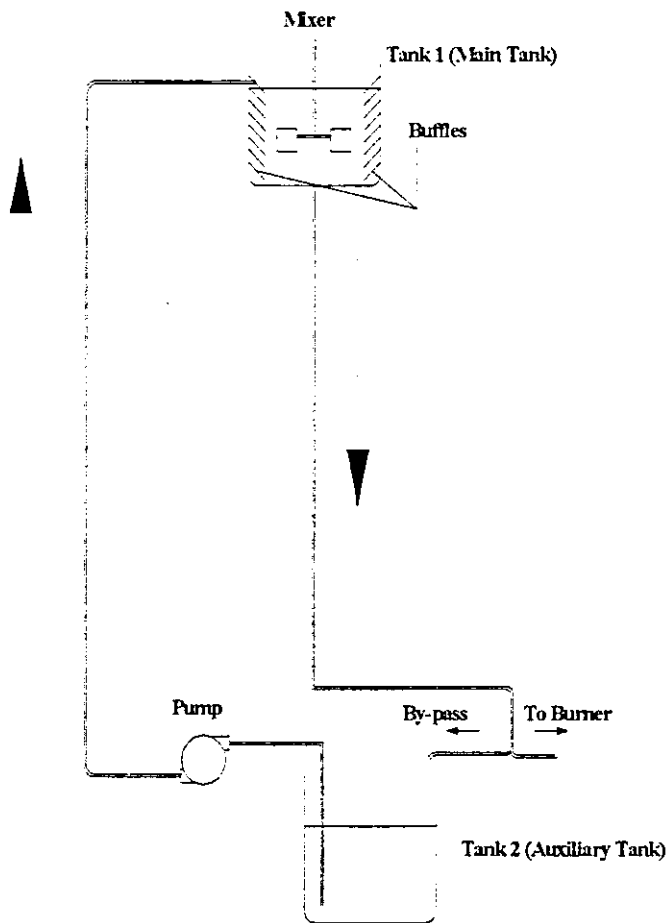


**Figure (4.2) Schematic diagram of the fuel supplying system.**

### 4.2.3 Cooling Water Supplying System

Cooling water with a flow rate reach to 1800 kg/hr is required to be used for cooling the combustion chamber. The water passes through the jacket of the chamber and the sampling probe.

Cooling tower is used to supply the chamber jacket with cold water, since the water that leaves the chamber is relatively warm.

Hilton combustion unit contains sensors to measure the temperatures of inlet and outlet water, which can be read in gages fixed at water entering and exiting connections.

Pump is also installed with by-pass system to regulate the flow and to give the best flow rate.

### 4.2.4 Air Supplying System

Medium pressure centrifugal air blower is used to supply the combustor with the necessary air required for combustion process, with a maximum rate of 160 kg/hr, which is regulated to a constant pressure of 250mm water gage.

## 4.2.5 Temperature Measurement

A five chromel-alomel thermocouples where used for the measurement of flame temperature along the axis of the nozzle tip, as shown in Figure (4.3).
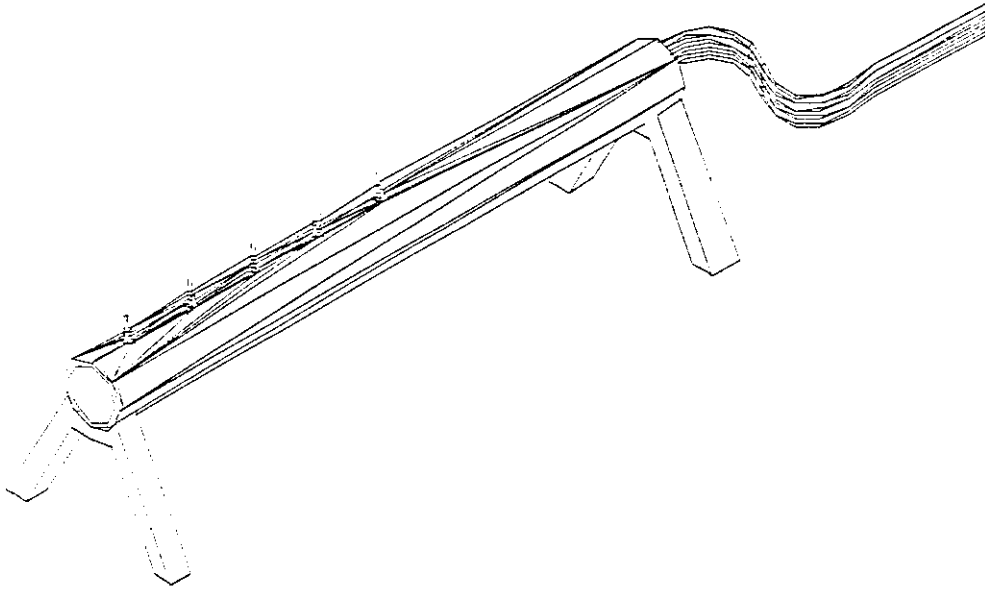
**Figure (4.3) Thermocouples stand**

These thermocouples are distributed uniformly at equal spaces of 3.5 cm. The thermocouples are externally connected to a digital microprocessor where the temperature readings are displayed for the temperature along the flame direction.

## 4.2.6 Gas Sampling System

The gas sampling system consists of the following:

1. Vacuum pump, which is used to absorb the sample from the flue gases by using sampling probe, which is located in the chamber as shown in figure (4.4).

2. Trap which is used to prevent moisture of water vapor entering suction line to the vacuum pump, which consists of glass flask and absorption material such as (cotton), where in this case the sample will be dry.

3. Balloons to collect the samples of flue gasses to be analyzed using gas analyzer (gas chromatograph).
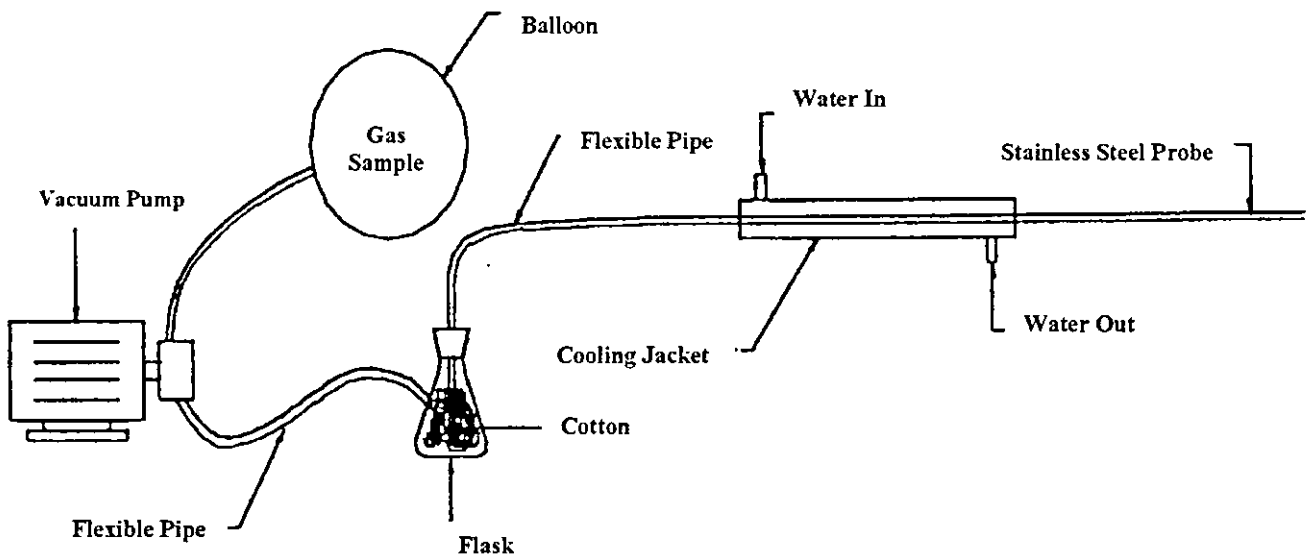


**Figure (4.4) Flue gas sampling system.**

## 4.3 Operation Techniques

### 4.3.1 Emulsion Preparation

Emulsion is prepared by adding water to the gas oil in the main tank, in order to achieve the required w/o mass ratio. The total mass flow rate for the different emulsions burned was always kept constant in all experiments (1.33 g/sec), which leads to decrease the amount of gas oil ratio by increasing the water added in the w/o emulsion.

The fuel is added first, with the circulation process (mixer and the flow through the auxiliary tank) is active, then the required amount of water is added. The circulation process is given about 15 minutes in order to achieving the best w/o emulsion.

### 4.3.2 Flowmeter Calibration

There are four flowmeters attached to the apparatus, they are used to measure flow rates for the liquid fuel, gas fuel, air, and water.

Since the density of the w/o emulsion only varies according to the percentage of water added, it was necessary to calibrate the flowmeter each time the emulsion ratio change, by measuring the mass of the emulsion at constant period of time.

### 4.3.3 Gas Chromatograph Setting Up

A gas chromatograph with a stainless steel column (for $CO_2$ analysis a porapak column was used, while for CO and $O_2$ analysis a molecular sieve column) with a length of 2.7 m and a diameter of 4 mm. Equipped with a thermal conductivity detector (TCD) and a gas sampling valve injector were used to analyze the samples of 0.5 ml of the flue gases.

The percentages of carbon dioxide, carbon monoxide, and oxygen analyzed by the gas chromatograph, are presented as ratios by volume of the flue gas sample studied.

### 4.4 Gas Oil Properties

Table (4.1) shows the elements analysis of the gas oil that had been used in the combustion experiments, other properties can be found in Table (B.23).

Table (4.1) Analysis of the used gas oil.

| Element | Percentage by weight (% wt.) |
|---|---|
| Carbon ( C ) | 82.75 |
| Hydrogen ($H_2$) | 13.9 |
| Sulfur (S) | 1.07 |
| Nitrogen ($N_2$) | 0.48 |
| Oxygen ($O_2$) | 1.80 |
| Summation | 100.00 |

# Chapter Five

# RESULTS AND DISCUSSION

All the results are related to the total evolved gases from the combustion of the emulsion.

## 5.1 Combustion Efficiency

Figure (5.1) shows the variation of the combustion efficiency ($\eta_{comb}$) with the air fuel ratio (A/F) of the emulsion at constant percentages of water. Generally, the efficiency increases with increasing the amount of water addition in the emulsion, due to the improve in the combustion process; it can also be noted that at a specific amount of water the combustion efficiency has a maximum value that occurs at an air fuel ratio around the theoretical air fuel ratio. The theoretical air fuel ratio is different for each ratio of added water, where it shifts to the lift as the added water ratio increases. As shown in Table (B.20).

The combustion efficiency increases as the air fuel ratio increases, till reaching the theoretical air fuel ratio, which gives the maximum value of the combustion efficiency, this is due to the decrease in the amount of the unburned fuel as the air fuel ratio approaches its theoretical value. As the air fuel ratio increases to values higher than the theoretical value, the efficiency decreases, this can be related to the cooling effect of the excess air on the chamber.

Figure (5.2) shows the variation of the combustion efficiency with the water percentage added to the gas oil at constant values of air fuel ratio. It can be seen

that the combustion efficiency increases slightly with increasing the water percentage.

In the case of air fuel ratio lower than the theoretical value, see Table (B.20), a rapid increase in combustion efficiency occurs. At A/F=12 the efficiency increases rapidly from about 79% (for 0% added water, which has a theoretical air fuel ratio 14.21) up to 93% (for 10% added water, which has a theoretical air fuel ratio 12.79).

At an air fuel ratio of 14, and for 10% water addition the maximum combustion efficiency was about 96%. For 5% water addition it was 95%, while it was 93% for pure oil.

Sample calculation of the combustion efficiency is presented in Appendix (A).

## 5.2 Thermal Efficiency of the Unit

Figure (5.3) shows the thermal efficiency ($\eta_{th}$) with air fuel ratio at constant percentages of added water for each. It can be seen that the thermal efficiency increases with increasing the amount of added water, which is due to the improve of the combustion process. Thermal efficiency increases with increasing air fuel ratio, at a specific amount of added water, by reaching the theoretical air fuel ratio it starts to decrease. This behavior can be explained by the fact that

increasing the air fuel ratio the unburned fuel decreases, till reaching the theoretical air fuel ratio. The thermal efficiency starts to decrease due to the effect of reducing the chamber temperature by the excess air that causes a reduction in the heat absorbed by the cooling water jacket.

Figure (5.4) shows the thermal efficiency with percentage of added water at constant values of air fuel ratio. It can be noted that the thermal efficiency increases by increasing the percentage of the added water.

At 14 air fuel ratio, For 10% water addition the maximum thermal efficiency was 72.6%, and for 5% water addition it was 71.9%, while it was 70.6% for pure oil.

Sample calculation of the thermal efficiency is presented in Appendix (A).

## 5.3 Gas Chromatograph Analysis

## 5.3.1 Carbon Dioxide ($CO_2$)

Figures (5.5) and (5.6) show the relation between carbon dioxide percentage by volume of flue gases and air fuel ratio for constant amounts of added water and the relation between carbon dioxide percentage by volume of flue gases and the added water for constant amounts of air fuel ratio respectively. As the air fuel

ratio increases the carbon dioxide increases to a maximum value, when approaching the theoretical air fuel ratio of that emulsion it begin to decrease.

At air fuel ratio 12, the maximum $CO_2$ percentage was observed for 10% added water, it was 9.43%, and the theoretical air fuel ratio was 12.8. For pure gas oil the percentage of $CO_2$ was 7.95% with a theoretical air fuel ratio of 14.21.

While for air fuel ratio equal to 20, the $CO_2$ percentage at 10% added water was the lowest and the $CO_2$ percentage for the pure oil was the highest. This phenomena can be explained by the fact that the theoretical air fuel ratio is shifted to the left with adding water, and the $CO_2$ percentage is increasing when the air fuel ratio approaches the theoretical value, and vise versa.

## 5.3.2 Carbon Monoxide (CO)

Figures (5.7) and (5.8) show the relation between carbon monoxide percentage by volume of flue gases and air fuel ratio for constant amounts of added water and the relation between carbon monoxide percentage by volume of flue gases and the added water for constant amounts of air fuel ratio respectively.

The carbon monoxide percentage decreases while increasing the air fuel ratio. The values of carbon monoxide at low values of air fuel ratios have large

variations for the different amounts of added water, while at higher values of air fuel ratios, those values become closer to each other.

As added water percentage increases for constant values of air fuel ratio, carbon monoxide decreases. At air fuel ratio 14, the CO amount was 1.2% for pure oil, while it decreases to 0.5% for 10% water addition, with a difference of 0.7%. For air fuel ratio 20, the CO amount was 0.4% for pure oil, while it decreases to 0.24% for the 10% water addition, with a lower difference of 0.16%.

### 5.3.3 Oxygen ($O_2$)

Figures (5.9) and (5.10) show the relation between oxygen percentage by volume of flue gases versus air fuel ratio and water added respectively. The oxygen percentage increases by increasing air fuel ratio, also it has the same behavior with adding water. This is due to the unreacted oxygen in the low air fuel ratios and the unreacted and excess air (containing oxygen) for the higher values of air fuel ratios.

### 5.4 Flame Distribution

Figure (5.11) shows the temperature readings along the flame for A/F ratio equal 20 for different emulsions with constant amounts of added water for each. The
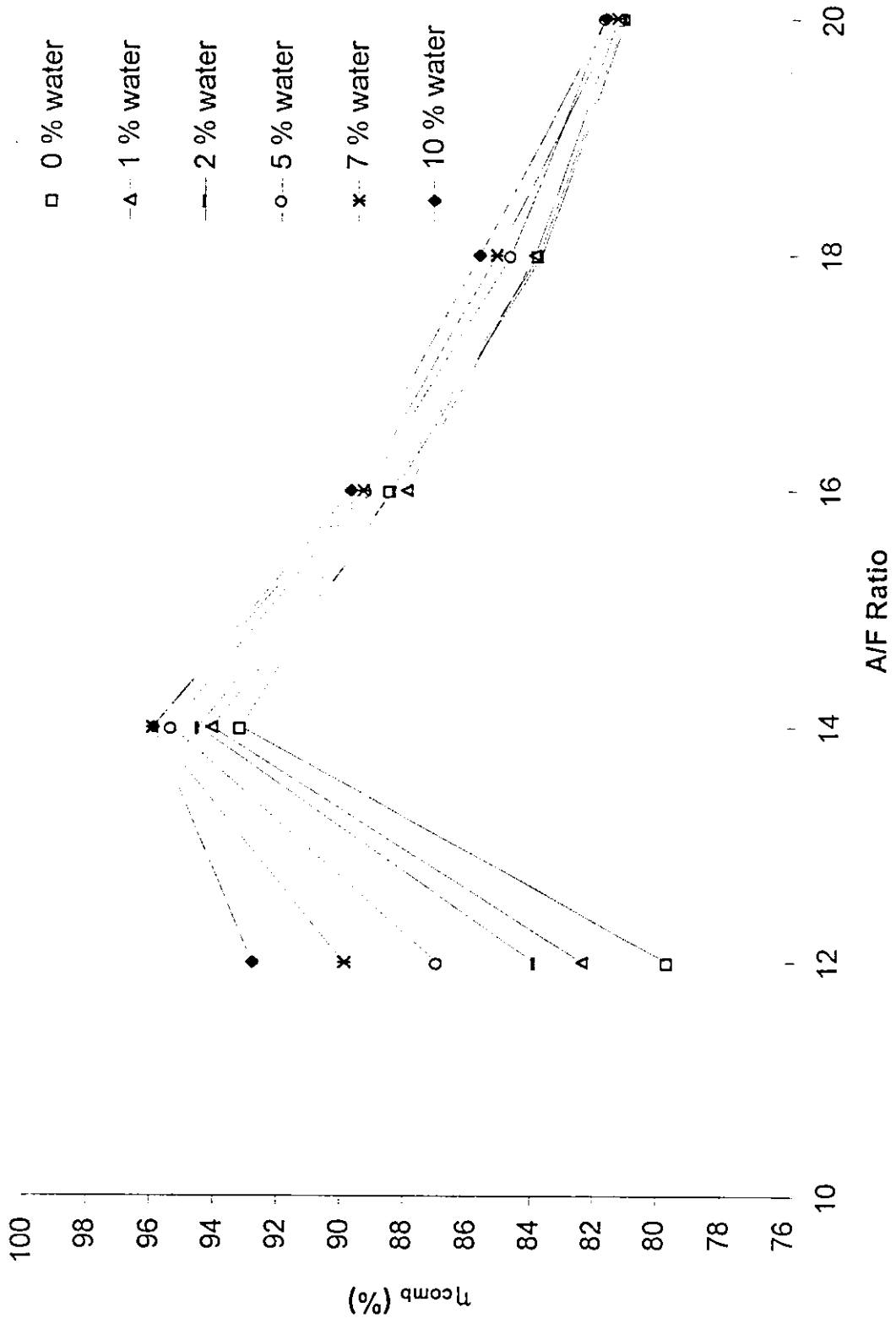
Figure (5.1) Combustion efficiency $(\eta_{comb})$ versus air fuel ratio for different percentages of water added to the emulsion.
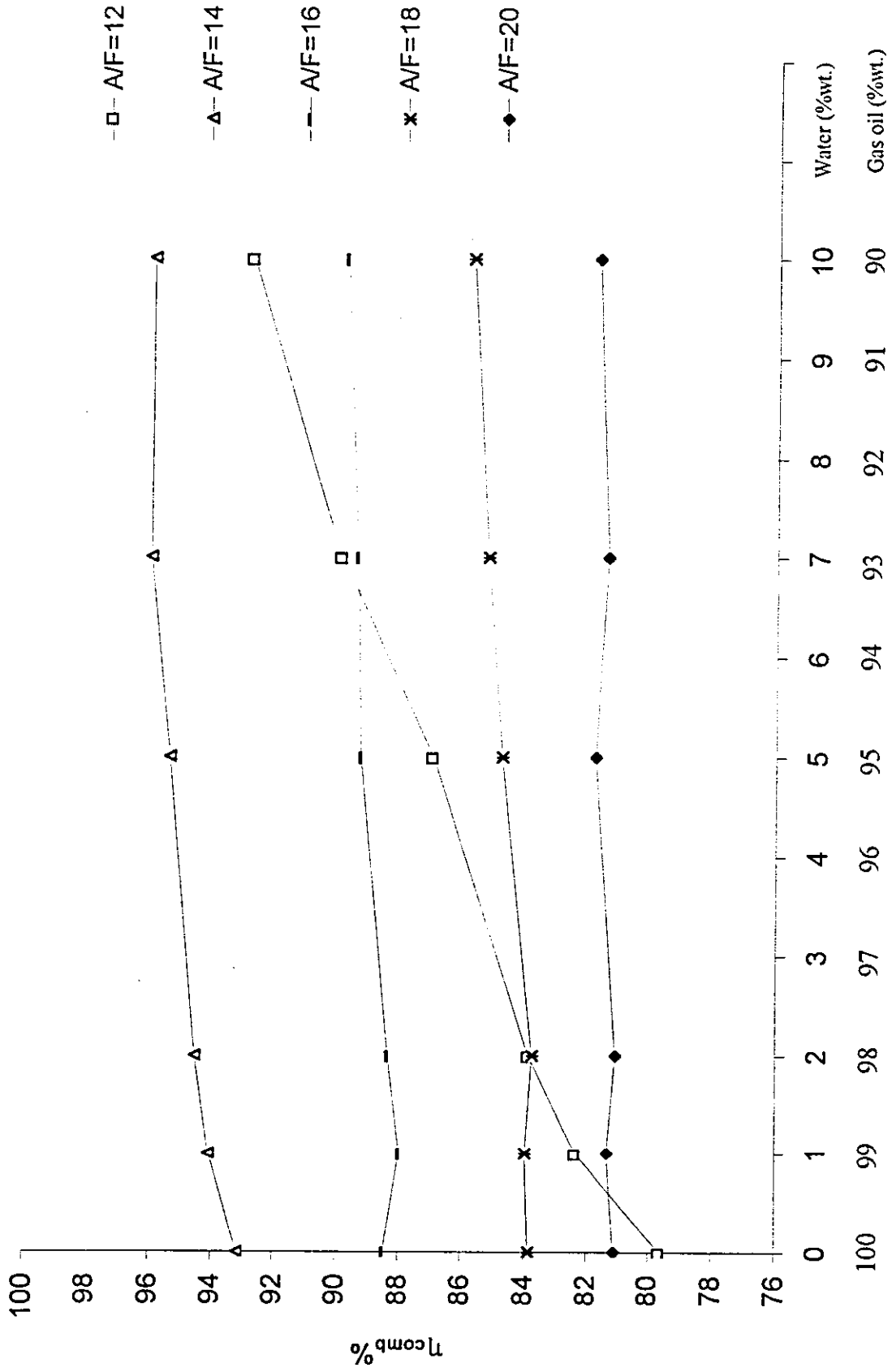
**Figure (5.2) Combustion efficiency $(\eta_{comb})$ versus percentage of water in the emulsion for different values of air fuel ratios.**
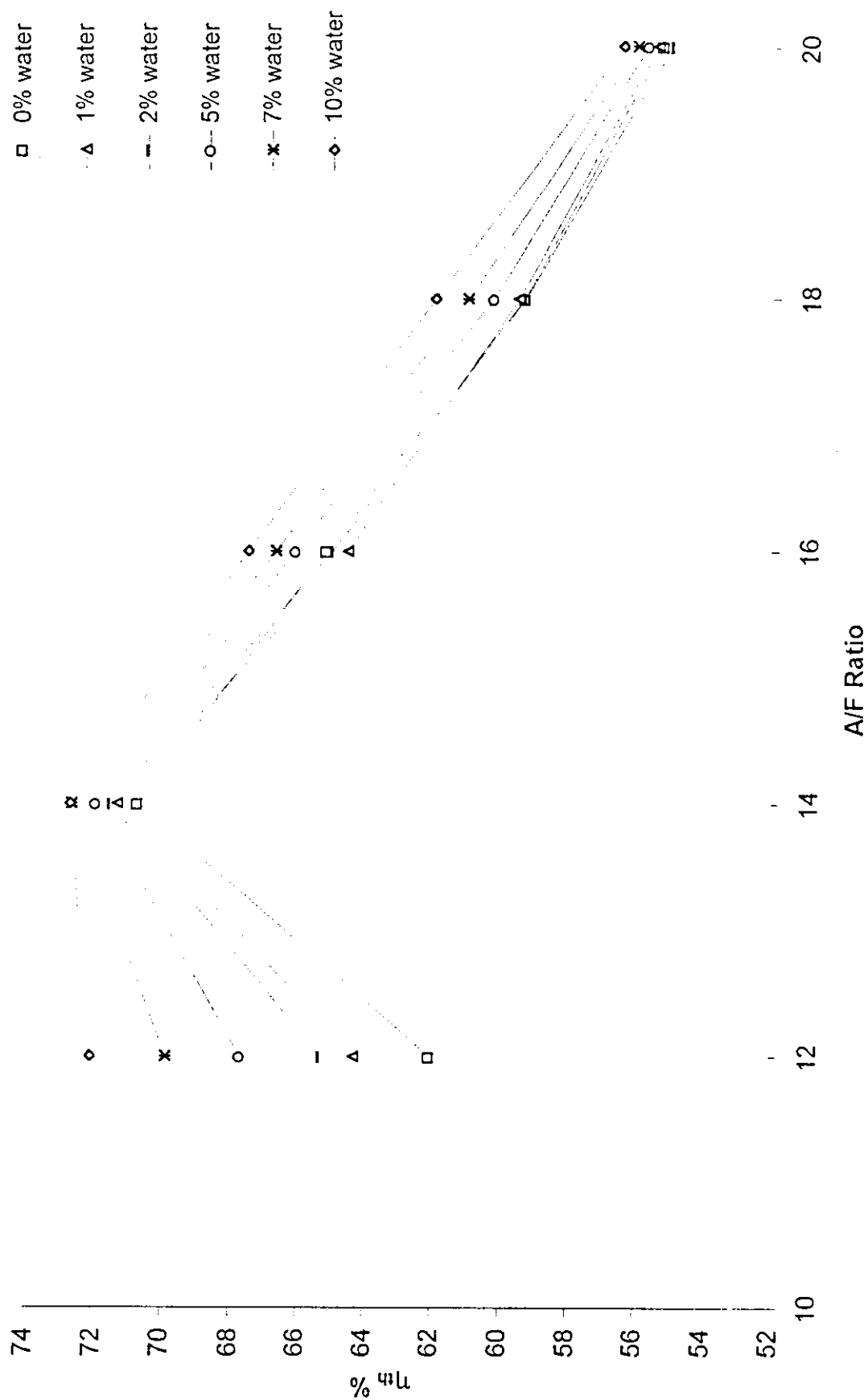
Figure (5.3) Combustion efficiency $\left(\eta_{th}\right)$ versus air fuel ratio for different percentages of water added in the emulsion.
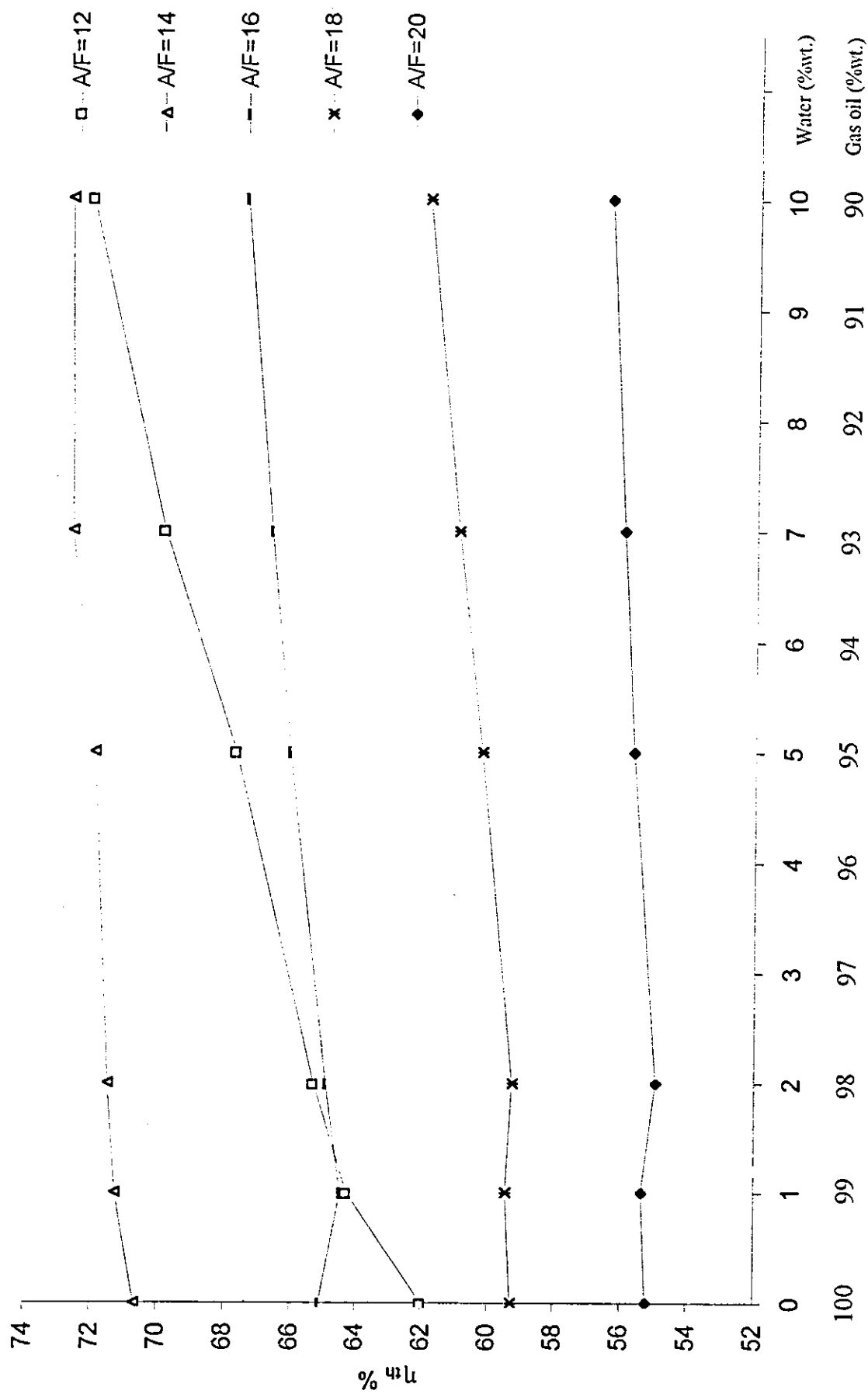
**Figure (5.4) Combustion efficiency ($\eta_{th}$) versus percentage of water in the emulsion for different values of air fuel ratios.**
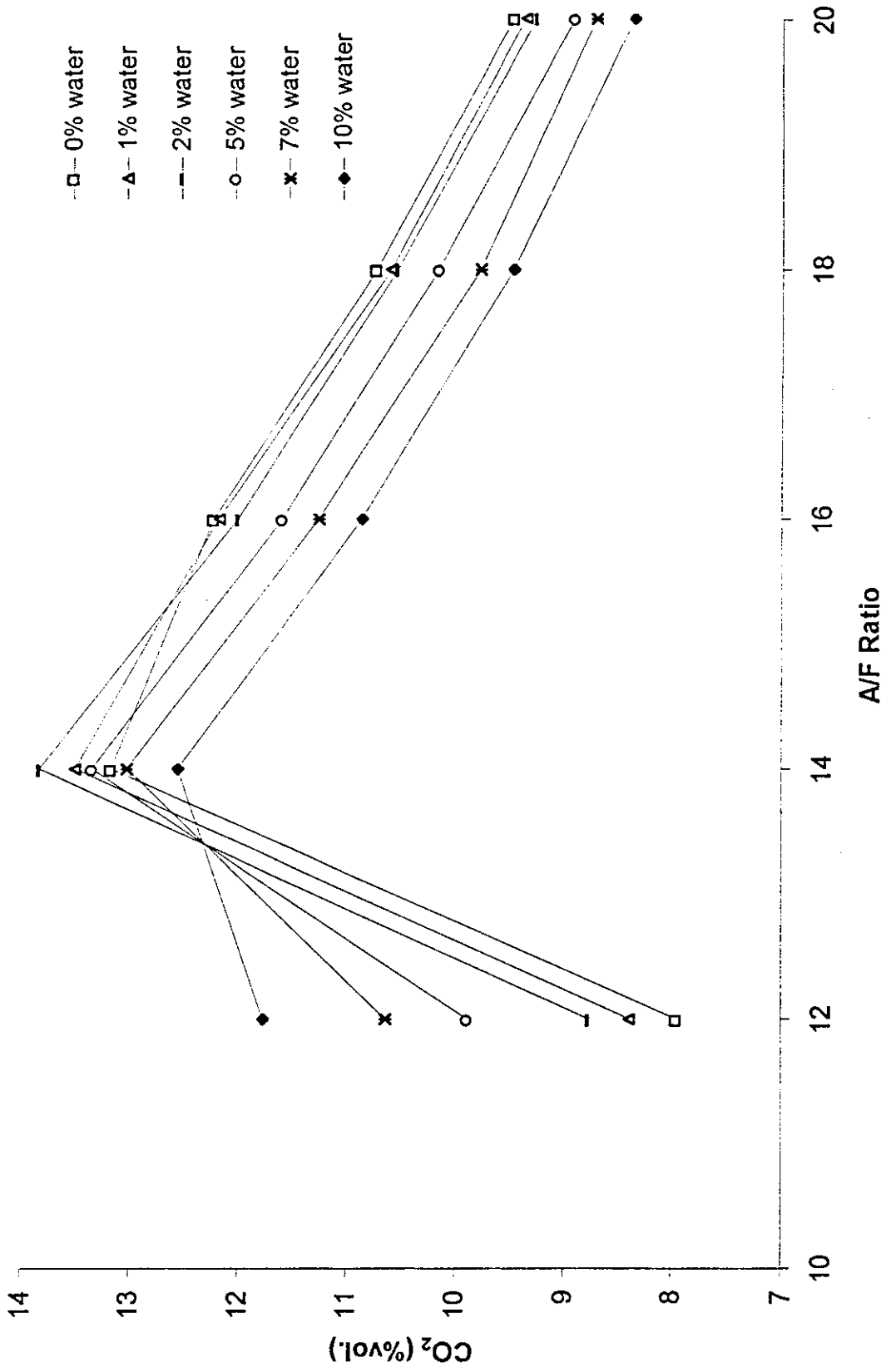
**Figure (5.5) Carbon dioxide (CO₂) versus air fuel ratio for different percentage of water in the emulsion.**
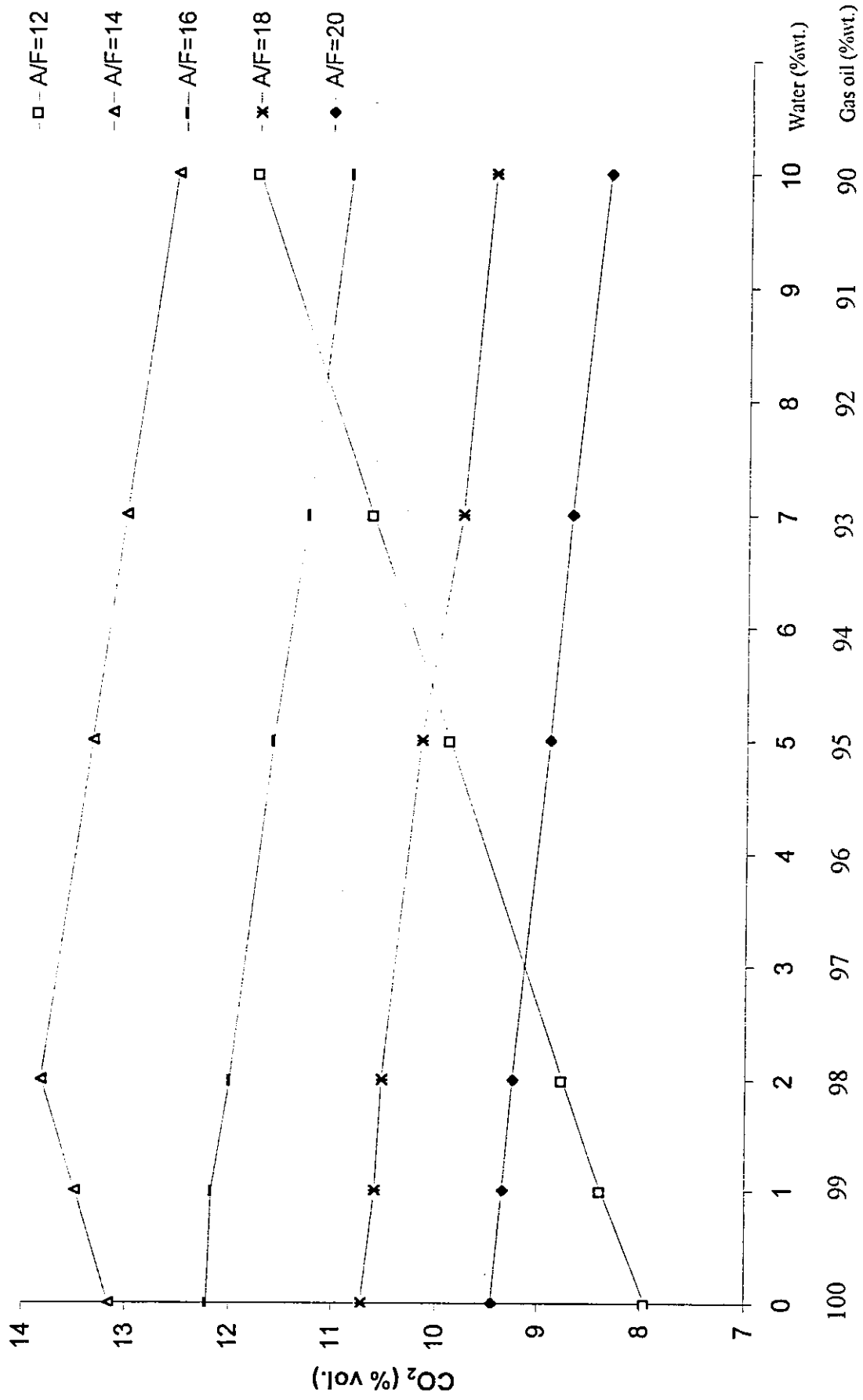
**Figure (5.6) Carbon dioxide (CO₂) versus percentage of water added to the emulsion for different values of air fuel ratios.**
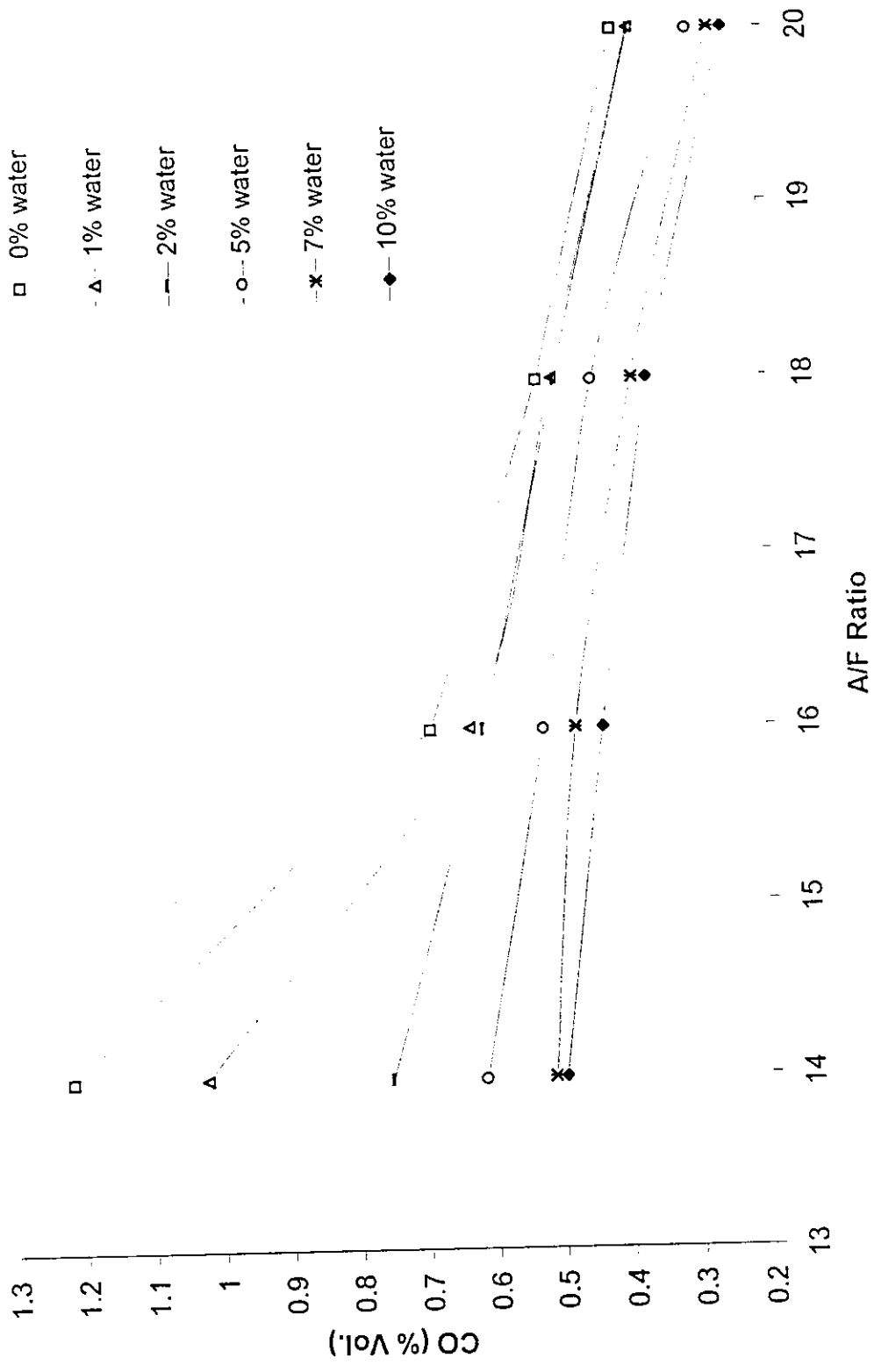
Figure (5.7) Carbon monoxide (CO) versus air fuel ratio for different percentages of water added to the emulsion.
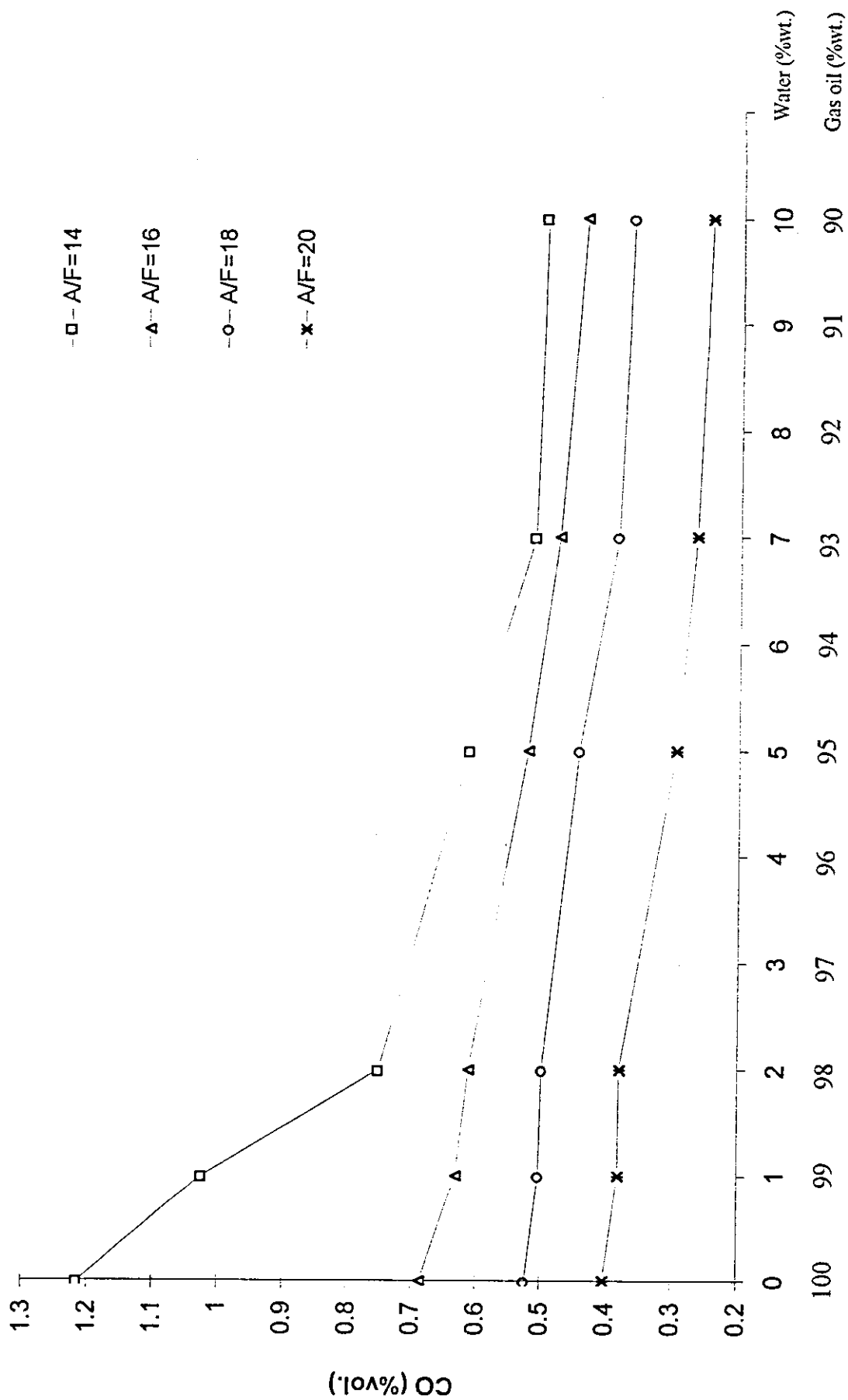
**Figure (5.8) Carbon monoxide (CO) versus percentage of water added to the emulsion for different values of air fuel ratios.**
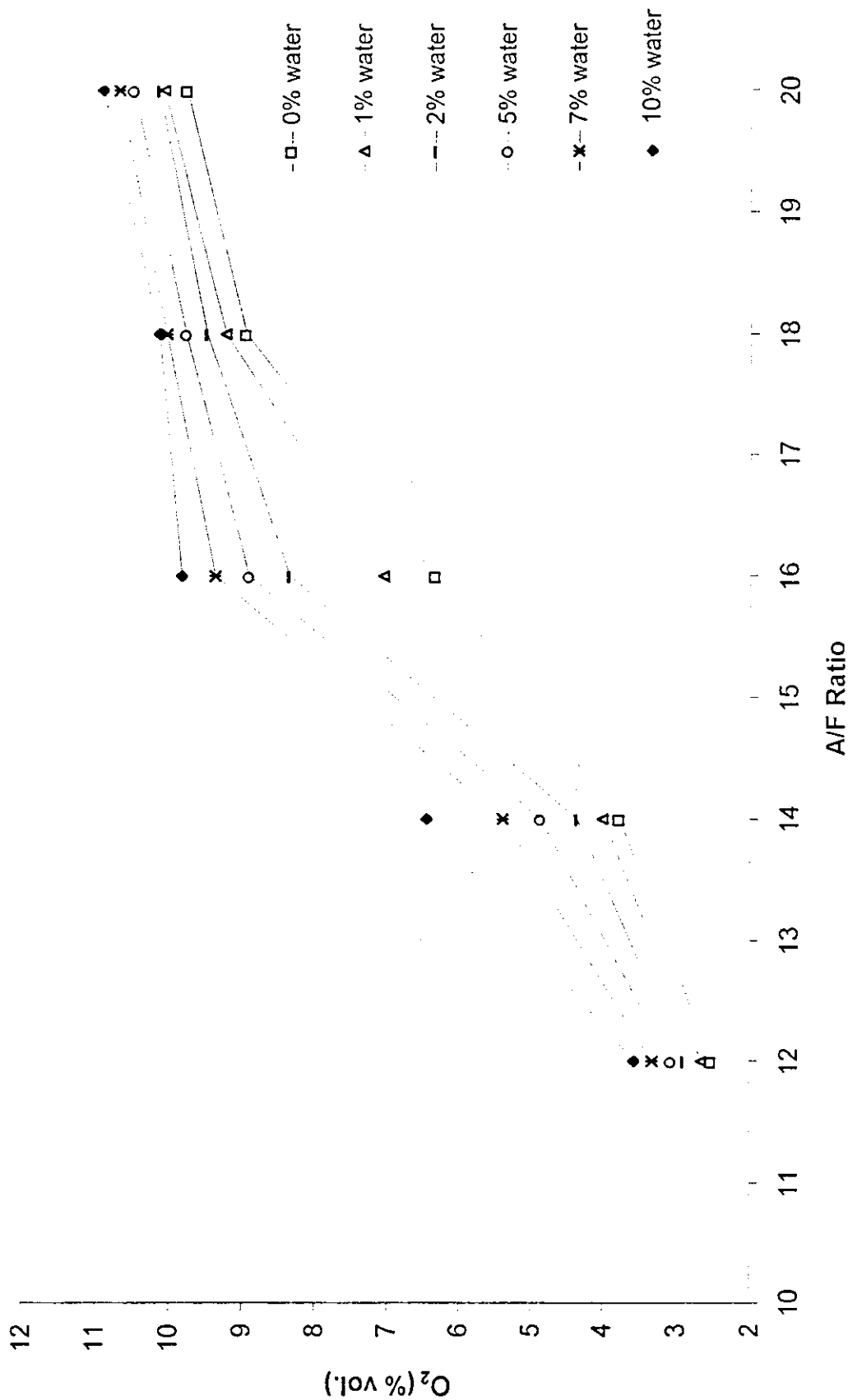
Figure (5.9) Oxygen (O₂) versus air fuel ratio for different percentages of water added to the emulsion.
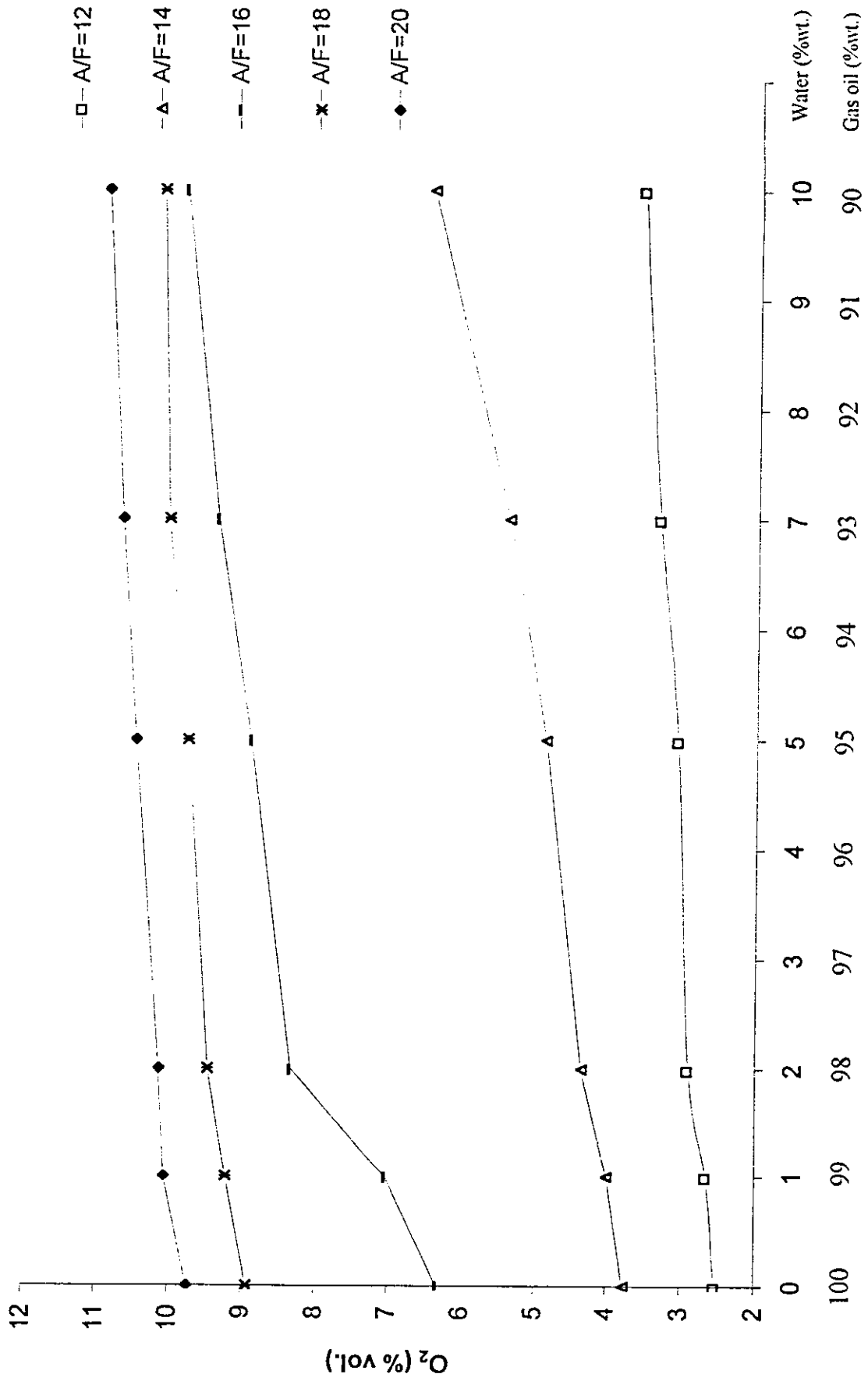
**Figure (5.10) Oxygen (O₂) versus percentage of water added to the emulsion for different values of air fuel ratios.**
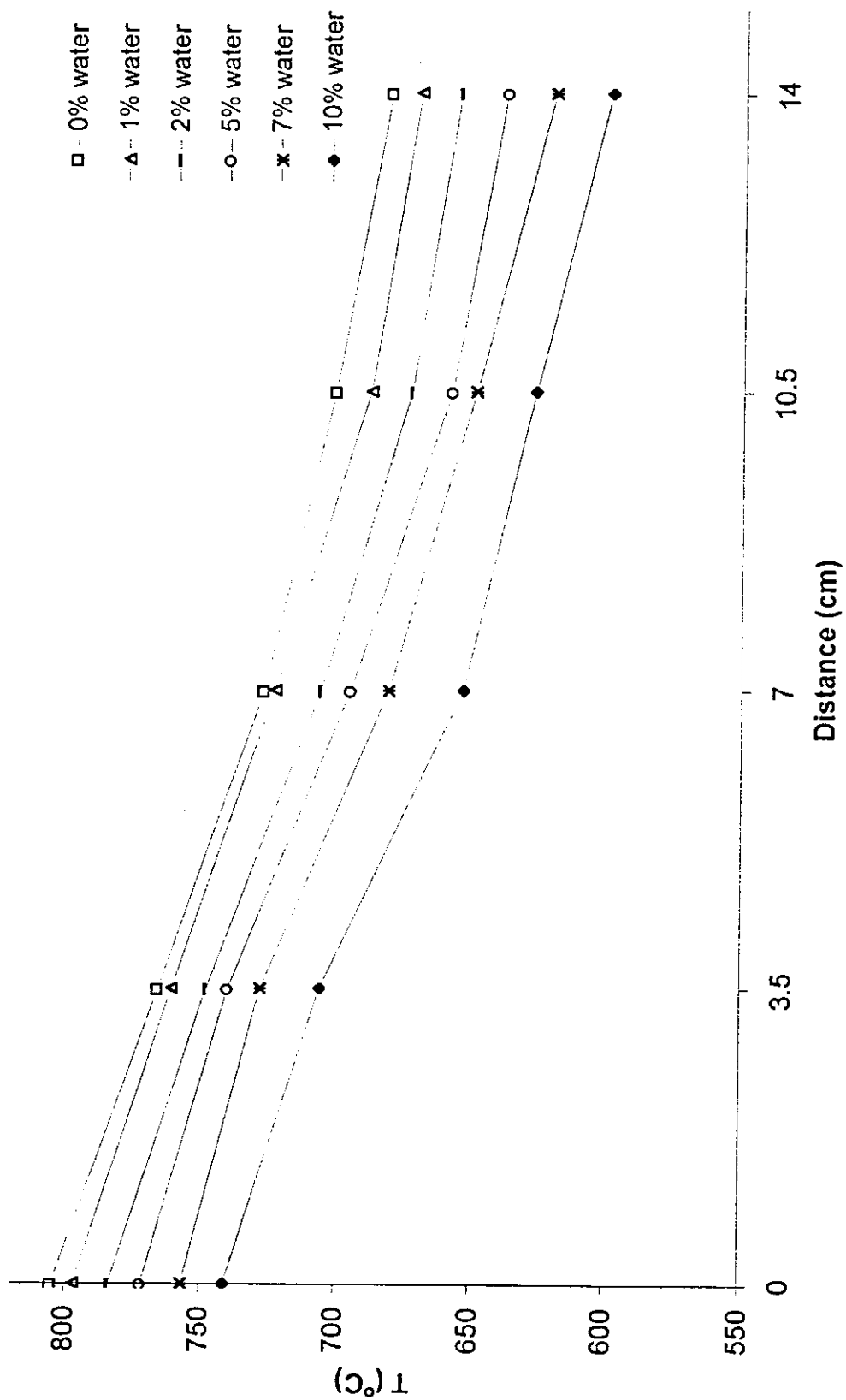
**Figure (5.11) Temperature distribution for the flame versus distance between the thermocouples at A/F=20.**
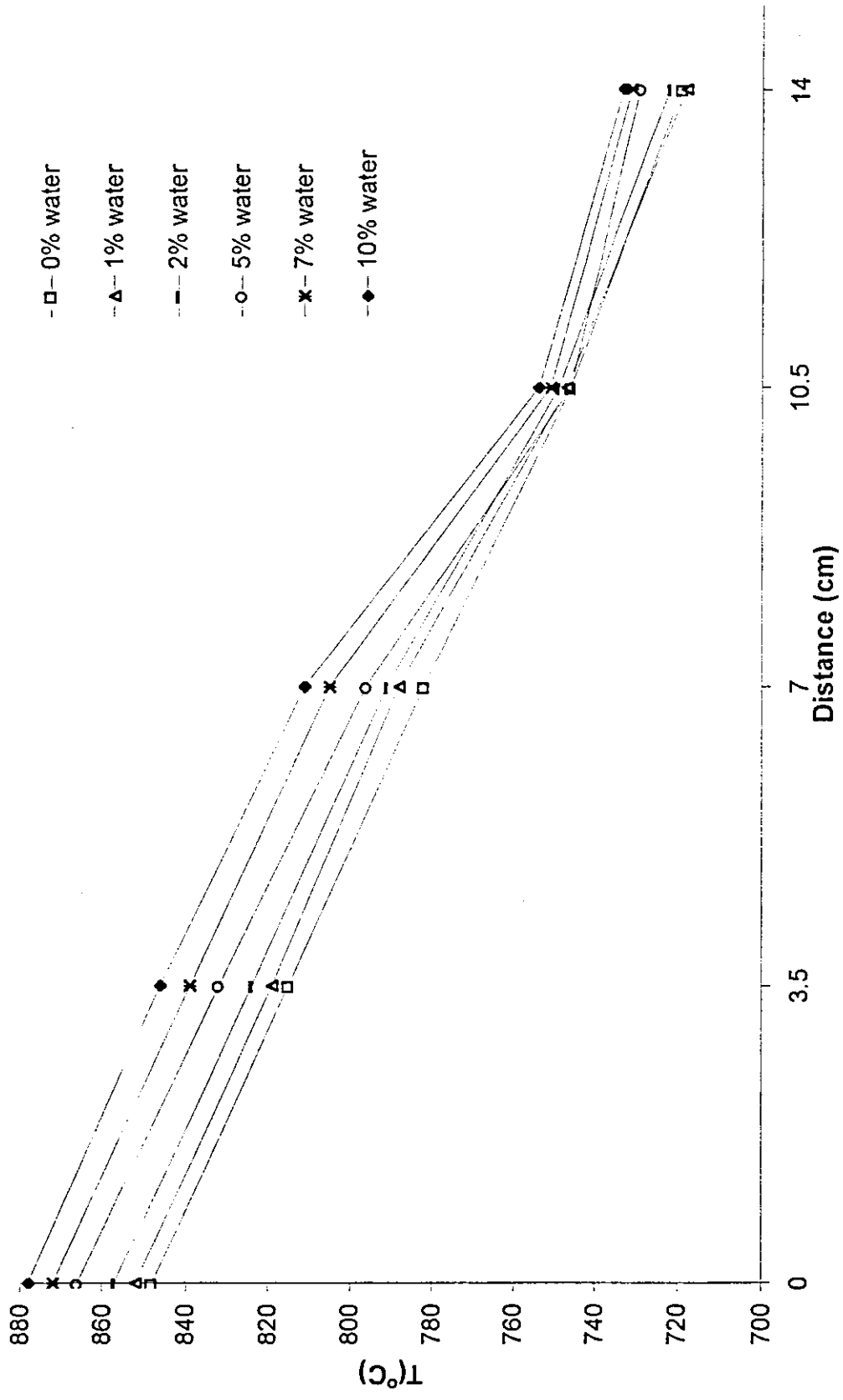
**Figure (5.12) Temperature distribution for the flame versus distance between the thermocouples at A/F=12.**

# Chapter Six

# CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Conclusions

1. Combustion and thermal efficiencies increase with the increase of water added to gas oil as an emulsion, the maximum amount of water added was 10 %wt.

2. Related to the emulsion sample, carbon dioxide percentage by volume decrease with increasing the amount of water added for excess air, while for insufficient air the $CO_2$ percentage increase with increasing the water addition.

3. Related to the emulsion sample, carbon monoxide percentage decreases with increasing the water amount in the emulsion, related to the emulsion sample.

4. Related to the emulsion sample, oxygen percentage increases with increasing the water amount in the emulsion

5. The temperature distribution along the combustion chamber decrease with adding water for excess air, while increase with adding water for the insufficient air.

## 5.2 Recommendations

1. Studying the effects of adding more than 10 %wt. of water, and finding the optimum value for water added to the emulsion. Which was not applicable due to the combustion setup used in the experiments.

2. Using different emulsifying agent, and study the effect of add these agents on the emulsion stability and combustion process.

3. Study the effect of add water on other types of fuels, such as fuel oil.

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# Appendix (A)

## SAMPLE CALCULATION

The sample of calculations will be taken for an emulsion of 1% water and 99% gas oil by weight, with an A/F ratio equals 14 (Experiment 2).

| $\dot{m}_w = 400$ g/s | $\dot{m}_a = 67.032$ kg/hr | $\dot{m}_{em} = 1.33$ g/s | $CV_e = 42568$ J/g |
|---|---|---|---|
| $T_{w(in)} = 21\ ^\circ C$ | $T_{w(out)} = 45.3\ ^\circ C$ | $T_{a(in)} = 46.8\ ^\circ C$ | $T_{a(out)} = 658\ ^\circ C$ |
| $Cp_{w(in)} = 4.181325$ | $Cp_{w(out)} = 4.179005$ | $Cp_{a(in)} = 1.007442$ | $Cp_{a(out)} = 1.12743$ |

The gas oil analysis can be seen in table (4.1) in chapter Four by weight, as following (% wt.):

C =82.75% , H$_2$=13.9% , O$_2$=1.8%

N$_2$=0.48% , S =1.07%.

For 99% gas oil by weight, each element should be correct to a new value by multiply by 0.99. The new values then become (% wt.):

C =81.9225% , H$_2$=13.761% , O$_2$=1.782%

N$_2$=0.4752% , S =1.0593%.

- **Calculation of the theoretical Air/Fuel Ratio(A/F$_{st}$)**

$$\left(\frac{A}{F}\right)_{st} = \frac{2.66C + 7.94H_2 + 0.998S - O_2}{0.232}$$

$$\left(\frac{A}{F}\right)_{st} = \frac{2.66(0.81923) + 7.94(0.13761) + 0.998(0.010593) - (0.01782)}{0.232}$$

Thus $\left(\dfrac{A}{F}\right)_{st} = 14.07118.$

- **Calculation of the thermal efficiency**

$$\eta_{th} = \frac{Q_w}{Q_{cv} + Q_a}$$

Where $Q_w = \dot{m}_w \overline{Cp}_w \left(T_{w(out)} - T_{w(in)}\right)$

$$\overline{Cp}_w = \frac{Cp_{w(in)} - Cp_{w(out)}}{2} = \frac{(4.181325 + 4.179005)}{2} = 4.180165 \ \text{kJ/kg.K.}$$

$Q_w = 400 * 4.180165(45.3 - 21)$

$Q_w = 40.6312 \ \text{kJ/s.}$

$$Q_{cv} = \dot{m}_e * CV_e = \frac{1.33 * 42568}{1000}$$

$Q_{cv} = 56.61544 \ \text{kJ/s.}$

$Q_a = \dot{m}_a \overline{Cp}_a (T_{a(in)} - T_{a(ref)})$

Note: the subscript (ref) here refers to 25 °C temperature.

$$\overline{Cp}_a = \frac{Cp_{a(in)} + Cp_{a(ref)}}{2} = \frac{1.007442 + 1.00708}{2} = 1.007261 \ \text{kJ/kg.K.}$$

$Q_a = (\dfrac{67.032}{3.6})(1.007261)(46.8 - 25) = 0.408864 \ \text{kJ/s.}$

$\therefore \ \eta_{th} = \dfrac{40.6312}{(56.61544 + 0.408864)} = 71.25243 \ \%.$

- **Calculation of the combustion efficiency**

$$\eta_{comb} = \frac{Q_w + Q_{pro}}{Q_{cv} + Q_a}$$

Where:

$Q_w$, $Q_a$ and $Q_{cv}$ were calculated in the previous paragraph.

$$Q_{pro} = (\dot{m}_a + \dot{m}_e)\overline{Cp}_a(T_{a(out)} - T_{a(in)})$$

$$\overline{Cp}_a = \frac{Cp_{a(in)} + Cp_{a(out)}}{2} = \frac{(1.007442 + 1.12743)}{2} = 1.067436 \text{ J/kg.K.}$$

$$Q_{pro} = (\frac{67.032}{3.6} + 1.33)(1.067436)(658-46.8) = 13.01572 \text{ kJ/s.}$$

$$\eta_{comb} = \frac{(40.6312) + (13.01572)}{(56.61544) + (0.408864)} = 94.0773\%.$$

# Appendix (B)

## RESULTS TABLES

### Experiment 1

Table (B.1) Fuel, air, water mass flow rates and water, air inlet and outlet temperatures (pure gas oil).

| Run # | Air/Fuel Ratio | $\dot{m}_f$ (g/s) | $\dot{m}_a$ (kg/hr) | $\dot{m}_w$ (g/s) | $T_{w(in)}$ °C | $T_{w(out)}$ °C | $T_{a(in)}$ °C | $T_{a(out)}$ °C |
|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 1.33 | 57.456 | 400 | 20.5 | 41.9 | 47.5 | 602 |
| 2 | 14 | 1.33 | 67.032 | 400 | 20.3 | 44.7 | 46 | 656 |
| 3 | 16 | 1.33 | 76.608 | 400 | 20.2 | 42.7 | 45.6 | 608 |
| 4 | 18 | 1.33 | 86.184 | 400 | 20 | 40.5 | 44.7 | 576 |
| 5 | 20 | 1.33 | 95.76 | 400 | 19.7 | 38.8 | 43.7 | 552 |

Table (B.2) Flame temperatures, $CO_2$, CO, and $O_2$ %vol. (pure gas oil).

| Run # | Air/Fuel Ratio | $T_{(1)}$ °C | $T_{(2)}$ °C | $T_{(3)}$ °C | $T_{(4)}$ °C | $T_{(5)}$ °C | $CO_2$ %Vol. | CO %Vol. | $O_2$ %Vol. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 848 | 815 | 782 | 746 | 719 | 7.9512 | 8.9851 | 2.521 |
| 2 | 14 | 884 | 841 | 816 | 795 | 730 | 13.157 | 1.2147 | 3.765 |
| 3 | 16 | 876 | 830 | 806 | 779 | 723 | 12.214 | 0.6874 | 6.3235 |
| 4 | 18 | 821 | 796 | 753 | 720 | 698 | 10.715 | 0.5231 | 8.9329 |
| 5 | 20 | 805 | 766 | 727 | 701 | 681 | 9.4521 | 0.4033 | 9.7439 |

Table (B.3) Fuel, water, products, and inlet air energies (pure gas oil).

| Run # | Air/Fuel Ratio | $Q_{cv}$ (kJ/s) | $Q_w$ (kJ/s) | $Q_{pro}$ (kJ/s) | $Q_a$ (kJ/s) | $\eta_{th}$ % | $\eta_{comb}$ % |
|---|---|---|---|---|---|---|---|
| 1 | 12 | 57.34295 | 35.7806 | 10.17689 | 0.361712 | 62.00644 | 79.6426 |
| 2 | 14 | 57.34295 | 40.8 | 12.9875 | 0.393855 | 70.6655 | 93.15982 |
| 3 | 16 | 57.34295 | 37.62138 | 13.50578 | 0.441544 | 65.10636 | 88.47903 |
| 4 | 18 | 57.34295 | 34.2763 | 14.21244 | 0.475028 | 59.28312 | 83.86447 |
| 5 | 20 | 57.34295 | 31.93546 | 14.98982 | 0.50101 | 55.20967 | 81.12391 |

## Experiment 2

Table (B.4)  Emulsion, air, water mass flow rates and water, air inlet and outlet temperatures (emulsion with 1% water).

| Run # | Air/Fuel Ratio | $\dot{m}_e$ (g/s) | $\dot{m}_a$ (kg/hr) | $\dot{m}_w$ (g/s) | $T_{w(in)}$ °C | $T_{w(out)}$ °C | $T_{a(in)}$ °C | $T_{a(out)}$ °C |
|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 1.33 | 57.456 | 400 | 20.9 | 42.8 | 47.5 | 609 |
| 2 | 14 | 1.33 | 67.032 | 400 | 21 | 45.3 | 46.8 | 658 |
| 3 | 16 | 1.33 | 76.608 | 400 | 21.1 | 43.1 | 46.1 | 605 |
| 4 | 18 | 1.33 | 86.184 | 400 | 21.3 | 41.6 | 44.3 | 568 |
| 5 | 20 | 1.33 | 95.76 | 400 | 21.3 | 40.2 | 42.5 | 546 |

Table (B.5) Flame temperatures, $CO_2$, CO, and $O_2$ %vol. (emulsion with 1% water).

| Run # | Air/Fuel Ratio | $T_{(1)}$ °C | $T_{(2)}$ °C | $T_{(3)}$ °C | $T_{(4)}$ °C | $T_{(5)}$ °C | $CO_2$ %Vol. | CO %Vol. | $O_2$ %Vol. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 852 | 819 | 788 | 747 | 718 | 8.3865 | 8.4236 | 2.6548 |
| 2 | 14 | 893 | 853 | 837 | 828 | 809 | 13.488 | 1.0229 | 3.996 |
| 3 | 16 | 864 | 822 | 796 | 768 | 719 | 12.168 | 0.6312 | 7.0345 |
| 4 | 18 | 814 | 785 | 744 | 712 | 690 | 10.587 | 0.5033 | 9.2154 |
| 5 | 20 | 797 | 761 | 723 | 688 | 670 | 9.3456 | 0.3813 | 10.054 |

Table (B.6) Fuel, water, products, and inlet air energies (emulsion with 1% water).

| Run # | Air/Fuel Ratio | $Q_{cv}$ (kJ/s) | $Q_w$ (kJ/s) | $Q_{pro}$ (kJ/s) | $Q_a$ (kJ/s) | $\eta_{th}$ % | $\eta_{comb}$ % |
|---|---|---|---|---|---|---|---|
| 1 | 12 | 56.61544 | 36.61617 | 10.31276 | 0.361712 | 64.26466 | 82.36447 |
| 2 | 14 | 56.61544 | 40.6312 | 13.01572 | 0.408864 | 71.25243 | 94.0773 |
| 3 | 16 | 56.61544 | 36.78306 | 13.4177 | 0.452264 | 64.45513 | 87.96702 |
| 4 | 18 | 56.61544 | 33.9391 | 13.99719 | 0.46538 | 59.45798 | 83.97969 |
| 5 | 20 | 56.61544 | 31.59764 | 14.83842 | 0.468852 | 55.3526 | 81.34647 |

## Experiment 3

Table (B.7) Emulsion, air, water mass flow rates and water, air inlet and outlet temperatures (emulsion with 2% water).

| Run # | Air/Fuel Ratio | $\dot{m}_e$ (g/s) | $\dot{m}_a$ (kg/hr) | $\dot{m}_w$ (g/s) | $T_{w(in)}$ °C | $T_{w(out)}$ °C | $T_{a(in)}$ °C | $T_{a(out)}$ °C |
|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 1.33 | 57.456 | 400 | 20.2 | 42.2 | 45 | 615 |
| 2 | 14 | 1.33 | 67.032 | 400 | 19.3 | 43.4 | 43.9 | 654 |
| 3 | 16 | 1.33 | 76.608 | 400 | 20 | 41.9 | 42.8 | 594 |
| 4 | 18 | 1.33 | 86.184 | 400 | 20.2 | 40.2 | 42.1 | 560 |
| 5 | 20 | 1.33 | 95.76 | 400 | 20.15 | 38.7 | 41 | 542 |

Table (B.8) Flame temperatures, $CO_2$, CO, and $O_2$ %vol. (emulsion with 2% water).

| Run # | Air/Fuel Ratio | $T_{(1)}$ °C | $T_{(2)}$ °C | $T_{(3)}$ °C | $T_{(4)}$ °C | $T_{(5)}$ °C | $CO_2$ %Vol. | CO %Vol. | $O_2$ %Vol. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 857 | 824 | 791 | 749 | 722 | 8.7623 | 7.8815 | 2.897 |
| 2 | 14 | 890 | 851 | 833 | 822 | 805 | 13.821 | 0.7512 | 4.351 |
| 3 | 16 | 858 | 818 | 787 | 760 | 708 | 11.995 | 0.6122 | 8.3379 |
| 4 | 18 | 799 | 772 | 732 | 701 | 677 | 10.525 | 0.4986 | 9.4651 |
| 5 | 20 | 784 | 748 | 706 | 673 | 655 | 9.2461 | 0.3796 | 10.129 |

Table (B.9) Fuel, water, products, and inlet air energies (emulsion with 2% water).

| Run # | Air/Fuel Ratio | $Q_{cv}$ (kJ/s) | $Q_w$ (kJ/s) | $Q_{pro}$ (kJ/s) | $Q_a$ (kJ/s) | $\eta_{th}$ % | $\eta_{comb}$ % |
|---|---|---|---|---|---|---|---|
| 1 | 12 | 56.02492 | 36.78494 | 10.4749 | 0.32151 | 65.28353 | 83.8737 |
| 2 | 14 | 56.02492 | 40.30052 | 12.98674 | 0.354459 | 71.48095 | 94.51551 |
| 3 | 16 | 56.02492 | 36.61812 | 13.21725 | 0.381513 | 64.91834 | 88.3505 |
| 4 | 18 | 56.02492 | 33.43955 | 13.82997 | 0.41232 | 59.25087 | 83.75592 |
| 5 | 20 | 56.02492 | 31.01461 | 14.75807 | 0.428657 | 54.93826 | 81.08022 |

## Experiment 4

Table (B.10) Emulsion, air, water mass flow rates and water, air inlet and outlet temperatures (emulsion with 5% water).

| Run # | Air/Fuel Ratio | $\dot{m}_e$ (g/s) | $\dot{m}_a$ (kg/hr) | $\dot{m}_w$ (g/s) | $T_{w(in)}$ °C | $T_{w(out)}$ °C | $T_{a(in)}$ °C | $T_{a(out)}$ °C |
|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 1.33 | 57.456 | 400 | 20 | 42.1 | 47.1 | 620 |
| 2 | 14 | 1.33 | 67.032 | 400 | 19.8 | 43.3 | 46.2 | 649 |
| 3 | 16 | 1.33 | 76.608 | 400 | 19.7 | 41.3 | 44.7 | 575 |
| 4 | 18 | 1.33 | 86.184 | 400 | 19.8 | 39.5 | 43.5 | 547 |
| 5 | 20 | 1.33 | 95.76 | 400 | 19.8 | 38 | 41.2 | 527 |

Table (B.11) Flame temperatures, $CO_2$, CO, and $O_2$ %vol. (emulsion with 5% water).

| Run # | Air/Fuel Ratio | $T_{(1)}$ °C | $T_{(2)}$ °C | $T_{(3)}$ °C | $T_{(4)}$ °C | $T_{(5)}$ °C | $CO_2$ %Vol. | CO %Vol. | $O_2$ %Vol. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 866 | 832 | 796 | 746 | 729 | 9.8792 | 6.318 | 3.058 |
| 2 | 14 | 886 | 846 | 831 | 815 | 796 | 13.332 | 0.6132 | 4.859 |
| 3 | 16 | 840 | 799 | 765 | 737 | 692 | 11.588 | 0.5217 | 8.8922 |
| 4 | 18 | 775 | 758 | 717 | 684 | 662 | 10.151 | 0.4427 | 9.7543 |
| 5 | 20 | 772 | 740 | 695 | 658 | 638 | 8.8956 | 0.2955 | 10.46 |

Table (B.12) Fuel, water, products, and inlet air energies (emulsion with 5% water).

| Run # | Air/Fuel Ratio | $Q_{cv}$ (kJ/s) | $Q_w$ (kJ/s) | $Q_{pro}$ (kJ/s) | $Q_a$ (kJ/s) | $\eta_{th}$ % | $\eta_{comb}$ % |
|---|---|---|---|---|---|---|---|
| 1 | 12 | 54.26799 | 36.95269 | 10.53384 | 0.355279 | 67.65008 | 86.93461 |
| 2 | 14 | 54.26799 | 39.29534 | 12.8255 | 0.397607 | 71.88312 | 95.34487 |
| 3 | 16 | 54.26799 | 36.11699 | 12.69112 | 0.422247 | 66.0392 | 89.24466 |
| 4 | 18 | 54.26799 | 32.93871 | 13.42686 | 0.446085 | 60.20153 | 84.74157 |
| 5 | 20 | 54.26799 | 30.43008 | 14.2869 | 0.434016 | 55.62882 | 81.7465 |

## Experiment 5

Table (B.13) Emulsion, air, water mass flow rates and water, air inlet and outlet temperatures (emulsion with 7% water).

| Run # | Air/Fuel Ratio | $\dot{m}_e$ (g/s) | $\dot{m}_a$ (kg/hr) | $\dot{m}_w$ (g/s) | $T_{w(in)}$ °C | $T_{w(out)}$ °C | $T_{a(in)}$ °C | $T_{a(out)}$ °C |
|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 1.33 | 57.456 | 400 | 19.9 | 42.2 | 44 | 626 |
| 2 | 14 | 1.33 | 67.032 | 400 | 19.8 | 43 | 43.4 | 631 |
| 3 | 16 | 1.33 | 76.608 | 400 | 19.8 | 41.1 | 42.5 | 552 |
| 4 | 18 | 1.33 | 86.184 | 400 | 20 | 39.5 | 41.6 | 529 |
| 5 | 20 | 1.33 | 95.76 | 400 | 19.9 | 37.8 | 40.1 | 504 |

Table (B.14) Flame temperatures, $CO_2$, CO, and $O_2$ %vol. (emulsion with 7% water).

| Run # | Air/Fuel Ratio | $T_{(1)}$ °C | $T_{(2)}$ °C | $T_{(3)}$ °C | $T_{(4)}$ °C | $T_{(5)}$ °C | $CO_2$ %Vol. | CO %Vol. | $O_2$ %Vol. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 872 | 839 | 805 | 751 | 731 | 10.634 | 5.2715 | 3.321 |
| 2 | 14 | 880 | 840 | 825 | 797 | 756 | 13.012 | 0.5127 | 5.3869 |
| 3 | 16 | 823 | 774 | 748 | 715 | 670 | 11.249 | 0.4754 | 9.3582 |
| 4 | 18 | 761 | 735 | 702 | 669 | 645 | 9.765 | 0.3856 | 10.021 |
| 5 | 20 | 757 | 728 | 681 | 649 | 620 | 8.6984 | 0.2664 | 10.658 |

Table (B.15) Fuel, water, products, and inlet air energies (emulsion with 7% water).

| Run # | Air/Fuel Ratio | $Q_{cv}$ (kJ/s) | $Q_w$ (kJ/s) | $Q_{pro}$ (kJ/s) | $Q_a$ (kJ/s) | $\eta_{th}$ % | $\eta_{comb}$ % |
|---|---|---|---|---|---|---|---|
| 1 | 12 | 53.08961 | 37.2875 | 10.70716 | 0.30543 | 69.83327 | 89.88598 |
| 2 | 14 | 53.08961 | 38.79342 | 12.47943 | 0.345079 | 72.59969 | 95.95423 |
| 3 | 16 | 53.08961 | 35.61492 | 12.16308 | 0.375082 | 66.6139 | 89.36365 |
| 4 | 18 | 53.08961 | 32.60374 | 12.97172 | 0.400261 | 60.95312 | 85.20392 |
| 5 | 20 | 53.08961 | 29.92816 | 13.60793 | 0.404541 | 55.94661 | 81.38478 |

## Experiment 6

Table (B.16) Emulsion, air, water mass flow rates and water, air inlet and outlet temperatures (emulsion with 10% water).

| Run # | Air/Fuel Ratio | $\dot{m}_e$ (g/s) | $\dot{m}_a$ (kg/hr) | $\dot{m}_w$ (g/s) | $T_{w(in)}$ °C | $T_{w(out)}$ °C | $T_{a(in)}$ °C | $T_{a(out)}$ °C |
|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 1.33 | 57.456 | 400 | 19.7 | 42 | 44.8 | 628 |
| 2 | 14 | 1.33 | 67.032 | 400 | 19 | 41.5 | 43.5 | 612 |
| 3 | 16 | 1.33 | 76.608 | 400 | 18.7 | 39.6 | 42.6 | 528 |
| 4 | 18 | 1.33 | 86.184 | 400 | 18.7 | 37.9 | 42 | 507 |
| 5 | 20 | 1.33 | 95.76 | 400 | 18.5 | 36 | 41.5 | 490 |

Table (B.17) Flame temperatures, $CO_2$, CO, and $O_2$ %vol. (emulsion with 10% water).

| Run # | Air/Fuel Ratio | $T_{(1)}$ °C | $T_{(2)}$ °C | $T_{(3)}$ °C | $T_{(4)}$ °C | $T_{(5)}$ °C | $CO_2$ %Vol. | CO %Vol. | $O_2$ %Vol. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 878 | 846 | 811 | 754 | 733 | 11.765 | 3.7699 | 3.564 |
| 2 | 14 | 868 | 826 | 813 | 779 | 738 | 12.542 | 0.4962 | 6.4434 |
| 3 | 16 | 801 | 749 | 726 | 696 | 646 | 10.851 | 0.4354 | 9.8124 |
| 4 | 18 | 740 | 716 | 681 | 647 | 622 | 9.4651 | 0.3645 | 10.121 |
| 5 | 20 | 741 | 706 | 653 | 627 | 599 | 8.3475 | 0.2461 | 10.879 |

Table (B.18) Fuel, water, products, and inlet air energies (emulsion with 10% water).

| Run # | Air/Fuel Ratio | $Q_{cv}$ (kJ/s) | $Q_w$ (kJ/s) | $Q_{pro}$ (kJ/s) | $Q_a$ (kJ/s) | $\eta_{th}$ % | $\eta_{comb}$ % |
|---|---|---|---|---|---|---|---|
| 1 | 12 | 51.44174 | 37.28799 | 10.7315 | 0.318294 | 72.04012 | 92.77329 |
| 2 | 14 | 51.44174 | 37.62441 | 12.0507 | 0.346955 | 72.64986 | 95.91883 |
| 3 | 16 | 51.44174 | 34.94871 | 11.55752 | 0.377226 | 67.44387 | 89.74752 |
| 4 | 18 | 51.44174 | 32.10527 | 12.34553 | 0.409908 | 61.91756 | 85.72689 |
| 5 | 20 | 51.44174 | 29.26275 | 13.13576 | 0.442055 | 56.40055 | 81.71821 |

## Calorific values for the emulsions ($CV_e$)

The experiments based in a value of the calorific value in each run, these values can be seen in table (B.19).

Table (B.19) Calorific values for the different emulsions used in the experiments.

| Water percentage in Emulsion (%wt.) | Calorific Value ($CV_e$) (J/g) |
|---|---|
| 0 | 43115 |
| 1 | 42568 |
| 2 | 42124 |
| 5 | 40803 |
| 7 | 39917 |
| 10 | 38678 |

## Stoichiometric (Theoretical) air fuel ratio $(A/F)_{st}$

The following table shows the theoretical air fuel ratio for the different emulsions used in this work.

Table (B.20) Stoichiometric (theoretical) air fuel ratio for different water percentages in emulsion.

| Water percentage in Emulsion (%wt.) | $(A/F)_{st}$ |
|---|---|
| 0 | 14.21331293 |
| 1 | 14.0711798 |
| 2 | 13.92904667 |
| 5 | 13.50264728 |
| 7 | 13.21838103 |
| 10 | 12.79198164 |

## Specific heat for air and water (*Cp*).

The specific heat for air and water vary with temperature, So it is important to calculate the value of the specific heat for both air and water at constant temperature.

Equation (B.1) and table (B.21) show the specific heat for water, while equation (B.2) and table (B.22) show the specific heat for air.

$$Cp_w = 4.218 - 3.31161\text{E-3}*T + 1.00622\text{E-4}*T^2 - 1.45826\text{E-6}*T^3$$
$$+ 1.09368\text{E-8}*T^4 - 3.12477\text{E-11}*T^5. \tag{B.1}$$

Note: *T* in the above equation in the °C.

Table (B.21) Specific heat at constant pressure for water (Duffie, 1991)

| *T* (°C) | *Cp_w* (kJ/kg.K) |
|---|---|
| 0 | 4.218 |
| 20 | 4.182 |
| 40 | 4.178 |
| 60 | 4.184 |
| 80 | 4.196 |
| 100 | 4.216 |

$$Cp_a = 1.00753 - 3.73811\text{E-5}*T + 8.05516\text{E-7}*T^2 - 1.02475\text{E-9}*T^3$$
$$+ 5.31806\text{E-13}*T^4 - 9.73852\text{E-17}*T^5. \tag{B.2}$$

Note: *T* in the above equation in the °C.

Table (B.22) Specific heat at constant pressure for air (Turns, 1996)

| T (°C) | *Cp_a* (kJ/kg.K) | T (°C) | *Cp_a* (kJ/kg.K) | T (°C) | *Cp_a* (kJ/kg.K) |
|---|---|---|---|---|---|
| 27 | 1.007 | 327 | 1.051 | 627 | 1.121 |
| 77 | 1.009 | 377 | 1.063 | 677 | 1.131 |
| 127 | 1.014 | 427 | 1.075 | 727 | 1.141 |
| 177 | 1.021 | 477 | 1.087 | 827 | 1.159 |
| 227 | 1.03 | 527 | 1.099 | 927 | 1.175 |
| 277 | 1.04 | 577 | 1.11 | 1027 | 1.189 |

## Physical properties of the gas oil

Table (B.23) Physical properties of the gas oil. [*]

| | |
|---|---|
| Density @ 15 °C | 0.84 gm/ml. |
| Total Sulfur | 1.07 %wt. |
| Flash Point P.M | 67 °C |
| Viscosity Red wood at 100 F | 34.6 Sec |
| Pour Point | -6 °C |
| Ash | 0 %wt. |
| Water by distillation | Nil %vol. |
| Diesel index | 61.7 |

* Information in this table is from Jordan Petroleum refinery Co. LTD.

# ملخص

## تأثير تواجد الماء على كفاءة احتراق زيت الغاز

إعداد
طارق خليل راضي

المشرف
أ.د. محمد احمد حمدان

المشرف المشارك
د. يحيى حمد الخريشة

الهدف الرئيسي من هذا العمل هو دراسة عملية احتراق مستحلب مـــن المـــاء و زيـــت الغـــاز وذلـــك باستخدام حجرة احتراق مختبريه صغيرة.

تم استخدام نسب وزنية مختلفة من الماء هـــي 1%، 2%، 5%، 7% و 10% لتكويـــن المـــستحلب، و مقارنتها مع زيت الغاز النقي عند نسب مختلفة من الهواء و الوقود. لضمان اسـتقرار المـستحلب تـم استخدام طريقة خلط ميكانيكية لإعطاء مستوى عال من الاضطراب.

تم دراسة كفاءة الاحتراق و الكفاءة الحرارية، توزيع الحرارة على طـول الـشعلة، بالإضافـة لتحليـل الغازات العادمة. حيث أظهرت النتائج زيادة في كل من كفاءة الاحتراق و الكفاءة الحرارية وذلك بزيـادة نسبة الماء المضاف ضمن النسب المختلفة التي تمت دراستها.