# INFLUENCE OF COMPRESSION RATIO ON THE PERFORMANCE CHARACTERISTICS OF A SPARK IGNITION ENGINE

**By**

**AINA TOPE**

**DEPARTMENT OF MECHANICAL ENGINEERING**

**AHMADU BELLO UNIVERSITY, ZARIA**

**NIGERIA**

**FEBRUARY, 2012**

**INFLUENCE OF COMPRESSION RATIO ON THE PERFORMANCE CHARACTERISTICS OF A SPARK IGNITION ENGINE**

**BY**

**AINA TOPE**

**MSC/ENG/11404/2007-08**

**A THESIS SUBMITTED TO THE POST GRADUATE SCHOOL, AHMADU BELLO UNIVERSITY, ZARIA**

**IN PARTIAL FULFILMENT OF THE AWARD OF MASTERS OFSCIENCE IN MECHANICAL ENGINEERING (ENERGY)**

**MECHANICAL ENGINEERING DEPARMENT**

**FACULTY OF ENGINEERING**

**AHMADU BELLO UNIVERSITY**

**ZARIA**

**FEBRUARY, 2012**

## DECLARATION

I declare that the work in this thesis titled ‘’INFLUENCE OF COMPRESSION RATIO ON THE PERFORMANCE CHARACTERISTICS OF A SPARK IGNITION ENGINE’’ has been performed by me in the Department of Mechanical Engineeringunder the supervision of Prof. C.O. Folayan and Dr. G.Y. Pam.

The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this work has been presented for another degree or diploma at any university.

| | | |
|---|---|---|
| Aina, Tope | | |
| Name of student | (Signature) | (Date) |

## CERTIFICATION

This thesis entitled ''INFLUENCE OF COMPRESSION RATIO ON THE PERFORMANCE CHARACTERISTICS OF A SPARK IGNITION ENGINE'' by **Aina, Tope**meets the regulations governing the award of the degree of Master of Science ofAhmadu Bello University, Zaria, and is approved for its contribution to knowledge and literary presentation.

| | | | |
|---|---|---|---|
| Prof. C.O. Folayan<br>Committee | (Signature) | Chairman, Supervisory | _____<br>(Date) |
| Dr. G.Y. Pam<br>Member, Supervisory Committee | _____<br>(Signature) | | _____<br>(Date) |
| Dr. D.S. Yawas<br>Head of Department | _____<br>(Signature) | | _____<br>(Date) |
| Prof. A. A. Joshua<br>Dean, School of Postgraduate Studies | _____<br>(Signature) | | _____<br>(Date) |

## ACKNOWLEDGEMENTS

I give glory and honour to Almighty God for His immeasurable help at every time of my need. I thank God so much for seeing me through the course of this research.

I wish to express my profound gratitude to my able supervisors, Prof. C.O. Folayan and Dr. G.Y. Pam both of the department of Mechanical Engineering, Ahmadu Bello University, Zaria for their immense contributions and guidance in ensuring the successful completion of this research.

Special thanks to all my lecturers in Mechanical Engineering Department especially the head of department in the person of Dr. D.S. Yawas, Dr. F.O. Anafiand Dr. Mrs. R.B.O Suleiman (for her encouragement and support with the Engineering Equation Solver (EES) computer programme used in this research). Further, my sincere gratitude goes to all the non-academic staff of the department especially AlhajiShehuModele for all the valuable ideas and assistance in the departmental laboratory.

My appreciation goes to my brothers and sisters:Mr. AnthonyOluwasegunAina, Engr. ToyinAinaand Mrs. Beatrice MopelolaAdedayo. I also appreciate the efforts of my friends:Miss. ObiageliNnekaNze, Mr. Bakare Samuel and Kehinde Adebayo.

This section will lack completeness without mentioning my “parents”, Mrs. C.A. Akolo and Mr. J. Joriah

## ABSTRACT

The need to improve the performance characteristics of the gasoline engine has necessitated the present research. Increasing the compression ratio below detonating values to improve on the performance is an option. The compression ratio is a factor that influences the performance characteristics of internal combustion engines. This work is a an experimental and theoretical investigation of the influence of the compression ratio on the brake power, brake thermal efficiency, brake mean effective pressure and specific fuel consumption of aRicardo variable compression ratio spark ignition engine. A range of compression ratios of 5, 6, 7, 8 and 9, and engine speeds of1100 to 1600rpm, in increments of 100rpm, were utilised. The results showsthat as the compression ratio increases, the actual fuel consumption decreasesaveragely by 7.75%, brake thermal efficiency improves by 8.49 % and brake power also improves by 1.34%. The optimum compression ratio corresponding to maximum brake power, brake thermal efficiency, brake mean effective pressure and lowest specific fuel consumption is 9.The theoretical values were compared with experimental values. The grand averages of the percentage errorsbetween the theoretical and experimental valuesfor all the parameters were evaluated. The small values of the percentage errors between the theoretical and experimental values show that there is agreement between the theoretical and experimental performance characteristics of the engine.

## TABLE OF CONTENTS


| TITLE | PAGE |
|---|---|
| COVER PAGE . . . . . | i |
| TITLE PAGE . . . . . | iii |
| DECLARATION . . . . . | iv |
| CERTIFICATION . . . . . | v |
| ACKNOWLEDGEMENTS . . . . . | vi |
| ABSTRACT . . . . . | vii |
| TABLE OF CONTENTS . . . . . | viii |
| LIST OF FIGURES . . . . . | xiii |
| LIST OF TABLES . . . . . | xix |
| LIST OF PLATES . . . . . | xxiv |
| LIST OF APPENDICES . . . . . | xxv |
| ABBREVIATIONS AND SYMBOLS . . . . . | xxvi |

**CHAPTER ONE:** INTRODUCTION

1.1 Advantages and Applications of Internal Combustion (IC) Engines . . . . . 2

1.2 Thermal efficiency of IC engines . . . . . 3

1.3 Effect of Compression Ratio on the Thermal Efficiency of SI Engine 5

1.4 Statement of the problem . . . . . 6

1.5 The Present Research . . . . . 7

1.6 Aim and Objectives . . . . . 7

1.7 Significant of Research . . . . . 8

**CHAPTER TWO**: LITERATURE REVIEW

2.1 Review of Related Past Works . . . . . 9

2.2 The Four Stroke Internal Combustion (IC) Engine . . 15

2.2.1 *Structure and operation of a four stroke SI engine* . . 15

2.3 Engine Performance Parameters . . . . 17

2.3.1 *Definition of essential parameters* . . . . 18

**CHAPTER THREE:** MATERIALS AND METHODS

3.1 Description of Test Engine . . . . . 22

3.2 Experimental Set-up of the Ricardo Variable Compression Ratio Engine. 22

3.3 The Engine . . . . . 24

3.4 The Fuel System. . . . . 25

3.5 Repairs of the Ricardo Engine . . . . . 25

3.5.1 *Repairs of the central cooling system into the laboratory* . 26

3.5.2 *Repairs on the electric motor* . . . . 26

3.5.3 *Repairs of the fuel system* . . . . 26

3.5.4 *Repairs of the ignition system*. . . . . 27

3.5.5 *Replacement of the conveyor belt for the Tachometer* . 27

3.6 Variation of the Compression Ratio . . . . . 27

3.7 Experimental Procedure . . . . . 29

3.7.1 *Calibration of the Ricardo engine* . . . . 29

3.7.2 *Test Procedure* . . . . . 30

3.8 Calculation of Mass Flow Rate of the Fuel . . . . 31

3.9 Measurement of Air Consumption . . . . . 32

3.10 Operation of the Ricardo Engine and Measurement of Break Load 33

3.11 Theoretical Determination of Performance Characteristics . . 34

3.11.1 Calculation of torque gain/loss . . . . 34

3.11.2 Error analysis . . . . . 36

**CHAPTER FOUR:** RESULTS AND DISCUSSION

4.1 Discussion of Results . . . . . 48

4.1.1 *Effect of varying experimental compression ratio on the engine brake power* . . . . . 48

4.1.2 *Effect of varying experimental compression ratio on the engine brakethermal efficiency* . . . . . 48

4.1.3 *Effect of varying the experimental compression ratio on brake mean effective pressure*. . . . . 49

4.1.4 *Effect of varying experimental compression ratio on the fuel consumption parameters* . . . . . 50

4.1.5 *Effect of varying experimental compression ratio on the volumetric efficiency* . . . . . 50

4.2 Improvement in the Engine Performance Characteristics from Increase in the Compression Ratio . . . . 51

4.3 Comparison between the Experimental and Theoretical values . 53

4.4 Comparison between Experimental and Theoretical Performance . 80

4.4.1 *Brake power* . . . . . 80

4.4.2 *Brake thermal efficiency* . . . . . 81

4.4.3 *Specific fuel consumption* . . . . . 81

4.4.4 *Brake mean effective pressure* . . . . 82

**CHAPTER FIVE:** SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary . . . . . 83

5.2 Conclusions . . . . . 85

5.3 Recommendations . . . . . 86

REFERENCES . . . . . 87

APPENDICES . . . . . 90

## LIST OF FIGURES

Figure 1.1. Electric power generation by IC engine . . . 2

Figure 1.2. Engine classification chart. . . . . 3

Figure 2.1. Schematic diagram of the Retrofit test engine. . . 11

Figure 2.2. Main components of an IC engine . . . . 15

Figure 2.3. The operations of an engine on four stroke cycle . . 16

Figure 3.1. Schematic diagram of the Ricardo variable compression ratio engine . . . . . 23

Figure 3.2. Schematic diagram of the fuel system . . . 25

Figure 3.3. Schematic diagram showing the cylinder head, clearance volume and the displaced volume in a spark ignition (SI) engine. . 28

Figure 4.1. Variation of experimental brake power with compression ratio for different engine speeds . . . . . 43

Figure 4.2. Variation of experimental brake power with engine speed for different compression ratios . . . . . 44

Figure 4.3. Variation of experimental thermal efficiency with compression ratio for different engine speeds . . . . 44

Figure 4.4. Variation of experimental thermal efficiency with engine speed for different compression ratios . . . 45

Figure 4.5. Variation of brake mean effective pressure with compression ratio for different engine speeds . . . . . 45

Figure 4.6. Variation of brake mean effective pressure with engine speed fordifferent compression ratios . . . . . 46

Figure 4.7. Variation of experimental specific fuel consumption with compression ratio for different engine speeds . . 46

Figure 4.8. Variation of experimental specific fuel consumption with engine speed for different compression ratios . . . 47

Figure 4.9. Variation of experimental volumetric efficiency with compression ratio for different engine speeds . . . . 47

Figure 4.10. Variation of brake power with compression ratio at engine speed of 1100 rpm. . . . . 58

Figure 4.11. Variation of brake power with compression ratio at engine speed of 1200 rpm. . . . . 58

Figure 4.12. Variation of brake power with compression ratio at engine speed of 1300 rpm. . . . . 59

Figure 4.13. Variation of brake power with compression ratio at engine speed of 1400 rpm. . . . . 59

Figure 4.14. Variation of brake power with compression ratio at engine speed of 1500 rpm. . . . . 60

Figure 4.15. Variation of brake power with compression ratio at engine speed of 1600 rpm. . . . . 60

Figure 4.16. Variation of brake thermal efficiency with compression ratio at engine speedof 1100 rpm . . . . . 61

Figure 4.17. Variation of brake thermal efficiency with compression ratio at engine speed of 1200 rpm . . . . . 61

Figure 4.18. Variation of brake thermal efficiency with compression ratio at engine speed of 1300 rpm . . . . . 62

Figure 4.19. Variation of brake thermal efficiency with compression ratio at engine speed of 1400 rpm . . . . . 62

Figure 4.20. Variation of brake thermal efficiency with compression ratio at engine speed of 1500 rpm . . . . . 63

Figure 4.21. Variation of brake thermal efficiency with compression ratio at engine speed of 1600 rpm . . . . . 63

Figure 4.22. Variation of specific fuel consumption with compression ratio at engine speed of 1100 rpm . . . . . 64

Figure 4.23. Variation of specific fuel consumption with compression ratio at enginespeed of 1200 rpm . . . . . 64

Figure 4.24. Variation of specific fuel consumption with compression ratio at enginespeed of 1300 rpm . . . . . 65

Figure 4.25. Variation of specific fuel consumption with compression ratio at engine speed of 1400 rpm . . . . . 65

Figure 4.26. Variation of specific fuel consumption with compression ratio at engine speed of 1500 rpm . . . . . 66

Figure 4.27. Variation of specific fuel consumption with compression ratio at engine speed of 1600 rpm . . . . . 66

Figure 4.28. Variation of brake mean effective pressure with compression ratio at engine speed of 1100 rpm . . . . . 67

Figure 4.29. Variation of brake mean effective pressure with compression ratio at engine speed of 1200 rpm . . . . . 67

Figure 4.30. Variation of brake mean effective pressure with compression ratio at engine speed of 1300 rpm . . . . . 68

Figure 4.31. Variation of brake mean effective pressure with compression ratio at engine speed of 1400 rpm . . . . . 68

Figure 4.32. Variation of brake mean effective pressure with compression ratio at engine speed of 1500 rpm . . . . . 69

Figure 4.33. Variation of brake mean effective pressure with compression ratio at engine speed of 1600 rpm . . . . . 69

Figure 4.34. Variation of brake power with engine speed at compression ratio of 5 . . . . . 70

Figure 4.35. Variation of brake power with engine speed at compression ratio of 6 . . . . . 70

Figure 4.36. Variation of brake power with engine speed at compression ratio of 7 . . . . . 71

Figure 4.37. Variation of brake power with engine speed at compression ratio of 8 . . . . . 71

Figure 4.38. Variation of brake power with engine speed at compression ratio of 9 . . . . . 72

Figure 4.39. Variation of brake thermal efficiency with engine speed at compression ratio of 5 . . . . . 72

Figure 4.40. Variation of brake thermal efficiency with engine speed at compression ratio of 6 . . . . . 73

Figure 4.41. Variation of brake thermal efficiency with engine speed at compression ratio of 7 . . . . . 73

Figure 4.42. Variation of brake thermal efficiency with engine speed at compression ratio of 8 . . . . . 74

Figure 4.43. Variation of brake thermal efficiency with engine speed at compression ratio of 9 . . . . . 74

Figure 4.44. Variation of specific fuel consumption with engine speed at compression ratio of 5 . . . . . 75

Figure 4.45. Variation of specific fuel consumption with engine speed at compression ratio of 6 . . . . . 75

Figure 4.46. Variation of specific fuel consumption with engine speed at compression ratio of 7 . . . . . 76

Figure 4.47. Variation of specific fuel consumption with engine speed at compression ratio of 8 . . . . . 76

Figure 4.48. Variation of specific fuel consumption with engine speed at compression ratio of 9 . . . . . 77

Figure 4.49. Variation of brake mean effective pressure with engine speed at compression ratio of 5 . . . . . 77

Figure 4.50. Variation of brake mean effective pressure with engine speed at compression ratio of 6 . . . . . 78

Figure 4.51. Variation of brake mean effective pressure with engine speed at compression ratio of 7 . . . . . 78

Figure 4.52. Variation of brake mean effective pressure with engine speed at compression ratio of 8 . . . . . 79

Figure 4.53. Variation of brake mean effective pressure with engine speed at compression ratio of 9 . . . . . 79

## LIST OF TABLES


Table 1.1. Heat Balance Sheets for IC Engines . . . . 5

Table 2.1. Properties of Vegetable Oils . . . . . 14

Table 3.1. The RicardoEngine specifications . . . . 24

Table 3.2: Compression Ratios and Corresponding Micrometer Readings 27

Table 4.1. Initial Experimental Conditions . . . . 37

Table 4.2. Experimental Readings of Fuel Consumption time, Manometer ReadingandBrake Load at Compression Ratio of 5 . . 38

Table 4.3. Experimental Readings of Fuel Consumption time, Manometer Readingand Brake Load at Compression Ratio of 6 . . 38

Table 4.4. Experimental Readings of Fuel Consumption time, Manometer Readingand Brake Load at Compression Ratio of 7 . . 39

Table 4.5. Experimental Readings of Fuel Consumption time, Manometer Readingand Brake Load at Compression Ratio of 8 . . 39

Table 4.6. Experimental Readings of Fuel Consumption time, Manometer Readingand Brake Load at Compression Ratio of 9 . . 39

Table 4.7. Calculated values of Mass Flow Rate of Fuel and Mass Flow Rate of Air from Experimental Measurements at Compression Ratio of 5 . . . . . 40

Table 4.8. Calculated values of Mass Flow Rate of Fuel and Mass Flow Rate of Air from Experimental Measurements at Compression Ratio of 6 . . . . . 40

Table 4.9. Calculated values of Mass Flow Rate of Fuel and Mass Flow Rate of Air from Experimental Measurements at Compression Ratio of 7 . . . . . 40

Table 4.10. Calculated values of Mass Flow Rate of Fuel and Mass Flow Rate of Air from Experimental Measurements at Compression Ratio of8 . . . . . 41

Table 4.11. Calculated values of Mass Flow Rate of Fuel and Mass Flow Rate of Air from Experimental Measurements at Compression Ratio of 9 . . . . . 41

Table 4.12. Calculated Values of Brake Torque, Brake Power, Brake Mean Effective Pressure, Specific Fuel Consumption, Brake Thermal Efficiency and Volumetric Efficiency from Experimental Readings at Compression Ratio of 5 . . . . . 41

Table 4.13. Calculated Values of Brake Torque, Brake Power, Brake Mean Effective Pressure, Specific Fuel Consumption, Brake Thermal Efficiency and Volumetric Efficiency from Experimental Readings at Compression Ratio of 6 . . . . . 42

Table 4.14. Calculated Values of Brake Torque, Brake Power, Brake Mean Effective Pressure, Specific Fuel Consumption, Brake Thermal Efficiency and Volumetric Efficiency from Experimental Readings at Compression Ratio of 7 . . . . . 42

Table 4.15. Calculated Values of Brake Torque, Brake Power, Brake Mean Effective Pressure, Specific Fuel Consumption, Brake Thermal Efficiency and Volumetric Efficiency from Experimental Readings at Compression Ratio of 8 . . . . . 42

Table 4.16. Calculated Values of Brake Torque, Brake Power, Brake Mean Effective Pressure, Specific Fuel Consumption, Brake Thermal Efficiency and Volumetric Efficiency from Experimental Readings at Compression Ratio of 9 . . . . . 43

Table 4.17. Improvement in Brake Power . . . . . 51

Table 4.18. Improvement in Brake Thermal Efficient . . . 51

Table 4.19. Reduction in Specific Fuel Consumption . . . 52

Table 4.20. Improvement in Brake Mean Effective Pressure . . 52

Table 4.21. Percentage Error between the Experimental and Theoretical values for Brake Power and Brake Mean Effective Pressure at Compression Ratio of 5 . . . . . 53

Table 4.22. Percentage Error between the Experimental and Theoretical values for Brake Power and Brake Mean Effective Pressure at Compression Ratio of 6 . . . . . 53

Table 4.23. Percentage Error between the Experimental and Theoretical values for Brake Power and Brake Mean Effective Pressure at Compression Ratio of 7 . . . . . 54

Table 4.24. Percentage Error between the Experimental and Theoretical values for Brake Power and Brake Mean Effective Pressure at Compression Ratio of 8 . . . . . 54

Table 4.25. Percentage Error between the Experimental and Theoretical values for Brake Power and Brake Mean Effective Pressure at Compression Ratio of 9 . . . . . 55

Table 4.26. Percentage Error between the Experimental and Theoretical values for Specific Fuel Consumption and Thermal Efficiency at Compression Ratio of 5 . . . . . 55

Table 4.27. Percentage Error between the Experimental and Theoretical values for Specific Fuel Consumption and Thermal Efficiency at Compression Ratio of 6 . . . . . 56

Table 4.28. Percentage Error between the Experimental and Theoretical values for Specific Fuel Consumption and Thermal Efficiency at Compression Ratio of 7 . . . . . 56

Table 4.29. Percentage Error between the Experimental and Theoretical values for Specific Fuel Consumption and Thermal Efficiency at Compression Ratio of 8 . . . . . 57

Table 4.30. Percentage Error between the Experimental and Theoretical values for Specific Fuel Consumption and Thermal Efficiency at Compression Ratio of 9 . . . . . 57

Table 5.1. Grand Averages of the Percentage Error . . . 84

## LIST OF PLATES


Plate 2.1 The piston, with the 15:1 compression ratio crown assembled of a natural gas HCCI engine . . . . . 13

Plate 3.1 Ricardo E6/T variable compression ratio single cylinder four stroke petrol engine . . . . . 22

Plate 3.2 Dynamometer of the Ricardo variable compression ratio engine 24

Plate 3.3 Compression ratio chart for the Ricardo engine . . 29

## LIST OF APPENDICES

Appendix A. Engineering Equation Solver (*EES*) computer programme (Modelled equations for experimental analysis) . . 90

Appendix B. Engineering Equation Solver (*EES*) computer programme (Modelled equations for theoretical analysis) . . . 100

Appendix C. Formatted Equations for Experimental Analysis . . 110

Appendix D. Formatted Equations for Theoretical Analysis . . 125

## ABBREVIATIONS AND SYMBOLS

### ABBREVIATIONS

| Abbreviation | Explanation |
|---|---|
| ***BDC*** | ***Bottom Dead Center*** - This is the position of the piston at the end of its travel when moving towards the crankcase. |
| ***BMEP*** | ***Brake Mean Effective Pressure*** |
| ***IC*** | ***Internal Combustion*** |
| ***SFC*** | ***Specific Fuel Consumption*** |
| ***SI*** | ***Spark Ignition*** |
| ***TDC*** | ***Top Dead Center*** - This is the maximum travel of the piston toward the cylinder head. Clearance volume, ( ) is the space or volume between the top of the piston and the engine cylinder head when the piston is at TDC. It is also called combustion chamber |

## SYMBOLS

| | |
|---|---|
| $A$ | Piston Area ($mm^2$) |
| $A_0$ | Orifice area ($m^2$) |
| $B$ | Cylinder Bore (mm) |
| | Brake power (kW) |
| | Discharge coefficient |
| g | Acceleration due to gravity ($m/s^2$) |
| h | Manometer reading (mm-water) |
| $L$ | Cylinder Stroke length (mm) |
| $\dot{}$ | Mass flow rate of air (kg/s) |
| $\dot{}$ | Mass flow rate of fuel (kg/s) |
| | Engine Speed (rpm) |
| $n$ | Number of Cylinders |
| $\dot{}$ | Volumetric flow rate ($m^3/s$) |
| | Lower calorific value of the fuel (kJ/kg K) |
| | Compression Ratio |
| $\dot{}$ | Gas constant (kJ/kg K) |
| $R$ | Torque Arm (m) |
| $S$ | Cylinder Stroke (mm) |
| | Specific gravity of the fuel |
| $t$ | Time (sec) |
| | Torque (Nm) |
| | Swept Volume ($mm^3$) |
| | Volume of the fuel consumed ($m^3$) |

$V_c$ Clearance volume ($m^3$)

$W$ Brake Load (N)

Air density ($kg/m^3$)

Water density ($kg/m^3$)

Brake Thermal Efficiency (%)

Volumetric Efficiency (%)

# CHAPTER ONE

# INTRODUCTION

The internal combustion (IC) engine has been refined and developed over the last 100 years for a wide variety of applications. In most application of power generation and in transportation propulsion the power source has being the internal combustion engines. The reciprocating engine with its compact size and its wide range of power outputs and fuel options is an ideal prime mover for powering cars, trucks, off-highway vehicles, trains, ships, motor bikes as well aselectrical power generators for a wide range of large and small applications. Electricity generating sets used to provide primary power in remote locations or more generally for providing mobile and emergency or stand-by electrical power utilizes the IC engines (*Piston engine power plant, 2005*). In Germany, Dr. Nicolaus August Otto started manufacturing gas engines in 1866 (*Hillier and Pittuck, 1978*).

The IC engine is a heat engine in which burning of a fuel occurs in a confined space called a combustion chamber. This exothermic reaction of a fuel with an oxidizer creates gases of high temperature and pressure which are permitted to expand. The defining feature of an IC engine is that useful work is performed by the expanding hot gases acting directly to cause movement, for example by acting on piston, rotor, or even by pressing on and moving the entire engine itself (*Singer and Raper, 1999*).

## 1.1 Advantages and Applications of Internal Combustion Engines

**Spark Ignition (SI) Engines**– These are lightweight enginesoflow capital costand aresuited for applications in smaller and medium sized automobiles requiring power up to about 225 kW. They are also used in domestic electricity generation and outboard engines for smaller boats.

**Compression Ignition (CI) Engines-** These are suited for medium and large size mobile applications such as heavy trucks and buses, ships, auxiliary power units (emergency diesel generators in industries) where fuel economy and relatively large amount of power both are required (*Reaz, 2001).*

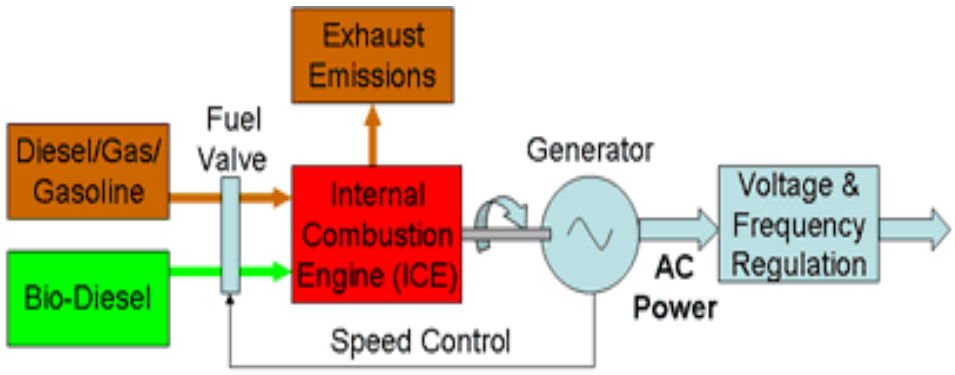



*Figure 1.1. Electric power generation by IC engine* (*Piston engine power plant, 2005*)

Figure 1.1 shows the electric power generation by IC engine and Figure 1.2 is an engine classification chart.

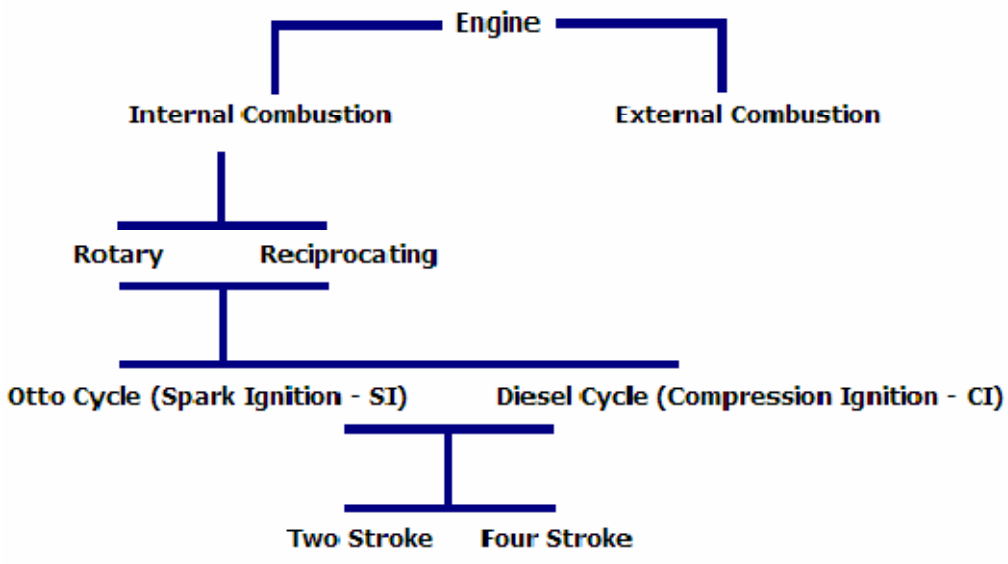



*Figure 1.2.Engine classificationchart*(*Reaz, 2001*)

## 1.2 Thermal Efficiency of ICEngines

There is a lot of concern nowadays about the efficiency of the internal combustion (IC) engine, and a lot of research is being done to improve it, so that we can get more work output, for the same amount of fuel burnt. Engineers have devised manymethods like turbo charging, cam-less engines and direct fuel injection (*Mohit and Lamar, 2010*). The following are also promising breakthrough technologies for improving the thermal efficiencies of reciprocating engines (*www.jsme.or.jp/English/jsme%20roadmap/N0.7*):

1) New combustion system for reducing oxides of Nitrogenlike pre-mixed compression ignition combustion.
2) Friction reduced by lubricant oil.
3) Mechanical, Electrical and recovering thermal and kinetic energies

4) Transfer from fossil fuel to biomass fuel

   The fuel cell is an important breakthrough technology currently under examination. It is expected to be put into practical use from 2015 to 2020.

The thermal efficiency of the working cycle characterizes the degree of perfection with which heat is converted into work. The thermal efficiency is the ratio of the energy output at the shaft to input energy from the fuel. Of all the energy present in the combustion chamber only some gets converted to useful output power. Most of the energy produced by these engines is wasted as heat. The average IC engine has thermal efficiency between 20 to 30%, which is very low (*Mohit and Lamar, 2010*).

If we consider a heat balance sheetsby *Mohits and Lamar* (*2010*) for the internal combustion engines for a spark ignition (gasoline) engine, we find that the brake load efficiency is between 21 to 28%, whereas loss to cooling water is between 12 to 27%, loss to exhaust is between 30 to 55 %, and loss due to incomplete combustion is between 0 to 45%.By analyzing the heat balance sheet we find that in gasoline engines loss due to incomplete combustion can be rather high leading to poor performance characteristics of the engine.

**In addition to friction losses and losses to the exhaust there are other engine operating parameters that affect thermal efficiency. These include the fuel calorific value, the compression ratio, and the ratio of specific heats,** ($\gamma$= / ).

Table 1.1. Heat balance sheets for internal combustion engines

| ENGINE | BRAKE LOAD EFFICIENCY | LOSS TO COOLING WATER | LOSS TO EXHAUST | OTHER LOSSES, FRICTION LOSSES AND LOSS DUE TO INCOMPLETE COMBUSTION |
|---|---|---|---|---|
| GASOLINE ENGINE OR SPARK IGNITION ENGINE | 21 % TO 28 % | 12 % TO 27 % | 30 % TO 55 % | 3 % TO 55 % ( INCOMPLETE COMBUSTION LOSS 0 TO 45 %) |
| DIESEL ENGINE OR COMPRESSION IGNITION ENGINE | 29 % TO 42 % | 15 % TO 35 % | 25 % TO 45 % | 21 % TO 0 % ( INCOMPLETE COMBUSTION LOSS 0 TO 5 % ) |

**1.3**

**Effect of Compression Ratio on the Thermal Efficiency of SI Engines**

Compression ratio ( ) is the ratio of the total volume of the combustion chamber when the piston is at the bottom dead center (BDC) to the total volume of the combustion chamber when piston is at the top dead center (TDC). Theoretically, increasing the compression ratio of an engine can improve the thermal efficiency of the engine by producing more power output. The ideal theoretical cycle,the Otto cycle, upon which spark ignition (SI) engine are based, has a theoretical efficiency, , which increases with compression ratio, andis given by (*Chaiyot, 2005*).

$$= (1 - \frac{}{}) \qquad (1.1)$$

where, γ is ratio of specific heats, and is 1.4 for air.

However, changing the compression ratio has effects on the actual engine for example, the combustion rate. Also over the load and speed range, the relative impact on brake power and thermal efficiency varies. Therefore, only testing on real engines can show the overall effect

of the compression ratio. Knocking, however, is a limitation for increasing the compression ratio (*Chaiyot, 2005*).

## 1.4 Statement of the Problem

The electricity power generation by Power Holding Company of Nigeria (PHCN) amount to about 3,700 MW, which is lower than the national demand of about 10,000 MW (*www.sweetcrudereports.com/2011/power*). This implies that PHCN meets less than 50% of the national demand. This has therefore necessitated establishments and families to generate their own electricity using small engines. Most of these engines that are bought off-shelf (in the market) are designed with a fixed compression ratio. These engines are to operate at maximum thermal efficiency or lowest specific fuel consumption.

The thermal efficiency, of the Otto cycle on which spark ignition engines are based is given by equation (1). This implies that thermal efficiency is dependent on compression ratio and ratio of specific heats. Compression ratio is a fundamental parameter in determining the thermal efficiency of the engine.For spark ignition (SI) engines, the compression ratio ranges from 6 to 12 (*Haresh and Swagatam 2008*). As a general rule, the energy in the fuel will be better utilized if the compression ratio is as high as possible within the detonation free range.

## 1.5 The Present Research

This work attempts to investigate for a giving four stroke Spark Ignition engine, the influence of compression ratio on the brake thermal efficiency, brake power, brake mean effective pressure, specific fuel consumption, and the economic benefits for each unit increase in compression ratio from 5 to 9; which is within detonation free range for spark ignition engines.

The concern is for us to ensure that smaller engines such as the generators that we use in the homes are fuel efficient, designed for optimum thermal efficiency within detonation free compression ratios in order to reduce the cost of our supplementing electricity power supply from PHCN.

## 1.6 Aim and Objectives

The aim of the research is to determine experimentally and theoretically, the influence of the compression ratios on the performance characteristics of a spark ignition engine.

The specific objectives of this research are as follows

(i) To determine experimentally the influence of compression ratio on:

a. brake power

b. brake mean effective pressure

c. brake thermal efficiency

d. specific fuel consumption.

(ii) To test the level of agreement of theoretical predictionswith derived performance characteristics equationsto predict theoretically,the influence of compression ratio on performance characteristics, a to d in (i)

## 1.7 Significance of Research

Adopting a higher compression ratio is one of the most important considerations regarding improved fuel consumption, thermal efficiency and power output in gasoline engines. Much research has been devoted to the effect of higher compression ratio in compression ignition engines, but little attention has been given to spark engines because of detonation at higher compression ratios. By far the most widely used IC engine is the spark-ignition gasoline engine (*www.personal.utulsa.edu/kenneth-weston/chapter6.pdf*). A four-stroke SI engine is different from a four-stroke CI engine in the combustion process and in the, pressure and temperature characteristics of the working gases. The compression ratio has a significant effect on the thermal efficiency for the respective engine types.

# CHAPTER TWO

# LITERATURE REVIEW

A lot of research has beendone to improve the performance of internal combustion engines. Below are some of the past works.

## 2.1 Review of Related Past Works

iAsif*et at.* (2008) conducted a research on performance evaluation of a single cylinder four stroke petrol engine. In the research, the actual size of the engine parameters like the bore, stroke, swept volume, clearance volume, compression ratio and engine speed were recorded and computed. Based on the actual size of the engine parameters, the indicated horse power, brake power, and friction horse power were determined and were found to be 1.54, 1.29 and 0.25 respectively. The mechanical efficiency and the thermal efficiency were also calculated and were found to be 83% and 20.5% respectively. The fuel consumption per hour was found to be 0.8 litre/hour while the fuel consumption per distance traveled was found to be 60 km/litre.

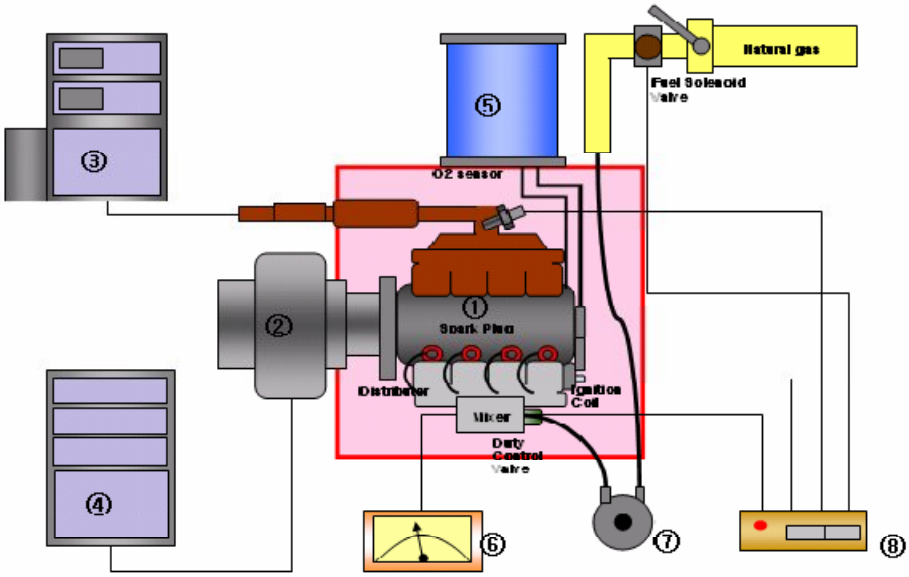
iiOwoade (1971) conducted a research on the performance of a variable compression ratio SI engine at full throttle. The research was conducted for compression ratios of 8, 9, 10 and 11. It was observedthat a compression ratio of 10.5 gave the maximum brake horse power. Above this value (compression ratio of 10.5), there was a decrease in brake horse power at

each ignition setting. Also, the values for the thermal efficiency for both the hypothetical and actual engine increased with the compression ratio

iiiYuh and Tohru (2005) carried out a research on the effect of higher compression ratio in two-stroke engines. The results showed that the actual fuel consumption improved by 1-3% for each unit increase in the compression ratio range of 6.6 to 13.6. It was observed that the rate of improvement was smaller as compared to the theoretical values. The discrepancies were mainly due to increased mechanical and cooling losses, short-circuiting at low loads and increased time losses at heavy loads. Power output also improved, but the maximum compression ratio was limited due to knock and the increase in thermal load. In addition, the investigation covered the implementation of higher compression ratio in practical engines by retarding the full-load ignition timing.

ivAbdel and Osman (1997) performed an experimental investigation on varying the compression ratio of spark ignition engines working under different ethanol-gasoline fuel blends.. The result showed that the engine indicated power improved with the percentage addition of the ethanol in the fuel blend. The maximum improvement occurred at 10% ethanol-90% gasoline fuel blends.

vChaiyot*et al.* (2005) conducted an experimental study on influence of compression ratio on the performance and emission of compressed natural gas (CNG) retrofit engine. For the engine testing, CNG dedicated engine was tested at 4 compression ratios of 9, 9.5, 10, and 10.5. The engine testing schematic diagram is shown in Figure 2.1




*1. Engine* *2. Dynamometer*
*3. Exhaust gas analyzer* *4. Dynamometer controller*
*5. Cooling tower* *6. Duty Monitor*
*7. Pressure Reducer* *8. Electronic control unit (ECU)*

*Figure2.1.Schematic diagram of retrofit test engine*

From the result of the engine testing, performance of the CNG dedicated engine was much more than original diesel engine. Moreover, the trend of engine power increased when compression ratio was increased. For the fuel consumption, the CNG dedicated engine had higher specific fuel consumption than original diesel engine. The diesel engine had the lowest specific fuel consumption around 136g/kWh but CNG dedicated engine had the lowest specific fuel consumption at compression ratio of 9.5 around 155g/kWh. It was shown that the existing diesel engine can be retrofitted and switches to

use CNG asalternative fuel which results on money saving, more power output and clean emissions.

viJan-Ola *et al*. (2002) carried out a research on the compression ratio influence on maximum load of a Natural Gas HCCI engine.A Volvo TD100 truck engine was used for the experiment. The engine was controlled in a closed-loop fashion by enriching the Natural Gas mixture with Hydrogen. The first section of the paper illustrated and discussed the potential of using hydrogen enrichment of natural gas to control combustion timing. Full-cycle simulation was carried out and compared to some of the experimental data and then used to enhance some of the experimental observations dealing with ignition timing, thermal boundary conditions, emissions and how they affect engine stability and performance. High load issues common to HCCI were discussed in light of the inherent performance and emissions tradeoff and the disappearance of feasible operating space at high engine loads. The problems of tighter limits for combustion timing, unstable operational points and physical constraints at high loads were discussed and illustrated by experimental results. It was concluded that the operational limits were affected by compression ratio at high load, based on the criteria discussed in the second part.

*Plate 2.1.The piston, with the 15:1 compression ratio crown assembled. To the left of the piston is shown the crowns for 17:1, 20:1 and 21:1 compression ratios.*

viiRatnakara*et al.* (2009) performed an experimental investigation on a single cylinder variable compression ratio compression ignition engine using neat Mahua oil as the fuel.Mahua oil was selected for the work with an intention to find the optimum compression ratio when used in compression ignition engines. Both the performance and exhaust analysis were carried out to find the best suited compression ratio. The tests were carried out at 7 different compression ratios viz.13.2, 13.9, 14.8, 15.7, 16.9, 18.1 and 20.2. All the experiments were carried out at standard test conditions like 70$^{o}$C cooling water temperature and at constant speed of 1500 rpm. The results showed that 15.7 is the best compression ratio with Mahua oil. All the results were obtained without any modifications on either engine side or fuel side. The properties of various vegetable oils in comparison to diesel were given as shown below.

Table2.1.Properties of vegetable oils.

| Properties | Diesel | Mahua oil | Jatropha oil | Karanji oil | Rapeseed oil | Rubber seed oil | Tobacco seed oil |
|---|---|---|---|---|---|---|---|
| Density ($kg/m^3$) | 840 | 920 | 918 | 927 | 918 | 926 | 920 |
| Calorific value (kj/kg) | 42390 | 38863 | 39774 | 35800 | 36890 | 38957 | 39400 |
| Cetane Number | 45-55 | 40 | 45 | 40 | 39 | 40 | 38 |
| Viscosity (cst) | 4.59 | 50 | 49.9 | 56 | 55 | 55.6 | 27.7 |
| Flash Point ($^0c$) | 75 | 260 | 240 | 250 | 275 | 242 | 220 |
| Carbon residue (%) | 0.1 | 0.4215 | 0.44 | 0.66 | 0.31 | 0.46 | 0.57 |

viiiHaresh and Swagatam (2009) carried out a new empirical correlations for simulating the influence of compression ratio on ignition delay and overall combustion duration in SI engines. It was shown from the graphs obtained that both compression ratio and intake generated swirl have considerable influence on the overall burn duration during the combustion process, while the influence of compression ratio being more predominant.

ixAndreas(2003) carried out a torque modeling and control of a variable compression ratio engine. A torque control strategy was developed for the SAAB variable compression (SVC) engine. The SVC engine was a new concept that enables the fuel consumption to be radically cut by varying the compression ratio. The main control objective was to make the output torque behave in a desirable way despite the influence of compression ratio changes. The controller was developed using a design method called internal model control (a way of both configuring and controller and determining parameters).

The controller was implemented andevaluated in a real engine. The controller was proved to reduce the effects from compression ratio changes.

## 2.2 The Four Stroke Internal Combustion (IC) Engine

An internal combustion engine uses air and fuel based on hydrocarbons and produces power and emissions. A schematic diagram is given in Figure 2.2.

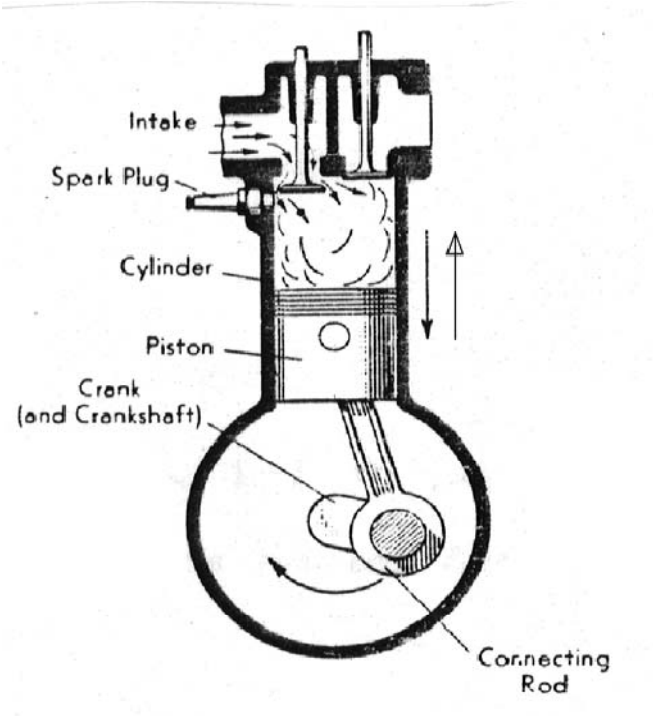



*Figure 2.2.Main components of an IC engine.*

### 2.2.1 Structure and operation of a four stroke SI engine

For a four stroke engine the combustion cycle is divided into four steps,illustrated in Figure. 2.3.

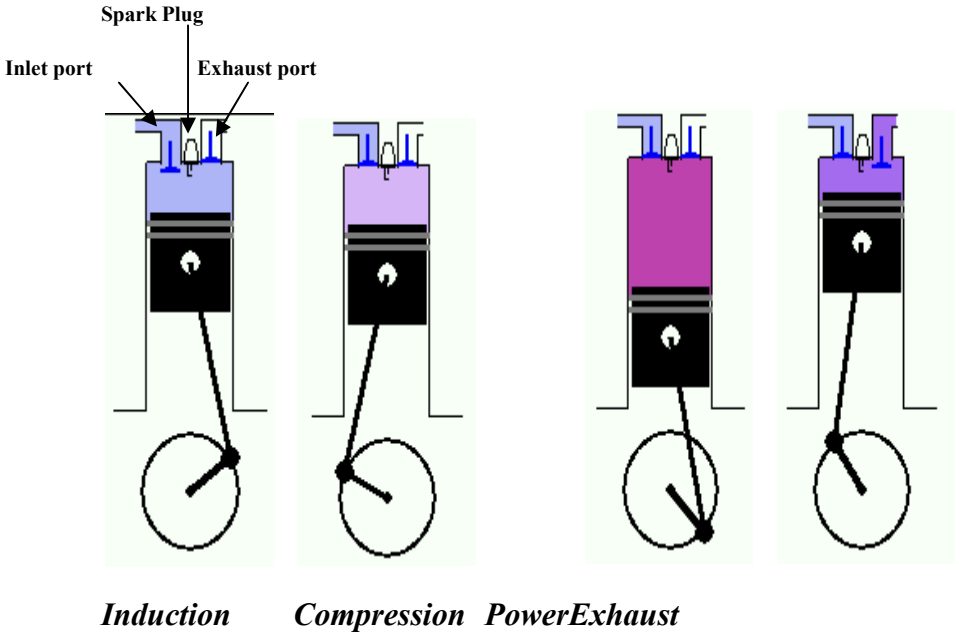



*Figure 2.3.Theoperation of an engine on four stroke cycle*

The first stroke is called the ***intake stroke***(from top dead center (TDC) to bottom dead center (BDC)). During this, the intake valve is open and while the piston moves downwards the cylinder is filled with air/fuel mixture. Due to the open inlet valves the cylinder pressure remains fairly constant.

A ***compression stroke***(BDC toTDC) follows, where the air/fuel mixture is compressed to higher pressure and temperature through mechanical work produced by the piston. Around $25^{o}$before TDC aspark ignites the mixture and initiates the combustion, whereas the flames propagates through the combustion chamber and add heat to the mixture.

The combustion continues into the ***expansion stroke***(TDC to BDC) and finishes around $40^{o}$after TDC. Work is produced during the expansion stroke when the volume expands.

Around $130^{o}$ after TDC the exhaust valve is opened and the blow down process starts, where the cylinder pressure decreases as the burned gases is blown out into the exhaust system by the higher pressure in the cylinder.

During the final stroke, ***exhaust stroke***(BDC to TDC), the valve is still open and therefore the pressure in the cylinder is close to the pressure in the exhaust system and the rest of the gases is pushed out into the exhaust system as the piston moves upwards. When the piston reaches TDC a new cycle starts with the intake stroke (*Andreas*, 2003).

## 2.3 Engine Performance Parameters

The term ‘’performance’’ usually means how well an engine is doing its required task of converting the input energy to useful energy. It is represented by typical characteristics curves, which show an engine’s performance.

Engine performance characteristics can be determined by the following two methods (*Jehad and Mohammed, 2003*):

i. Experimental results obtained from engine tests.
ii. Analytical calculations.

Performance evaluation of SI engines is of great importance for their economic operation. Some of the methods for assessing the engine performance include the determination of the engine brake power, thermal efficiency, specific fuel consumption, considering the compression ratio, the engine speed, and the brake mean effective pressure (*Asif et al, 2008*)

### 2.3.1 Definition of essential parameters

1. The engine torque, *T* is given by (*Eastop and McConkey, 1995*)

$$= \quad (2.1)$$

where, = brake load (N)

*R* = torque arm (m).

2. Brake Power ($B_P$) - This is the actual power output of the engine. It is the actual power available at the crankshaft and it is given by (*Eastop and McConkey, 1995*)

$$=2 \quad (2.2)$$

where,*N*= engine speed (rpm).

3. Brake mean effective pressure (*BMEP*) - This is the mean effective pressure which would have developed power equivalent to the brake power if the engine were frictionless. For a four stroke engine, it is given by

$$\quad (2.3)$$

Where,*n* = the number of cylinders

= swept volume ($mm^3$)

Substituting equation (2.2) into equation (2.3) and re-arranging,the brake mean effective pressure can be shown to be

$$BMEP= \quad (2.4)$$

therefore,

Thisimplies that the brake mean effective pressure is directly proportional to the torque.

4. Brake thermal efficiency ( ) – This is the ratio of the brake power to the fuel power, (heat supplied)

$$= \frac{}{} \quad (2.5)$$

and $= \cdot$ (2.6)

where, = mass flow rate of the fuel(*kg/s*)

= lower calorific value of the fuel (*kJ/kgK*)

5. Specific Fuel Consumption (*SFC*) – This is the total fuel consumed per kilowatt power developed per hour, in (kg/KW h) and it is given by (*Eastop and McConkey, 1995*).

$$SFC = \frac{}{} \quad 3600 \quad (2.7)$$

Combining equations (2.5) and (2.7), the specific fuel consumption can be shown to be

$$SFC = \frac{}{} \quad (2.8)$$

therefore,$SFC \quad \frac{1}{}$

This shows that specific fuel consumption is inversely proportional to the thermal efficiency.

6. Volumetric efficiency ( ) –Andreas (*2003*) shows that the air mass flow passing the intake valve, depends mainly on the engine speed, intake manifold pressure and air

temperature.The volumetric efficiency is a measure of the effectiveness of the engine to induced fresh air defined as the ratio of actual volume flow rate of air entering the cylinder ( / ), and the rate at which volume is displayed by the piston,——. The factor 2 in the denominator arises from the fact that the engine only induced fresh air in the cylinder every second revolution in a four stroke cycle. Using the above, the expression for the volumetric efficiency becomes

$$= \frac{}{/} \qquad (2.9)$$

7. Compression ratio ( ) - Compression ratio by Eastop and McConkey*(1995*) is giving by

$$= \frac{}{} \qquad (2.10)$$

where, = Cylinder clearance volume ($m^3$)

The compression ratio is one of the most important factors that determine how efficient the engine can utilize the energy in the fuel (equation(1)). As a general rule, the energy in the fuel will be better utilized ifthe compression ratio is as high as possible.

From equation (2.10), the swept volume can be shown to be

$$= ( \quad -1) \qquad (2.11)$$

Substituting equation (2.11) into (2.9), the volumetric efficiency in terms of the compression ratio and clearance volume can be shown to be

$$= \frac{}{( \quad -1) \quad /} \qquad (2.12)$$

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1 Description of Test Engine

In this section, a description of the testengineis given,and the major specifications.The experimental procedures andtheoretical determination of the performance characteristicsare also presented.

## 3.2 Experimental Set-up of the Ricardo Variable Compression Ratio Engine

The experimental set-up consists of the engine, the dynamometer and the instrumentation unit from where the readings are taken.

*Plate 3.1. RicardoE6/T variable compressionratiosingle cylinder four stroke petrol engine.*

## 3.3 The Engine

The Ricardo variable compression ratio engine with direct currentelectric dynamometer is a four stroke water-cooled single cylinder petrol engine. It has a 76.2mm cylinder bore and 111.1mm stroke.

Table 3.1.The Ricardoengine specifications.

| | |
|---|---|
| **Bore** | 76.2mm |
| **Stroke** | 111.1mm |
| **Compression ratio** | Variable |
| **Recommended maximum speed** | 2500 rpm |
| **Type of dynamometer** | Electric |
| **Dynamometer constant** | 3500 |
| **Ignition setting** | $50^{o}$ |
| **Throttle setting** | 0.7 |

*Plate 3.2.Dynamometer of the Ricardo engine.*

### 3.4 The Fuel System

The fuel system was fed from a 4.5litre fuel tank mounted on top of the instrumentation unit. The fuel flows into the bottom of a pipette graduated in volumes of 50 and 100ml. A length of clear plastic tubing connected to the top of the pipette gives an indication of the content of the fuel in the tank.The tap *T*(Figure 3.2) opens/closes the fuel flow from the pipette to the engine.

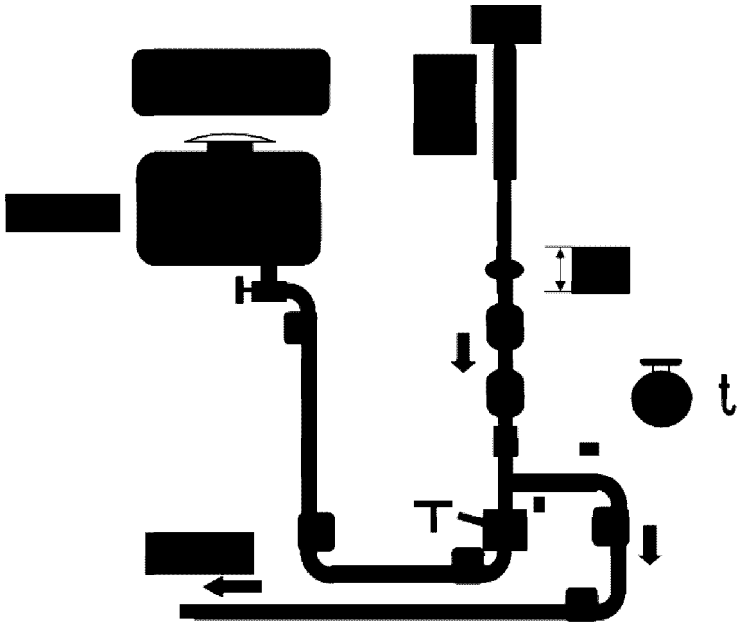



*Figure 3.2. Schematic diagram of the fuel system*

### 3.5 Repairs of the Ricardo Engine

At the beginning the equipment was not operational because the engine had not been used for a long time. It posed so many problems and delays before the experiments were performed. The problems were mainly from the central cooling system, electric motor, fuel system, ignition system, and the drive belt for the tachometer. All these shall be discussed in this section.

### 3.5.1 Repairs of the central cooling system into the laboratory

The original pump required to pump water into the laboratory was not functional, anirrigation water pump was hiredto lift the water from the underground tank (lower tank) to the header tank (upper tank); so that by gravity, it supplies the water on all the engines in the laboratory. The cooling water pump attached to the Ricardo engine was serviced by cleaning of the internal parts and the electrical circuits were replaced. This also made the supply of cooling water to the engine possible.

### 3.5.2 Repairs on the electric motor

The bed cables and burnt fuses on the motor of the Ricardo engine were replaced. After these repairs the motor came on.

### 3.5.3 Repairs of the fuel system

The fuel system was serviced by cleaning and replacing the lubricating oil. The carburetor and fuel pump were serviced to make the supply of fuel to the engine possible. The air filter placed on the carburetor requires that only clean air goes into the carburetor in order to prevent choking. Therefore, it was necessary to service the air filter. This was done by thorough cleaning of the air filter. The manometer system was serviced by cleaning and changing the manometer fluid to paraffin fluid instead of water for better sensitivity.

### 3.5.4 Repairs of the ignition system

The spark plug of the engine was changed to the conventional one because, the engine came with a special plug that could not be obtained elsewhere except by ordering. All the plug cables were also replaced with the conventional one.

### 3.5.5 Replacement of the conveyor belt for the tachometer

The conveyor belt for the tachometer was removed and changed to a new one because the existing belt was weak and could not transmit the effect of the engine speed to the tachometer. The tachometer measures the engine speed.

## 3.6 Variation of the Compression Ratio

Table 3.2.Compression ratios and corresponding micrometer readings.

| **Micrometre readings (mm)** | 0.135 | 0.36 | 0.503 | 0.605 | 0.697 |
|---|---|---|---|---|---|
| **Compression Ratio,** | 5 | 6 | 7 | 8 | 9 |

Variation of the compression ratio can be achieved byeither raising the cylinder head up in order to decrease it or by lowering the cylinder head down to increase the compression ratio.This can be understood clearly with Figure 3.3.

In order to vary the compression ratio while the engine is running, the cylinder clamp was released just enough to allow the cylinder nut to be rotated by means of the controlling handle (point 4 in Figure 3.1), clockwise to lower the compression ratio and anticlockwise to raise it. At all other times the cylinder clamp was kept tight.

A micrometer screw gauge that was supplied with the engine was permanently fixed on the engine close to the cylinder head. The compression ratios corresponding to the micrometer readings are given in Table 3.2. The curve provided (Plate 4) with the engine shows correctly the compression ratio corresponding to each micrometer reading. It was by these processes that the variation in the compression ratio was achieved.

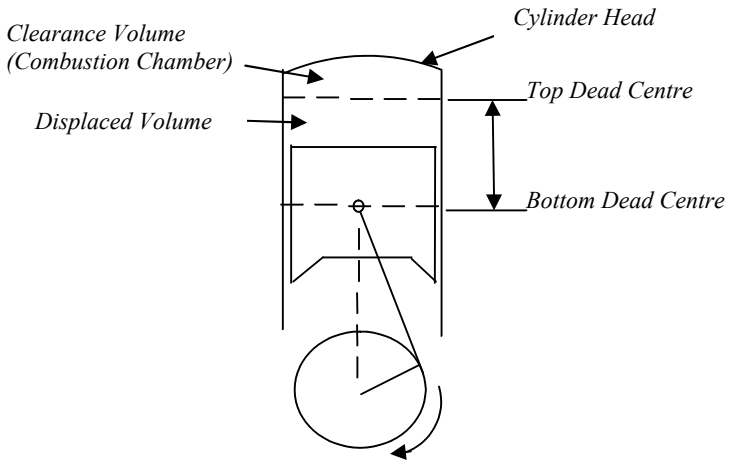



*Figure 3.3. Schematic diagram showing the cylinder head, clearance volume and the displaced volumein a spark ignition (SI) engine*

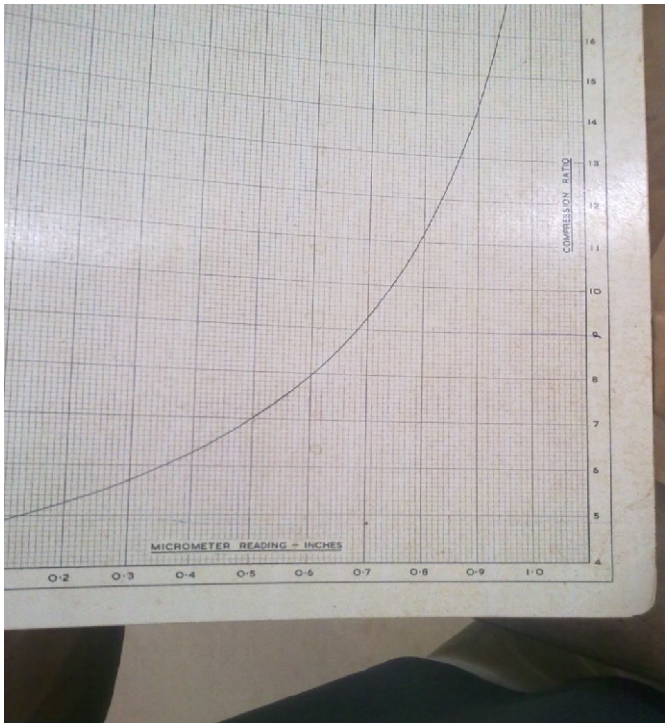



*Plate 3.3. Compression ratio chartfor the Ricardo engine*

## 3.7 Experimental Procedure

### 3.7.1 Calibration of the Ricardo engine

Before each engine test, the torque metre was zeroed and calibrated before use. The steps followed are:

i. The span control was set to its maximum clockwise position.

ii. The engine was allowed to run for about 30 minutes in order to overcome sticking of the bearing seals.

iii. The zero control was adjusted until the torque metre reads zero.

iv. A load of 4.54kg was hung on the calibration arm.

v. The engine was started again by running it until the torque metre reading settles down to a constant value.

vi. The span control was adjusted after which the torque reading was taken.

vii. The calibration load was removed and steps 1 to 6 were repeated until it was satisfactory that the span settings were correct.

### 3.7.2 Test procedure

i. A throttle setting of 0.7 (as recommended) was selected. This was maintained throughout the experiment.

ii. The needle valve controlling the strength of the mixture was maintained at one position for each set of the compression ratios readings.

iii. The cylinder head was adjusted with the aid of the hand crank and micro-metre, and the lowest possible compression ratio of 5.0 was obtained.

iv. The engine was started and the load adjusted to maintain the required speeds. The lowest possible speed was 1100rpm, and it was increased in intervals of 100 from 1100rpm to 1600rpm. This speed range was maintained for each compression ratio.

v. The fuel consumption, air consumption and load on the dynamometer were taken and recorded.

vi. Step (5) was repeated for various values of compression ratios, up to the highest possible value, each time the load was adjusted to maintain the original speed. The compression ratios were 5, 6, 7, 8, and 9.

vii. The mixture strength was varied and steps (3), (4), (5), and (6) were repeated.

### 3.8 Calculation of Mass Flow Rate of the Fuel

The fuel (petrol) consumption rate was determined by the time (t) taken by the engine to consume 50ml of the fuel. The specific gravity of petrol is 0.74. The mass flow rate of the fuel consumed is given by:

$$\dot{} = \varphi \quad (3.1)$$

And $\varphi =$ (3.2)

Where, =specific gravity of the fuel (0.74)

= density of water (1000 $kg/m^3$)

=volume of the fuel consumed ($50ml = 5x10^{-5}m3$)

$t$ = time (sec).

The time taken for the engine to consume 50ml of the fuel was 55.02 seconds, when the compression ratio and engine speed were 5 and 1100 rpm respectively. Thus, applying equation (3.1), the mass flow rate is given by

$$\dot{} = 0.74 \times 1000 \times \left(\frac{\quad}{\quad}\right) = 0.0006725 \text{ kg/s}$$

Similar calculations were carried out based on the time taken for the fuel to be consumed for engine speeds of 1200, 1300, 1400, 1500 and 1600 rpm. The results are given in table 4.1.1 to 4.15 for compression ratios of 5, 6, 7, 8 and 9.

### 3.9 Measurement of Air Consumption

To calculate the flow rate of air passing through the orifice plate, the induction pipe was connected to a large steel air cylinder-box by means of a hose. As the engine runs, air enters the box through an orifice in the air box. An inclined manometer on the engine's panel (point 11 in figure 3.1.) gives the pressure drop across the orifice; and hence the air consumption can be calculated. The volumetric flow rate, Q for real flow is given by (http://www.imnoeng.com/Flow/SmallOrificeGas.htm) Q =

$$\overline{\Delta} \qquad (3.3)$$

Where, = discharge coefficient which depends on the Reynolds number of the airflow (0.6 is a typical value)

= orifice area ($m^2$)

$\Delta P$ = drop in pressure

= air density

The mass flow rate of air, can be found by multiplying the volume flow rate, Q with the air density, .

$$= \quad Q \qquad (3.4)$$

Substituting for Q from equation (3.3) into equation (3.4),

$$= \quad \overline{2 \quad \Delta} \qquad (3.5)$$

The pressure drop across the orifice is measured on an inclined tube manometer. Expressing the pressure drop in terms of a height, *h* of a column of water,

$\Delta P =$ $g\ h$ (3.6) where,

*h* = manometer reading (mm-water)

g = acceleration due to gravity (9.81m/s$^2$)

$\rho_w$= water density (1000 kg/m$^3$)

The air density is calculated from the ambient pressure, and temperature, using equation of for a gas.

= — (3.7)

For air, *R* (gas constant) has a value of 0.287kJ/kg k.

Combining equations (3.5), (3.6) and (3.7), and substituting the values for , , , , the equation for the mass flow rate, in / of air can be given by

= 2.98 —. (3.8)

### 3.10 Operation of the Ricardo Engine and Measurement of Brake Load

The brake load was measured through a dynamometer as explained in the following procedure:

To kick-start the engine, the dynamometer motor was switched on by the switch gear. On kick-starting, when the motor runs the engine to gain momentum, the ignition was switched on and the engine ignited (fired). The motoring switch was turned on to the load (on the panel). This made the engine to develop power. When the switch gear was released (off), the motor became the load to the engine. The brake load was then measured and recorded with respect to the compression ratio and engine speed.The torque arm was measured andthe time taken for 50ml of the fuel to be consumed was taken and recorded.The brake torque was calculated by the product of the torque arm and brake load. Then the brake power was calculated by means of equation (2.2)

## 3.11 Theoretical Determination ofPerformance Characteristics

### 3.11.1 Calculation of torque gain/loss

Increase in compression ratio induces greater turning effect on the cylinder crank (*Heywood, 1988*). That means that the engine is getting more push on the piston, and hence more torque is generated.The torque gain due to compression ratio increase can be given as the ratio of a new compression ratio to the old compression ratio given by (*PhilipandDavid,1954*) as:

$$Torque\ gain = \left(\frac{\quad}{\quad}\right)^{0.4} \tag{3.9}$$

In the cylinders the combustion process takes place, and converts the energy in the fuel to power.Ideally, all the heat stored in the fuel may be converted to power; in that case the delivered power is given by taking the product of the heating value of the fuel, and the fuel mass flow rate, through the cylinders. However there will be losses during the energy

conversion, thus we have to multiply with the brake thermal efficiency, (fuel conversion efficiency) (*Andreas, 2003*)

$$= \quad \cdot \qquad (3.10)$$

If equation (2.2) and (3.10) are equated, an equation for the relation between the engine torque and mass flow rate of the fuel is developed as

$$T = \quad \frac{\qquad}{/} \qquad (3.11)$$

Where,*N* is the engine speed in rev/min

If the whole process is approximated to an Otto cycle(constant volume cycle), the conversion efficiency can be calculated by (*Andreas*, *2003*)

$$= k\left(1 - \frac{}{}\right) \qquad (3.12)$$

*K*in equation (3.12) is a constant and it is introduced because in equation (1.1), energy losses due to incomplete combustion, heat transfer from gas to cylinder walls and timing losses have been neglected.Thus, equation (3.11) becomes

$$T = -\left(1 - \frac{}{}\right) \frac{\qquad}{} \qquad \mathbf{(3.13)}$$

The values for*K* (from 1100 to 1600rpm in increments of 100rpm) were determined experimentally for a reference compression ratio of 7by means of equation (3.13). (Values for *K* are giving in Table 4.9). Compression ratio of 7 was used as the reference because it is mid-way of the operational compression ratios. When a value greater than 7 was utilised (example, 9), the percentage error between the experimental and theoretical value was increases; but with 7, the error reduces.

The theoretical torque gain from compression ratio of 7 to 8 and 7 to 9 were calculated by means of equation (3.9), and the theoretical brake torque were obtained by adding the torque

gain to the experimental brake torque obtained at compression ratio of 7. Similar calculations were carried out for the torque loss from compression ratio of 7 to 6 and 7 to 5 (appendix B). With the theoretical brake torque, the theoretical mass flow rate of the fuel with respect to the engine speeds, compression ratios and the *K* values, were calculated by

$$\dot{\quad} = \frac{\quad}{\quad}(1- \frac{\quad}{\quad})^{-1} \qquad \textbf{(3.14)}$$

With the calculated torque and the *K* values from the reference compression ratio, the theoretical mass flow rate of the fuel was calculated by means of equation (3.14). The theoretical brake power, brake mean effective pressure, brake thermal efficiency and specific fuel consumption were calculated by means of equations (2.2), (2.3), (2.5) and (2.7) respectively.The results are giving in tables 4.4.1 to 4.4.10, and the calculations carried out in Engineering Equation Solver (EES) computer programme are giving in appendix B.

### 3.11.2 Error analysis

The percentage error in the brake power, brake thermal efficiency, specific fuel consumption and brake mean effective pressure were calculated by (*Andreas*, *2003*).

$$Error = \frac{\quad}{\quad} \text{x} 100\% \qquad (3.15)$$

# CHAPTER FOUR

## RESULTS AND DISCUSSION

Equations used for calculating the derived values of brake power, indicated thermal efficiency, specific fuel consumption and the brake mean effective pressure are as modelledin appendix A and B using Engineering equation solver (*EES*) computer programme.

The Table of values for the experimental readings, calculated values from experimental readings, improvement in the performance characteristics from the increase in compression ratios, theoretical values and the error between the experimental and theoretical values are giving in this section.

Table 4.1.Initial experimental conditions

| | |
|---|---|
| **Ambient Temperature** | 32$^{o}$C (305 K) |
| **Atmospheric pressure** | 930 mmHg |
| **Specific gravity of fuel** | 0.740 |
| **Torque arm, R** | 0.48m (19inch) |

Table 4.2.Experimental readings of fuel consumption time,manometer reading and brake load at compression ratio of 5

| S/N | Engine Speed, N (rpm) | Time to consume 50ml of fuel, (sec) | Manometer reading, h(mm water) | Brake load, W (N) |
|---|---|---|---|---|
| 1 | 1100 | 55.02 | 3.3 | 66.2 |
| 2 | 1200 | 52.06 | 4.1 | 66.46 |
| 3 | 1300 | 50.10 | 4.7 | 65.63 |
| 4 | 1400 | 48.10 | 5.2 | 62.71 |
| 5 | 1500 | 44.50 | 5.5 | 60.21 |
| 6 | 1600 | 40.30 | 5.7 | 57.18 |

Table 4.3. Experimental readings of fuel consumption time, manometer reading andbrake loadat compression ratio of 6

| S/N | Engine Speed, N (rpm) | Time to consume 50ml of fuel, (sec) | Manometer reading, h(mm water) | Brake load, W (N) |
|---|---|---|---|---|
| 1 | 1100 | 58.40 | 3.4 | 65.42 |
| 2 | 1200 | 54.61 | 4.2 | 67.08 |
| 3 | 1300 | 53.98 | 4.9 | 67.08 |
| 4 | 1400 | 51.22 | 5.3 | 62.71 |
| 5 | 1500 | 48.67 | 5.6 | 61.46 |
| 6 | 1600 | 45.2 | 5.9 | 57.08 |

Table 4.4. Experimental readings of fuel consumption time, manometer reading and brake loadat compression ratio of 7

| S/N | Engine Speed N (rpm) | Time to consume 50ml of fuel (sec) | Manometer reading, h (mm water) | Brake load, W (N) |
|---|---|---|---|---|
| 1 | 1100 | 60.05 | 3.5 | 67.92 |
| 2 | 1200 | 56.60 | 4.2 | 68.54 |
| 3 | 1300 | 55.03 | 4.9 | 67.08 |
| 4 | 1400 | 53.90 | 5.3 | 65.62 |
| 5 | 1500 | 50.13 | 5.8 | 62.71 |
| 6 | 1600 | 46.50 | 6.1 | 59.17 |

Table 4.5. Experimental readings of fuel consumption time, manometer reading and brake load at compression ratio of 8

| S/N | Engine Speed N (rpm) | Time to consume 50ml of fuel (sec) | Manometer reading, h (mm water) | Brake load, W (N) |
|---|---|---|---|---|
| 1 | 1100 | 63.08 | 3.5 | 68.96 |
| 2 | 1200 | 59.89 | 3.9 | 68.75 |
| 3 | 1300 | 58.38 | 4.9 | 68.54 |
| 4 | 1400 | 58.22 | 5.5 | 65.83 |
| 5 | 1500 | 53.60 | 6.0 | 63.54 |
| 6 | 1600 | 52.20 | 6.2 | 59.58 |

Table 4.6. Experimental readings of fuel consumption time, manometer reading and brake load at compression ratio of 9

| S/N | Engine Speed N (rpm) | Time to consume 50ml of fuel (sec) | Manometer reading, h(mm water) | Brake load, W (N) |
|---|---|---|---|---|
| 1 | 1100 | 67.20 | 3.5 | 69.00 |
| 2 | 1200 | 65.80 | 4.3 | 68.96 |
| 3 | 1300 | 64.10 | 5.7 | 68.54 |
| 4 | 1400 | 62.80 | 5.7 | 66.04 |
| 5 | 1500 | 61.20 | 6.1 | 63.96 |
| 6 | 1600 | 58.80 | 6.6 | 60.63 |

Table 4.7. Calculated values of mass flow rate of fuel and mass flow rate of air from experimental measurements at compression ratio of 5

| S/N | Engine Speed, N (rpm) | $\dot{}$ (kg/s) | $\dot{}$ (kg/s) |
|---|---|---|---|
| 1 | 1100 | 0.0006725 | 0.003032 |
| 2 | 1200 | 0.0007170 | 0.003379 |
| 3 | 1300 | 0.0007385 | 0.003618 |
| 4 | 1400 | 0.0007692 | 0.003806 |
| 5 | 1500 | 0.0008315 | 0.003914 |
| 6 | 1600 | 0.0009181 | 0.003985 |

Table 4.8. Calculated values of mass flow rate of fuel and mass flow rate of air from experimental measurements at compression ratio of 6

| S/N | Engine Speed, N (rpm) | $\dot{}$ (kg/s) | $\dot{}$ (kg/s) |
|---|---|---|---|
| 1 | 1100 | 0.0006336 | 0.002665 |
| 2 | 1200 | 0.0006775 | 0.002955 |
| 3 | 1300 | 0.0006854 | 0.003203 |
| 4 | 1400 | 0.0007224 | 0.003325 |
| 5 | 1500 | 0.0007602 | 0.003427 |
| 6 | 1600 | 0.0008186 | 0.003538 |

Table 4.9. Calculated values of mass flow rate of fuel and mass flow rate of air from experimental measurements at compression ratio of 7

| S/N | Engine Speed N (rpm) | $\dot{}$ (kg/s) | $\dot{}$ (kg/s) | *K* |
|---|---|---|---|---|
| 1 | 1100 | 0.0006162 | 0.003122 | 0.2683 |
| 2 | 1200 | 0.0006537 | 0.003420 | 0.2784 |
| 3 | 1300 | 0.0006724 | 0.003694 | 0.287 |
| 4 | 1400 | 0.0006865 | 0.003842 | 0.2962 |
| 5 | 1500 | 0.0007381 | 0.004019 | 0.282 |
| 6 | 1600 | 0.0007957 | 0.004122 | 0.2633 |

Table 4.10.Calculated values of mass flow rate of fuel and mass flow rate of air from experimental measurements at compression ratio of 8

| S/N | Engine Speed N (rpm) | $\dot{}$ (kg/s) | $\dot{}$ (kg/s) |
|---|---|---|---|
| 1 | 1100 | 0.0005866 | 0.003077 |
| 2 | 1200 | 0.0006178 | 0.003296 |
| 3 | 1300 | 0.0006338 | 0.003694 |
| 4 | 1400 | 0.0006355 | 0.003914 |
| 5 | 1500 | 0.0006903 | 0.004088 |
| 6 | 1600 | 0.0007088 | 0.004156 |

Table 4.11. Calculated values of mass flow rate of fuel and mass flow rate of air from experimental measurements at compression ratio of9

| S/N | Engine Speed N (rpm) | $\dot{}$ (kg/s) | $\dot{}$ (kg/s) |
|---|---|---|---|
| 1 | 1100 | 0.0005506 | 0.003122 |
| 2 | 1200 | 0.0005623 | 0.003461 |
| 3 | 1300 | 0.0005772 | 0.003914 |
| 4 | 1400 | 0.0005892 | 0.003985 |
| 5 | 1500 | 0.0006046 | 0.004122 |
| 6 | 1600 | 0.0006293 | 0.004288 |

Table 4.12.Calculated values of brake torque, brake power, brake mean effective pressure, specific fuel consumption, brake thermal efficiency and volumetric efficiencyfrom experimental readingsat compression ratio of 5.

| N (rpm) | Torque,T (Nm) | (kW) | BMEP(bar) | SFC(g/kWh) | (%) | (%) |
|---|---|---|---|---|---|---|
| 1100 | 31.8 | 3.661 | 7.895 | 661.2 | 12.96 | 46.16 |
| 1200 | 31.9 | 4.007 | 7.920 | 638.6 | 13.42 | 47.16 |
| 1300 | 31.5 | 4.286 | 7.821 | 620.3 | 13.82 | 46.61 |
| 1400 | 30.1 | 4.411 | 7.473 | 627.9 | 13.65 | 45.52 |
| 1500 | 28.9 | 4.537 | 7.175 | 659.7 | 12.99 | 43.7 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1600 | 27.4 | 4.589 | 6.803 | 720.3 | 11.9 | 41.7 |

Table 4.13. Calculated values of brake torque, brake power, brake mean effective pressure, specific fuel consumption, brake thermal efficiency and volumetric efficiencyfrom experimental readings at compression ratio of6

| **N (rpm)** | **Torque, T (Nm)** | **(kW)** | **BMEP (bar)** | **SFC (g/kWh)** | **(%)** | **(%)** |
|---|---|---|---|---|---|---|
| 1100 | 31.4 | 3.730 | 8.044 | 611.4 | 14.02 | 46.85 |
| 1200 | 32.2 | 4.044 | 7.994 | 603.1 | 14.21 | 47.73 |
| 1300 | 32.2 | 4.368 | 7.969 | 565.0 | 15.17 | 47.57 |
| 1400 | 30.1 | 4.543 | 7.696 | 572.5 | 14.97 | 45.96 |
| 1500 | 29.5 | 4.632 | 7.324 | 590.9 | 14.51 | 44.09 |
| 1600 | 27.9 | 4.672 | 6.927 | 630.7 | 13.59 | 42.43 |

Table 4.14.Calculated values of brake torque, brake power, brake mean effective pressure, specific fuel consumption, brake thermal efficiency and volumetric efficiencyfrom experimental readings at compression ratio of 7

| **N (rpm)** | **Torque, T (Nm)** | **(kW)** | **BMEP(bar)** | **SFC(g/kWh)** | **(%)** | **(%)** |
|---|---|---|---|---|---|---|
| 1100 | 32.6 | 3.753 | 8.094 | 591.0 | 14.50 | 47.53 |
| 1200 | 32.9 | 4.132 | 8.168 | 569.5 | 15.05 | 47.73 |
| 1300 | 32.2 | 4.381 | 7.994 | 552.5 | 15.52 | 47.59 |
| 1400 | 31.5 | 4.616 | 7.821 | 535.4 | 16.01 | 55.96 |
| 1500 | 30.1 | 4.726 | 7.473 | 562.3 | 15.24 | 44.87 |
| 1600 | 28.4 | 4.756 | 7.051 | 602.3 | 14.23 | 43.14 |

Table 4.15. Calculated values of brake torque, brake power, brake mean effective pressure, specific fuel consumption, brake thermal efficiency and volumetric efficiencyfrom experimental readings at compression ratio of 8

| **N (rpm)** | **Torque, T (Nm)** | **(kW)** | **BMEP(bar)** | **SFC (g/kWh)** | **(%)** | **(%)** |
|---|---|---|---|---|---|---|
| 1100 | 33.1 | 3.811 | 8.218 | 554.1 | 15.47 | 46.85 |
| 1200 | 33.0 | 4.145 | 8.193 | 536.1 | 15.97 | 46.00 |
| 1300 | 32.9 | 4.477 | 8.168 | 509.7 | 16.82 | 47.59 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1400 | 31.6 | 4.630 | 7.845 | 494.1 | 17.35 | 46.82 |
| 1500 | 30.5 | 4.789 | 7.572 | 519.0 | 16.52 | 45.64 |
| 1600 | 28.6 | 4.790 | 7.101 | 532.8 | 16.09 | 43.50 |

Table 4.16. Calculated values of brake torque, brake power, brake mean effective pressure, specific fuel consumption, brake thermal efficiency and volumetric efficiency from experimental readingsat compression ratio of 9.

| **N (rpm)** | **Torque, T (Nm)** | **(kW)** | **BMEP (bar)** | **SFC(g/kWh)** | **(%)** | **(%)** |
|---|---|---|---|---|---|---|
| 1100 | 33.3 | 4.834 | 8.267 | 517.0 | 16.58 | 47.53 |
| 1200 | 33.1 | 4.157 | 8.218 | 486.9 | 17.60 | 48.30 |
| 1300 | 32.9 | 4.477 | 8.168 | 464.2 | 18.47 | 50.42 |
| 1400 | 31.7 | 4.645 | 7.870 | 456.6 | 18.77 | 47.66 |
| 1500 | 30.7 | 4.820 | 7.622 | 451.6 | 18.98 | 46.02 |
| 1600 | 29.1 | 4.873 | 7.225 | 464.8 | 18.44 | 44.88 |

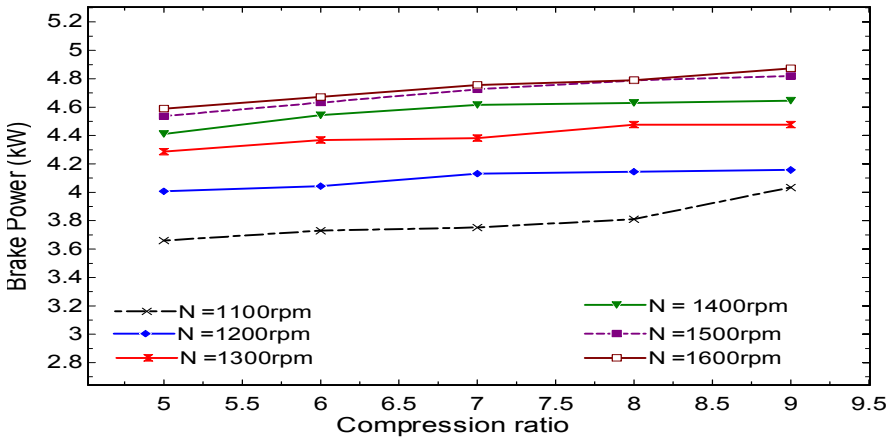



*Figure 4.1. Variation of experimental brake power with compression ratio for different engine speeds.*

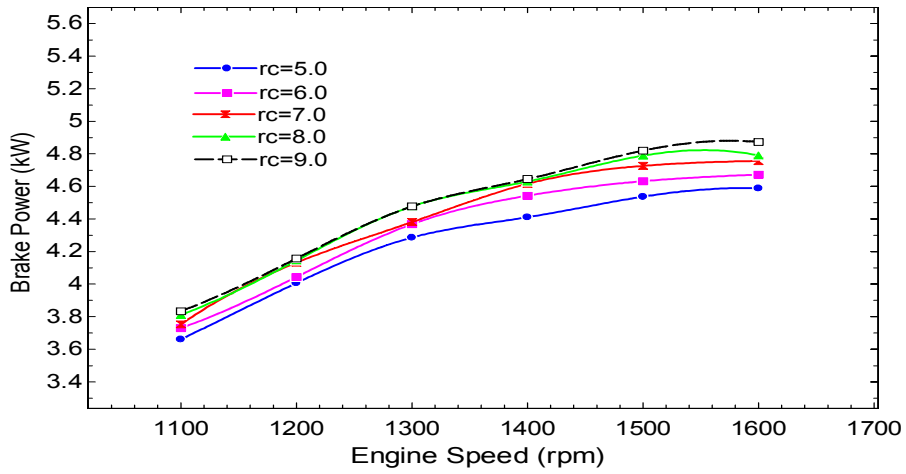



*Figure 4.2.Variation of experimental brake power with engine speed for different compression ratios*

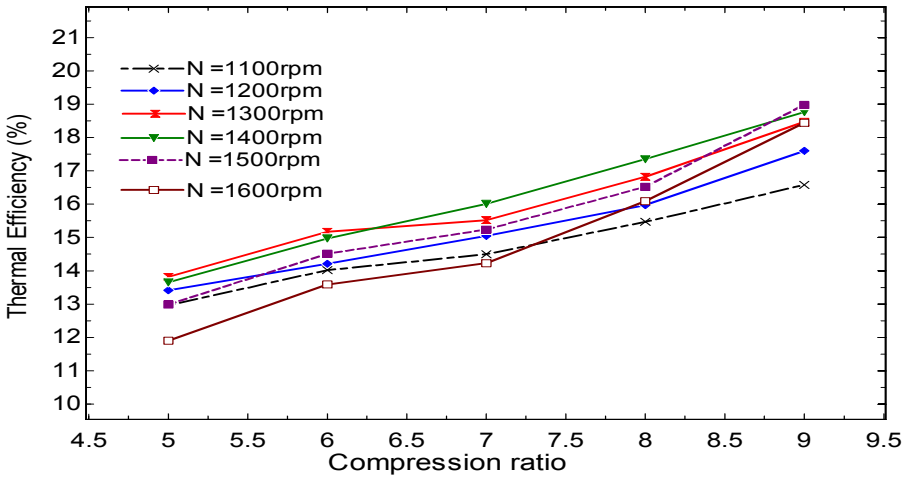



*Figure 4.3. Variation of experimental thermal efficiency with compression ratio for different engine speeds.*

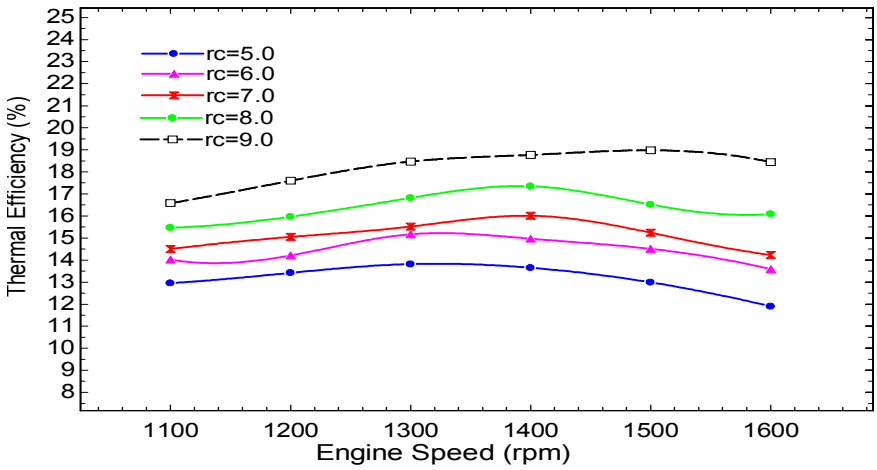



*Figure 4.4.Variation of experimental thermal efficiency with engine speed for different compression ratios.*

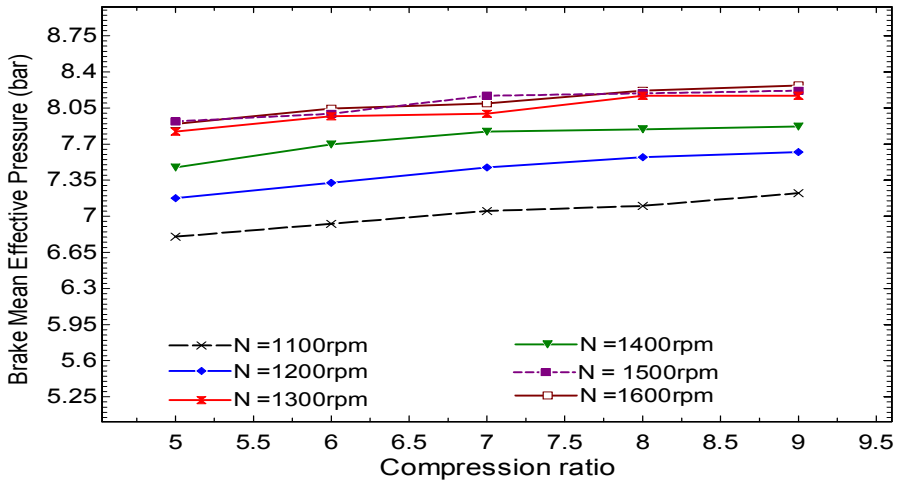



*Figure 4.5.Variations of brake mean effective pressure with compression ratio for different engine speeds.*

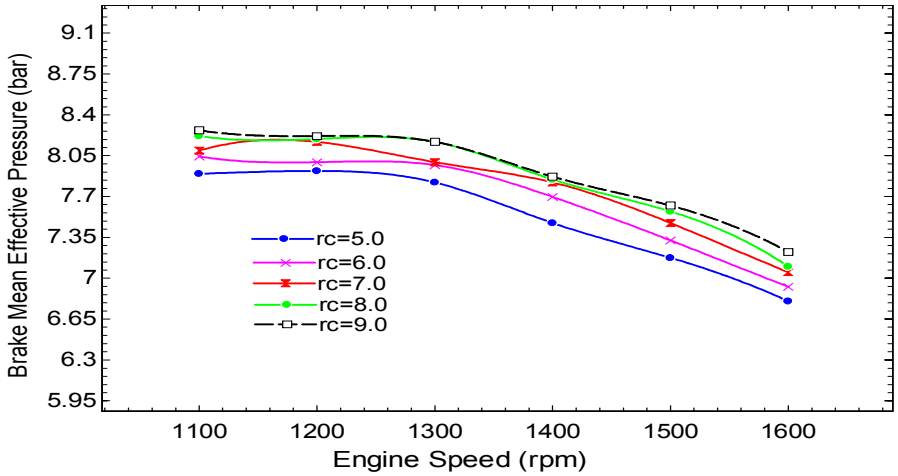



*Figure 4.6.Variations of brake mean effective pressure with engine speed for different compression ratios.*

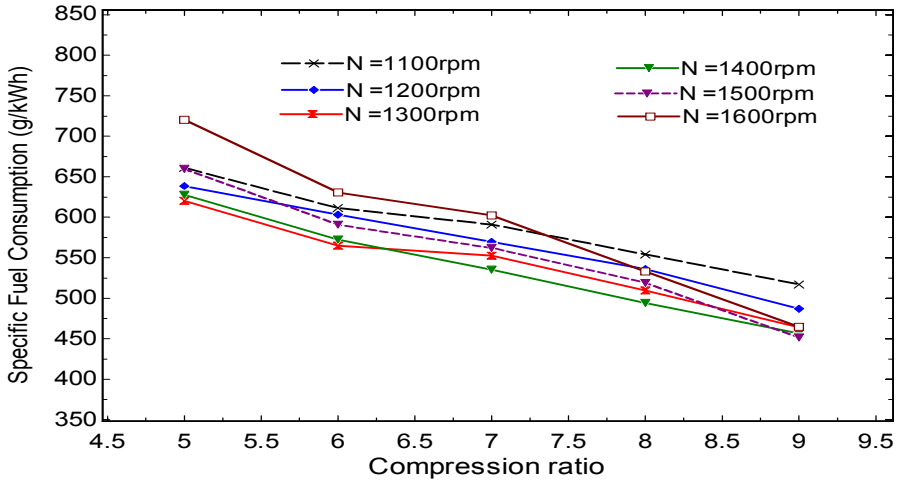



*Figure 4.7. Variation of experimental specific fuel consumption with compression ratio for different engine speeds.*

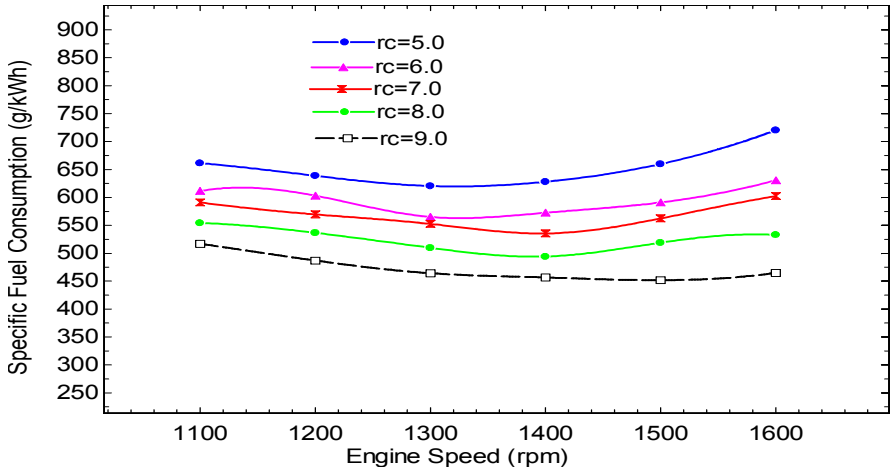



*Figure 4.8.Variation of experimental specific fuel consumption with engine speed for different compression ratios.*

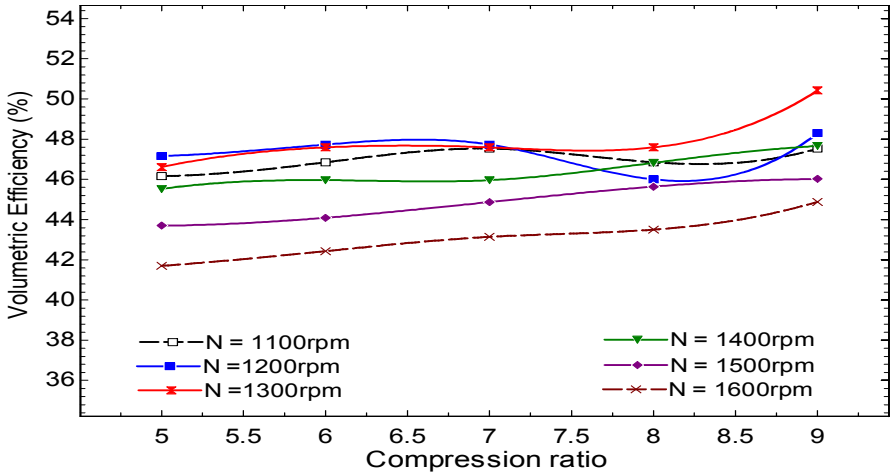



*Figure 4.9. Variation of experimental volumetric efficiency with compression ratio for different engine speeds.*

## 4.1 Discussion of Results

### 4.1.1 Effect of varying experimental compression ratio on the engine brake power

Figure4.1 shows the effects of varying the engine compression ratio on the engine's brake power at different compression ratios and engine speeds. It is noticed that the engine brake power increases as the compression ratio is increased. This is due to the increase in brake torque at high compression ratios. Increase in compression ratio induces greater turning effect on the cylinder crank. That means that the engine is giving more push on the piston, and hence more torque is generated. Equation (2.2) also shows that the engine torque is directly related to the brake power. The maximum brake power for this engine test occurred between 1500 and 1600rpm as shown in figure4.1 for compression ratio of 9. The maximum brake power for compression ratio of 5also occurs at 1600rpm, but it is significantly lower.The effect of varying compression ratio on brake power can also be shown in Figure4.2 by plotting the brake power against engine speeds for different compression ratios. It is shown that increase in compression ratio alongside the engine speed leads to greater brake power.

### 4.1.2 Effect of varying experimental compression ratio on the engine brake thermal efficiency

At the lowest compression ratio of 5 and highest engine speed of 1600rpm, the thermal efficiency is significantly lower. The mixture of fuel drawn in to the cylinder is not sufficiently compressed. At the same speed of 1600rpm and compression ratio of 9 however, thermal efficiency is seen to increase steadily.

Figure 4.3 show that compression ratio of 9 registered the highest thermal efficiency for the engine. By compressing the available air and fuel mixture into a very small space, together

with the heat of compression, causes better mixing and evaporation of the fuel. Greater combustion efficiency from increasing compression ratio means that the combustion of the fuel pays greater dividends by more energy released from the fuel. The net result is that the increase in energy available is greater. The highest thermal efficiency, according to figure 4.3 occurredat 1500rpm and compression ratio of 9

### 4.1.3 Effect of varying experimental compression ratio on brake mean effective pressure

Increase in the brake mean effective pressure in the cylinder(from high temperature and pressure of the working fluid at the end of combustion), is developed by increased in the compression ratiosas shown in figure 4.5. The figure also shows that the mean effective pressure reduces with engine speed. Equation 2.3 also agrees with this. As the compression ratio increases, the cylinder is subjected to higher temperatures, leading to higher brake mean effective pressures. Equation 2.4 also shows that brake mean effective pressure is directly proportional to the torque. From figure 4.5, compression ratios of 8 and 9 developed the highest brake mean effective pressure. A plot of the brake mean effective pressure against speed for the various compression ratios is shown in figure 4.6; similar resultsare obtained showing that increasing the compression ratio from 5 to 8 and 9, increases the brake mean effective pressure.

### 4.1.4 Effect of varying experimental compression ratio on fuel consumption parameters

The effects of varying the compression ratios on the engine's fuel consumption parameters are shown in figure 4.7. Figure 4.7 can be understood with the help of the result in Figure 4.3 and 4.4. From equation (2.8), the specific fuel consumption is inversely proportional to the thermal efficiency. As the compression ratio increases, the fuel mixture is sufficiently compressed thereby increasing the thermal efficiency, so that less fuel is used to produce the same amount of energy. Fuel consumption per kilowatts of time is reduced at higher compression ratios between 8 and 9. With the increase in compression ratios,a higher engine speed of 1600rpm favours the reduction in fuel consumption as shown in Figure4.7. Figure 4.8 further shows the variation of the specific fuel consumption with engine speed for different compression ratios. In the figure, it is clearly shown that the highest compression ratio of 9gave the lowest specific fuel consumption; whereas at compression ratio of 5, the specific fuel consumption recorded the highest value.

### 4.1.5 Effect of varying experimental compression ratio on volumetric efficiency

In general, the volumetric efficiency increases very slowly with increase compression ratio.However, Figure 4.9 shows that beyond compression ratio of 8, the volumetric efficiency increases rapidly. By increasing the compression ratio, the clearance volume reduces; therebyreducing the denominator of equation(2.12). At compression ratio of 9 and at low engine speeds of 1200 and 1300 rpm, the volumetric efficiency is relatively higher compared to high engine speeds of 1500 and 1600 rpm. This is because the engine speed is inversely proportional to the volumetric efficiency (equation 2.12).

## 4.2 Improvement in the Engine Performance Characteristics from Increase in the Compression Ratio

Improvement in the engine performance characteristics from increase in the compression ratio from 5 to 6, 6 to 7, 7 to 8 and 8 to 9 were calculated and tabulated.

Table 4.17.Improvement in brake power

| **N (rpm)** | **(%) Increase in (kW)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **=5** | **=6** | **=7** | **=8** | **=9** | **from =5 to =6** | **from =6 to =7** | **from =7 to =8** | **from =8 to =9** | **Average (%)** |
| 1100 | 3.661 | 3.730 | 3.753 | 3.811 | 3.834 | 1.88 | 0.62 | 1.55 | 0.60 | 1.16 |
| 1200 | 4.007 | 4.044 | 4.132 | 4.145 | 4.157 | 0.92 | 2.18 | 0.31 | 0.29 | 0.93 |
| 1300 | 4.286 | 4.368 | 4.381 | 4.477 | 4.417 | 1.91 | 0.29 | 2.91 | 1.34 | 1.61 |
| 1400 | 4.411 | 4.543 | 4.616 | 4.630 | 4.645 | 2.99 | 1.61 | 0.30 | 0.32 | 1.31 |
| 1500 | 4.537 | 4.632 | 4.726 | 4.789 | 4.820 | 2.09 | 2.03 | 1.33 | 0.65 | 1.53 |
| 1600 | 4.589 | 4.672 | 4.756 | 4.790 | 4.873 | 1.81 | 1.80 | 0.71 | 1.73 | 1.51 |
| | | | | | | | | Grand average = | | 1.34 |

Table 4.18.Improvement in brake thermal efficiency

| **N (rpm)** | **(%) Increase in** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **=5** | **=6** | **=7** | **=8** | **=9** | **from =5 to =6** | **from =6 to =7** | **from =7 to =8** | **from =8 to =9** | **Average (%)** |
| 1100 | 12.96 | 14.02 | 14.50 | 15.47 | 16.58 | 8.18 | 3.42 | 6.69 | 7.18 | 6.37 |
| 1200 | 13.42 | 14.21 | 15.05 | 15.97 | 17.6 | 5.81 | 5.91 | 6.11 | 10.21 | 7.01 |
| 1300 | 13.82 | 15.17 | 15.52 | 16.82 | 18.47 | 9.77 | 2.31 | 8.38 | 9.81 | 7.57 |
| 1400 | 13.65 | 14.97 | 16.01 | 17.35 | 18.77 | 9.67 | 7.23 | 8.37 | 8.18 | 8.34 |
| 1500 | 12.99 | 14.51 | 15.24 | 16.52 | 18.98 | 11.7 | 5.03 | 8.40 | 14.89 | 10.01 |
| 1600 | 11.9 | 13.59 | 14.23 | 16.09 | 18.44 | 14.2 | 4.71 | 13.07 | 14.61 | 11.65 |
| | | | | | | | | Grand average = | | 8.49 |

Table 4.19.Reduction in specific fuel consumption

| N (rpm) | (%) Increase in SFC (g/kW h) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | =5 | =6 | =7 | =8 | =9 | from =5 to =6 | from =6 to =7 | from =7 to =8 | from =8 to =9 | Average (%) |
| 1100 | 661.2 | 611.0 | 591.0 | 555.1 | 517.0 | 7.53 | 3.34 | 6.66 | 6.70 | 6.06 |
| 1200 | 638.6 | 603.1 | 569.5 | 536.1 | 486.9 | 5.56 | 5.57 | 5.86 | 9.18 | 6.54 |
| 1300 | 620.3 | 565.0 | 552.5 | 509.7 | 464.2 | 8.92 | 2.21 | 7.75 | 8.93 | 6.95 |
| 1400 | 627.9 | 572.5 | 535.4 | 494.1 | 456.6 | 8.82 | 6.48 | 7.71 | 7.59 | 7.65 |
| 1500 | 659.7 | 590.9 | 562.3 | 519.0 | 451.6 | 10.43 | 4.84 | 7.70 | 12.99 | 8.99 |
| 1600 | 720.3 | 630.7 | 602.3 | 532.8 | 464.8 | 12.44 | 4.50 | 11.54 | 12.76 | 10.31 |
| | | | | | | | | Grand average = | | 7.75 |

Table 4.20.Improvement in brake mean effective pressure

| N (rpm) | (%) Increase in BMEP(bar) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | =5 | =6 | =7 | =8 | =9 | from =5 to =6 | from =6 to =7 | from =7 to =8 | from =8 to =9 | Average (%) |
| 1100 | 7.89500 | 8.04396 | 8.09362 | 8.21775 | 8.26740 | 1.89 | 0.62 | 1.53 | 0.60 | 1.16 |
| 1200 | 7.91983 | 7.99431 | 8.16810 | 8.19292 | 8.21775 | 0.93 | 2.17 | 0.30 | 0.30 | 0.93 |
| 1300 | 7.82052 | 7.96948 | 7.99431 | 8.11810 | 8.16810 | 1.89 | 0.31 | 2.17 | 0.62 | 1.25 |
| 1400 | 7.47294 | 7.69638 | 7.82052 | 7.84534 | 7.87017 | 2.98 | 1.63 | 0.32 | 0.32 | 1.31 |
| 1500 | 7.17501 | 7.32398 | 7.47294 | 7.57225 | 7.62190 | 2.08 | 2.03 | 1.33 | 0.66 | 1.53 |
| 1600 | 6.80261 | 6.92674 | 7.05088 | 7.10053 | 7.22467 | 1.82 | 1.79 | 0.74 | 1.75 | 1.53 |
| | | | | | | | | Grand average = | | 1.29 |

## 4.3 Comparison between Experimental and Theoretical Values

Here, comparisons between the experimental and theoretical values are shown graphically for the various compression ratios in terms of the brake power, brake thermal efficiency, specific fuel consumption and brake mean effective pressure. The errors in the theoretical values are given in the tables.

Table 4.21.Percentage error between experimental and theoretical values for brake power and brake mean effective pressure at compression ratio of 5

| **N (rpm)** | **Experimental** | | **Theoretical** | | **Error (%)** | |
|---|---|---|---|---|---|---|
| | **(kW)** | **BMEP (bar)** | **(kW)** | **BMEP (bar)** | | **BMEP** |
| 1100 | 3.661 | 7.895 | 3.653 | 7.877 | -0.22 | -0.23 |
| 1200 | 4.007 | 7.920 | 4.022 | 7.951 | 0.37 | 0.39 |
| 1300 | 4.286 | 7.821 | 4.262 | 7.777 | -0.56 | -0.56 |
| 1400 | 4.411 | 7.473 | 4.488 | 7.604 | 1.75 | 1.75 |
| 1500 | 4.537 | 7.175 | 4.588 | 7.256 | 1.12 | 1.13 |
| 1600 | 4.589 | 6.803 | 4.610 | 6.834 | 0.46 | 0.46 |
| | | Average percentage error | | | =0.75% | =0.75% |

Table 4.22. Percentage error between experimental and theoretical values for brake power and brake mean effective pressure atcompression ratio of 6

| **N (rpm)** | **Experimental** | | **Theoretical** | | **Error (%)** | |
|---|---|---|---|---|---|---|
| | **(kW)** | **BMEP (bar)** | **(kW)** | **BMEP (bar)** | | **BMEP** |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1100 | 3.730 | 8.044 | 3.645 | 7.86 | -2.28 | -2.29 |
| 1200 | 4.044 | 7.994 | 4.014 | 7.935 | -0.74 | -0.74 |
| 1300 | 4.368 | 7.969 | 4.253 | 7.761 | -2.63 | -2.61 |
| 1400 | 4.543 | 7.696 | 4.478 | 7.587 | -1.43 | -1.42 |
| 1500 | 4.632 | 7.324 | 4.578 | 7.24 | -1.17 | -1.15 |
| 1600 | 4.672 | 6.927 | 4.599 | 6.817 | -1.56 | -1.59 |
| | | Average percentage error | | | =1.64% | =1.63% |

Table 4.23. Percentage error between experimental and theoretical values for brake power and brake mean effective pressure at compression ratio of 7

| **N (rpm)** | **Experimental** | | **Theoretical** | | **Error (%)** | |
|---|---|---|---|---|---|---|
| | **(kW)** | **BMEP (bar)** | **(kW)** | **BMEP (bar)** | | **BMEP** |
| 1100 | 3.753 | 8.094 | 3.76 | 8.108 | 0.19 | 0.17 |
| 1200 | 4.132 | 8.168 | 4.139 | 8.182 | 0.17 | 0.17 |
| 1300 | 4.381 | 7.994 | 4.389 | 8.009 | 0.17 | 0.19 |
| 1400 | 4.616 | 7.821 | 4.624 | 7.835 | 0.17 | 0.32 |
| 1500 | 4.726 | 7.473 | 4.735 | 7.487 | 0.19 | 0.19 |
| 1600 | 4.756 | 7.051 | 4.766 | 7.065 | 0.21 | 0.20 |
| | | Average percentage error | | | = 018% | =0.21% |

Table 4.24. Percentage error between experimental and theoretical values for brake power and brake mean effective pressure at compression ratio of 8

| **N (rpm)** | **Experimental** | | **Theoretical** | | **Error (%)** | |
|---|---|---|---|---|---|---|
| | **(kW)** | **BMEP (bar)** | **(kW)** | **BMEP (bar)** | | **BMEP** |
| 1100 | 3.811 | 8.218 | 3.875 | 8.356 | 1.68 | 1.68 |
| 1200 | 4.145 | 8.193 | 4.265 | 8.43 | 2.89 | 2.89 |
| 1300 | 4.477 | 8.168 | 4.525 | 8.256 | 1.07 | 1.08 |
| 1400 | 4.630 | 7.845 | 4.770 | 8.082 | 3.02 | 3.02 |
| 1500 | 4.789 | 7.572 | 4.891 | 7.735 | 2.13 | 2.15 |
| 1600 | 4.790 | 7.101 | 4.933 | 7.313 | 2.99 | 2.99 |
| | | Average percentage error | | | =2.29% | =2.30% |

Table 4.25.Percentage error betweenexperimental and theoretical values for brake power and brake mean effective pressure at compression ratio of 9

| **N (rpm)** | **Experimental** | | **Theoretical** | | **Error (%)** | |
|---|---|---|---|---|---|---|
| | **(kW)** | **BMEP (bar)** | **(kW)** | **BMEP (bar)** | | **BMEP** |
| 1100 | 3.834 | 8.267 | 3.881 | 8.368 | 1.23 | 1.22 |
| 1200 | 4.157 | 8.218 | 4.271 | 8.446 | 2.74 | 2.77 |
| 1300 | 4.477 | 8.168 | 4.532 | 8.269 | 1.23 | 1.24 |
| 1400 | 4.645 | 7.870 | 4.778 | 8.095 | 2.86 | 2.86 |
| 1500 | 4.820 | 7.622 | 4.899 | 7.747 | 1.64 | 1.64 |
| 1600 | 4.873 | 7.225 | 4.941 | 7.325 | 1.39 | 1.38 |
| | | Average percentage error | | | =%1.85 | =1.85% |

Table 4.26. Percentage error between experimental and theoretical values for specific fuel consumption and brake thermal efficiency at compression ratio of 5

| **N (rpm)** | **Experimental** | | **Theoretical** | | **Error (%)** | |
|---|---|---|---|---|---|---|
| | **SFC (g/kWh)** | **(%)** | **SFC (g/kWh)** | **(%)** | **SFC** | |
| 1100 | 661.2 | 12.96 | 673 | 12.74 | 1.78 | -1.69 |
| 1200 | 638.6 | 13.42 | 648.6 | 13.22 | 1.57 | -1.49 |
| 1300 | 620.3 | 13.82 | 629.2 | 13.62 | 1.43 | -1.45 |
| 1400 | 627.9 | 13.65 | 609.6 | 14.06 | -2.91 | 3.00 |
| 1500 | 659.7 | 12.99 | 640.3 | 13.39 | -2.94 | 3.08 |
| 1600 | 720.3 | 11.9 | 685.8 | 12.5 | -4.79 | 5.04 |
| | | Average percentage error | | | =2.57% | =2.13% |

Table 4.27. Percentage error between experimental and theoretical values for specific fuel consumption and thermal efficiency at compression ratio of 6

| **N (rpm)** | **Experimental** | | **Theoretical** | | **Error (%)** | |
|---|---|---|---|---|---|---|
| | **SFC (g/kWh)** | **(%)** | **SFC (g/kWh)** | **(%)** | **SFC** | |
| 1100 | 611.4 | 14.02 | 624.4 | 13.73 | 2.13 | -2.07 |
| 1200 | 603.1 | 14.21 | 601.8 | 14.24 | -0.22 | 0.21 |
| 1300 | 565.0 | 15.17 | 583.7 | 14.68 | 3.31 | -3.23 |
| 1400 | 572.5 | 14.97 | 565.6 | 15.15 | -1.21 | 1.2 |
| 1500 | 590.9 | 14.51 | 594.1 | 14.43 | 0.54 | -0.55 |
| 1600 | 630.7 | 13.59 | 636.3 | 13.47 | 0.88 | -0.88 |
| | | Average percentage error | | | =1.38% | =1.36% |

Table 4.28.Percentage error between the experimental and theoretical values for specific fuel consumption and thermal efficiency at compression ratio of 7

| **N (rpm)** | **Experimental** | | **Theoretical** | | **Error (%)** | |
|---|---|---|---|---|---|---|
| | **SFC (g/kWh)** | **(%)** | **SFC (g/kWh)** | **(%)** | **SFC** | |
| 1100 | 591.0 | 14.50 | 595.1 | 14.44 | 0.69 | -0.41 |
| 1200 | 569.5 | 15.05 | 573.5 | 14.98 | 0.7 | -0.47 |
| 1300 | 552.5 | 15.52 | 556.3 | 15.45 | 0.69 | -0.45 |
| 1400 | 535.4 | 16.01 | 539 | 15.94 | 0.67 | -0.44 |
| 1500 | 562.3 | 15.24 | 566.2 | 15.18 | 0.69 | -0.39 |
| 1600 | 602.3 | 14.23 | 606.4 | 14.17 | 0.68 | -0.42 |
| | | Average percentage error | | | =0.69% | =0.43% |

Table 4.29. Percentage error between experimental and theoretical values for specific fuel consumption and brake thermal efficiency at compression ratio of 8

| **N (rpm)** | **Experimental** | | **Theoretical** | | **Error (%)** | |
|---|---|---|---|---|---|---|
| | **SFC (g/kWh)** | **(%)** | **SFC (g/kWh)** | **(%)** | **SFC** | |
| 1100 | 554.1 | 15.47 | 565.7 | 15.15 | 2.09 | -2.07 |
| 1200 | 536.1 | 15.97 | 545.2 | 15.72 | 1.70 | -1.57 |
| 1300 | 509.7 | 16.82 | 528.9 | 16.21 | 3.77 | -3.63 |
| 1400 | 494.1 | 17.35 | 512.4 | 16.73 | 3.7 | -3.57 |
| 1500 | 519.0 | 16.52 | 538.2 | 15.93 | 3.69 | -3.57 |
| 1600 | 532.8 | 16.09 | 576.5 | 14.87 | 8.2 | -7.58 |
| | | Average percentage error | | | = 3.86% | = 3.67% |

Table 4.30. Percentage error between experimental and theoretical values for specific fuel consumption and brake thermal efficiency for compression ratio of 9

| **N (rpm)** | **Experimental** | | **Theoretical** | | **Error (%)** | |
|---|---|---|---|---|---|---|
| | **SFC (g/kWh)** | **(%)** | **SFC (g/kWh)** | **(%)** | **SFC** | |
| 1100 | 517.0 | 16.58 | 546.3 | 15.69 | 5.67 | -5.36 |
| 1200 | 486.9 | 17.60 | 526.5 | 16.28 | 8.13 | -7.5 |
| 1300 | 464.2 | 18.47 | 510.7 | 16.78 | 10.01 | -9.15 |
| 1400 | 456.6 | 18.77 | 494.9 | 17.32 | 8.34 | -7.73 |
| 1500 | 451.6 | 18.98 | 519.8 | 16.49 | 15.1 | -13.12 |
| 1600 | 464.8 | 18.44 | 556.7 | 15.4 | 19.77 | -16.49 |
| | | Average percentage error | | | =11.17% | =9.89% |

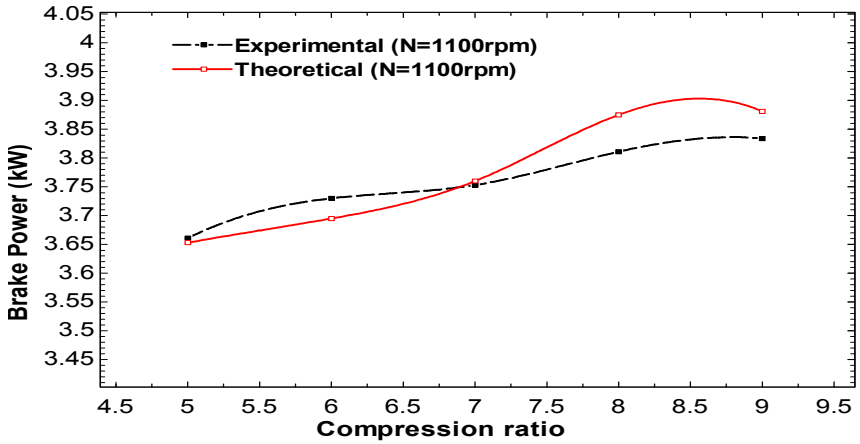



*Figure 4.10.Variation of brake power with compression ratio at engine speed of 1100rpm*

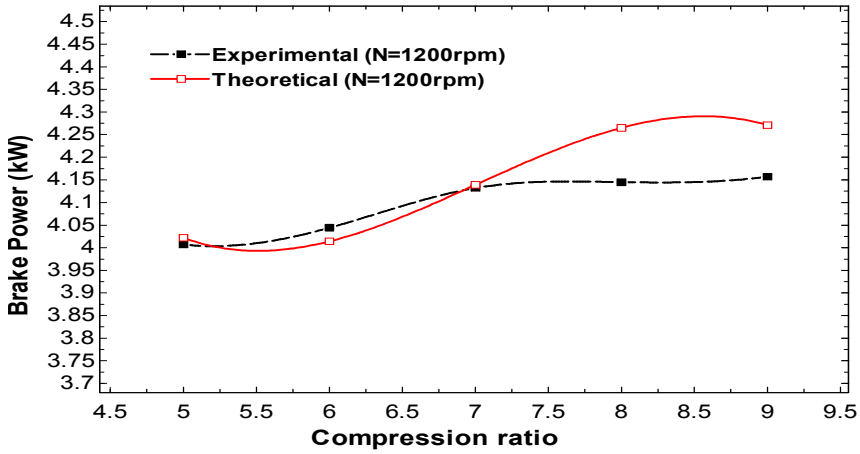



*Figure 4.11.Variation of brake power with compression ratio at engine speed of 1200rpm*

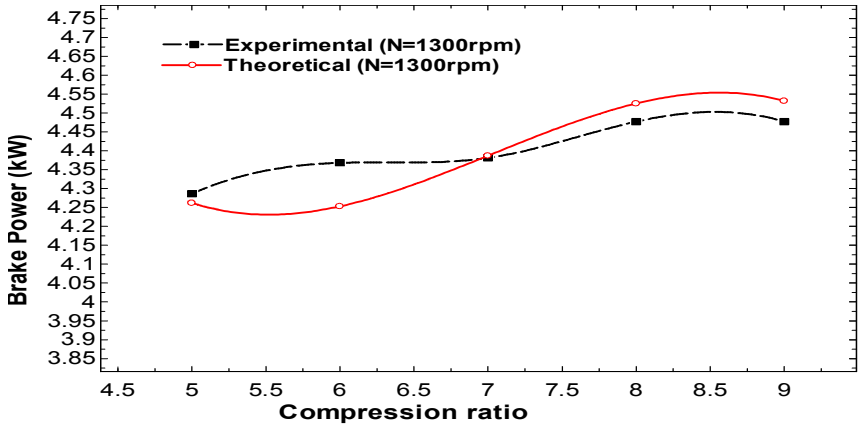



*Figure4.12.Variation of brake power with compression ratio at engine speed of 1300rpm*

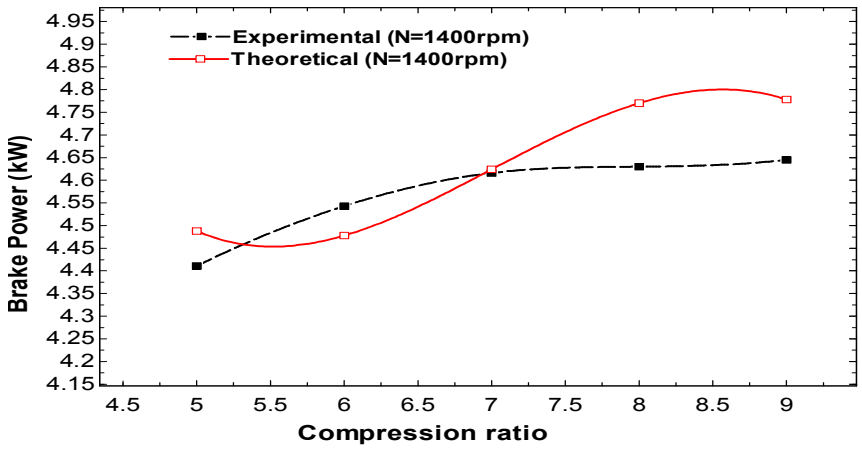



*Figure 4.13.Variation of brake power with compression ratio at engine speed of 1400rpm*

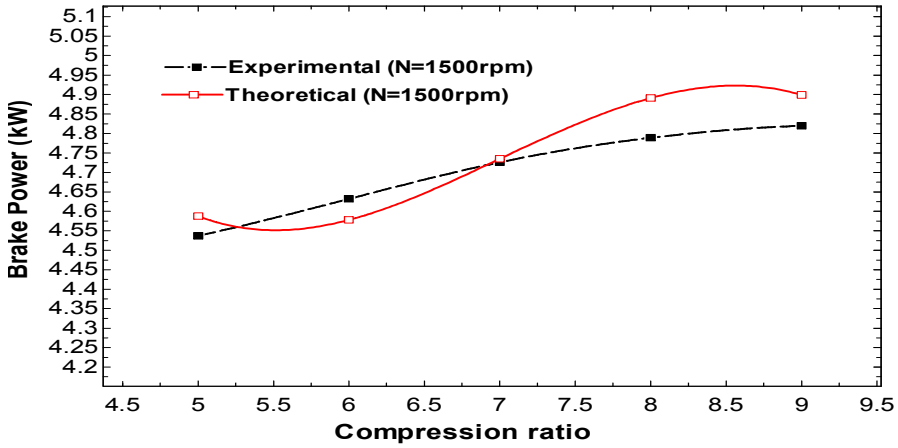



*Figure 4.14.Variation of brake power with compression ratio at engine speed of 1500rpm*

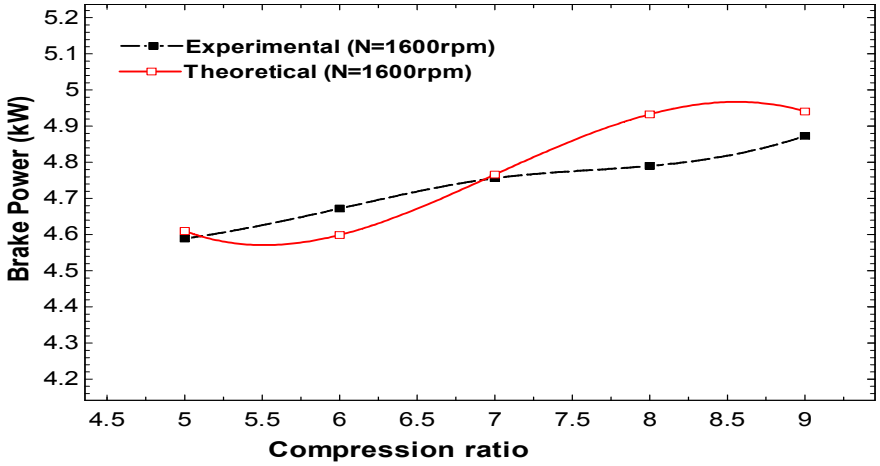



*Figure 4.15.Variation of brake power with compression ratio at engine speed of 1600rpm*

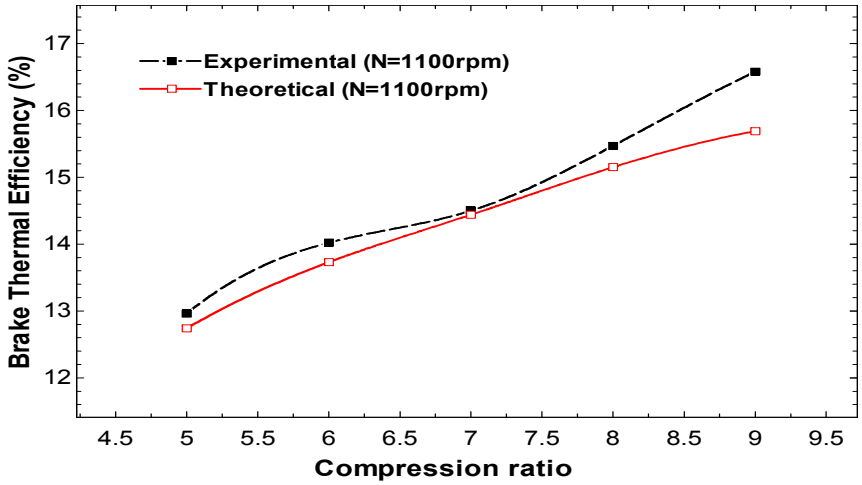



*Figure 4.16.Variation of brake thermal efficiency with compression ratio at engine speed of 1100rpm*

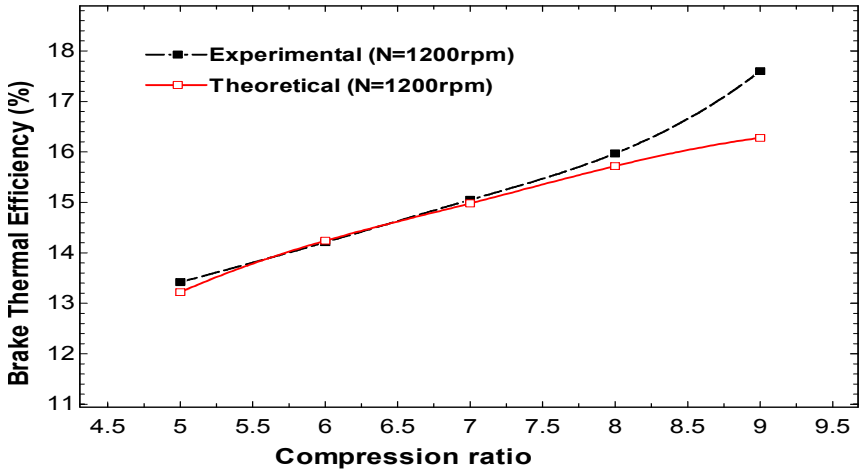



*Figure4.17.Variation of brake thermal efficiency with compression ratio at engine speed of 1200rpm*

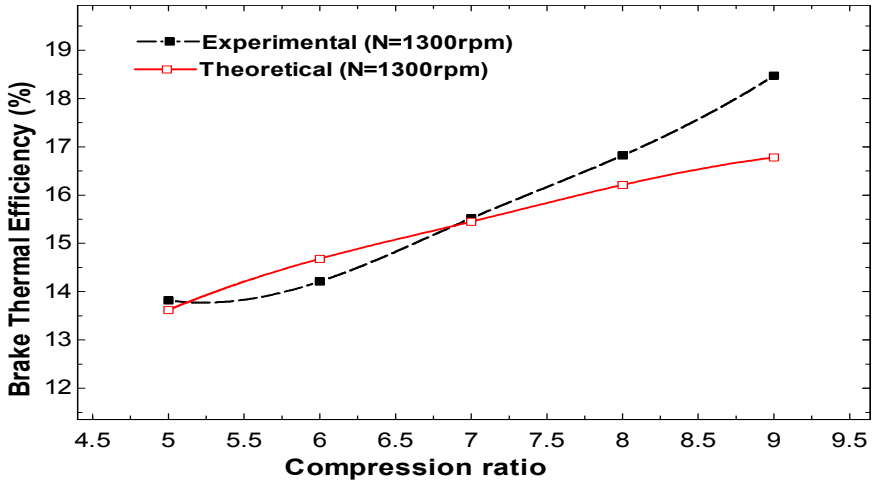



*Figure 4.18.Variation of brake thermal efficiency with compression ratio at engine speed of 1300rpm*

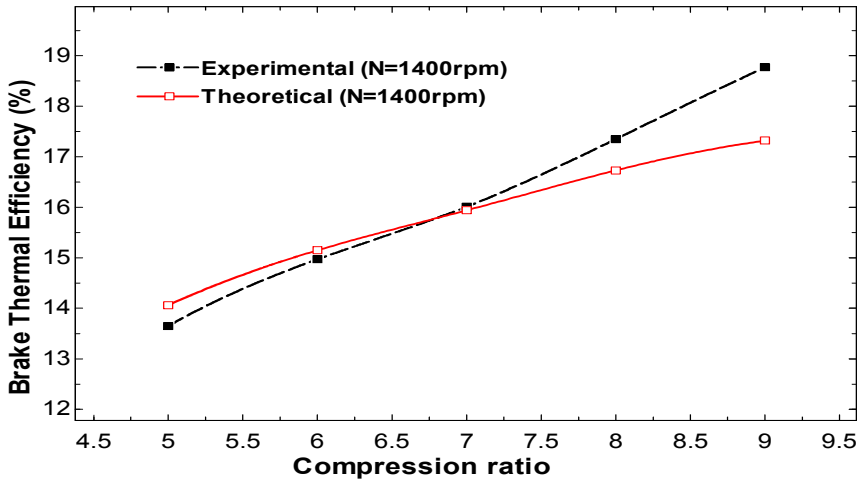



*Figure 4.19.Variation of brake thermal efficiency with compression ratio at engine speed of 1400rpm*

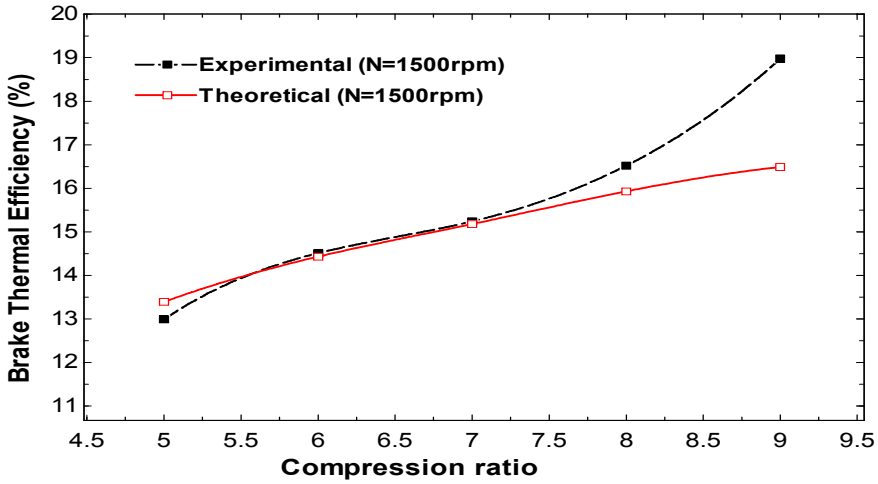



*Figure 4.20.Variation of brake thermal efficiency with compression ratio at engine speed of 1500rpm*

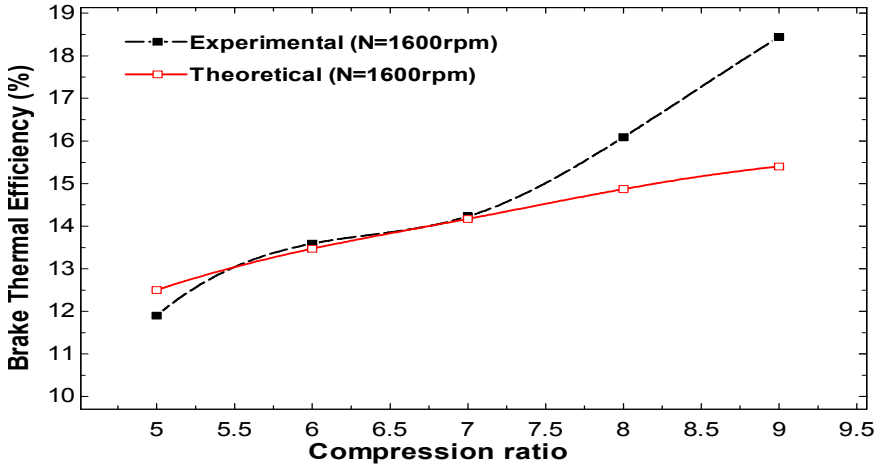



*Figure 4.21.Variation of brake thermal efficiency with compression ratio at engine speed of 1600rpm*

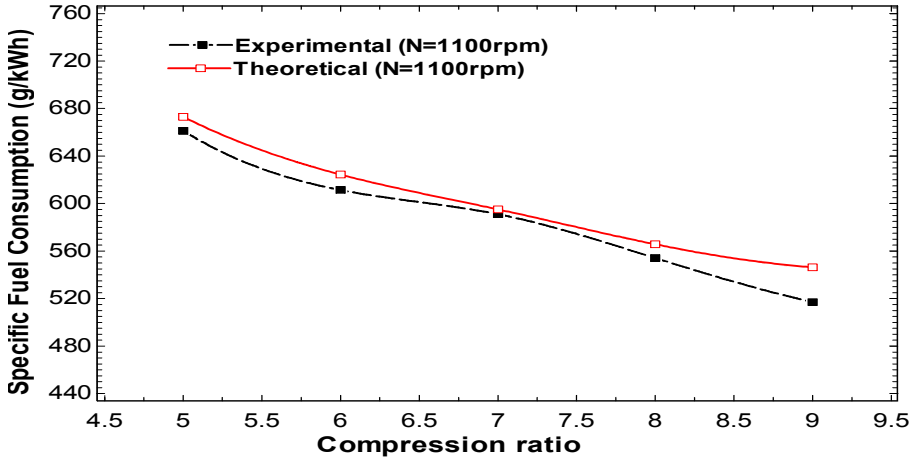



*Figure 4.22.Variation of thespecific fuel consumption with compression ratio at engine speed of 1100rpm.*

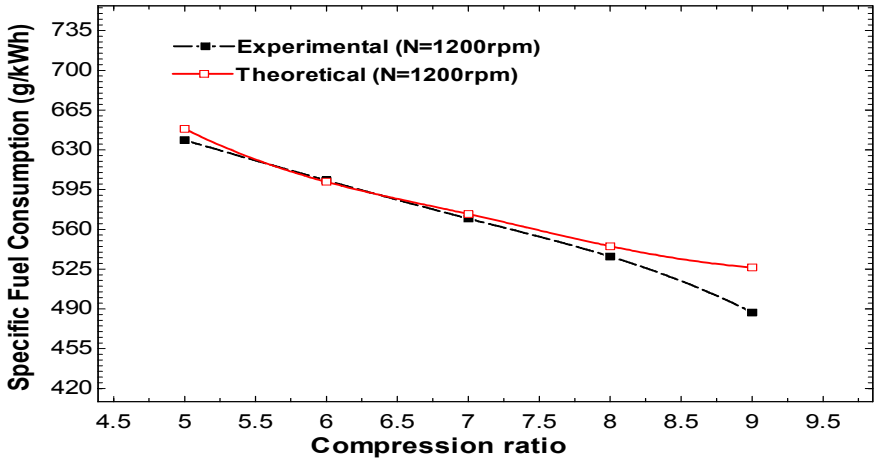



*Figure 4.23.Variation of thespecific fuel consumption with compression ratio at engine speed of 1200rpm.*

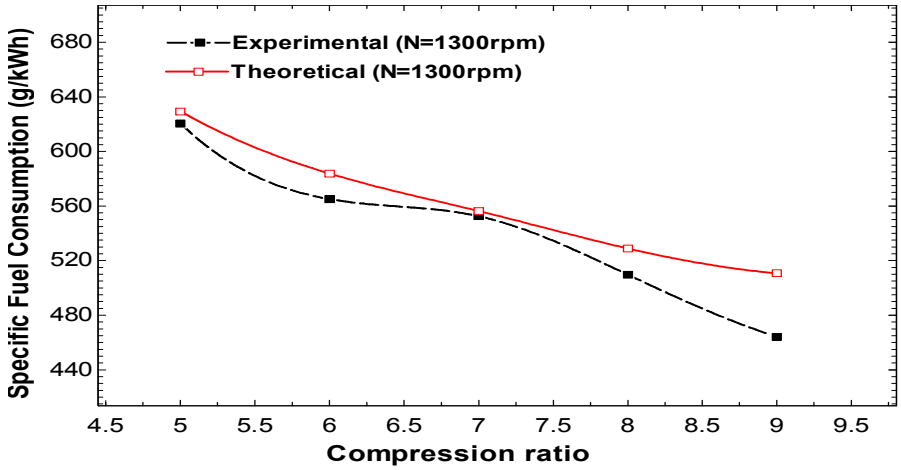



*Figure 4.24.Variation of thespecific fuel consumption with compression ratio at engine speed of 1300rpm.*

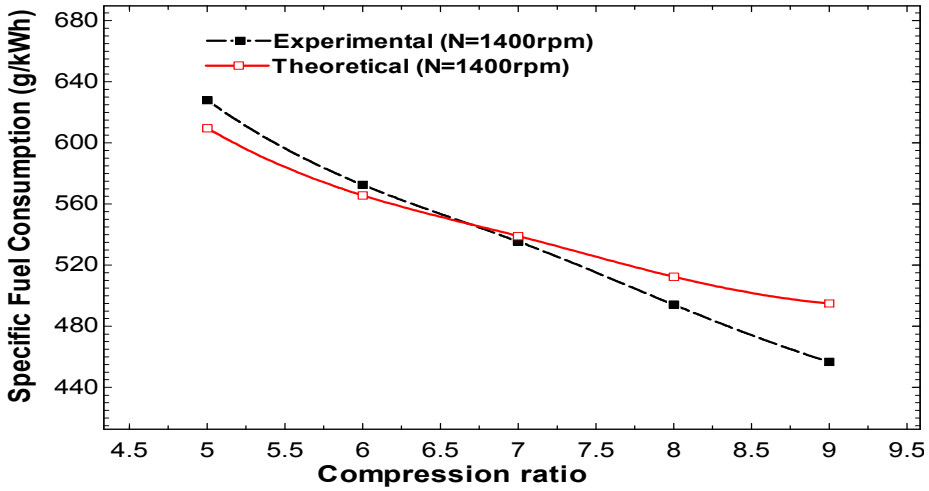



*Figure 4.25.Variation of thespecific fuel consumption with compression ratio at engine speed of 1400rpm.*

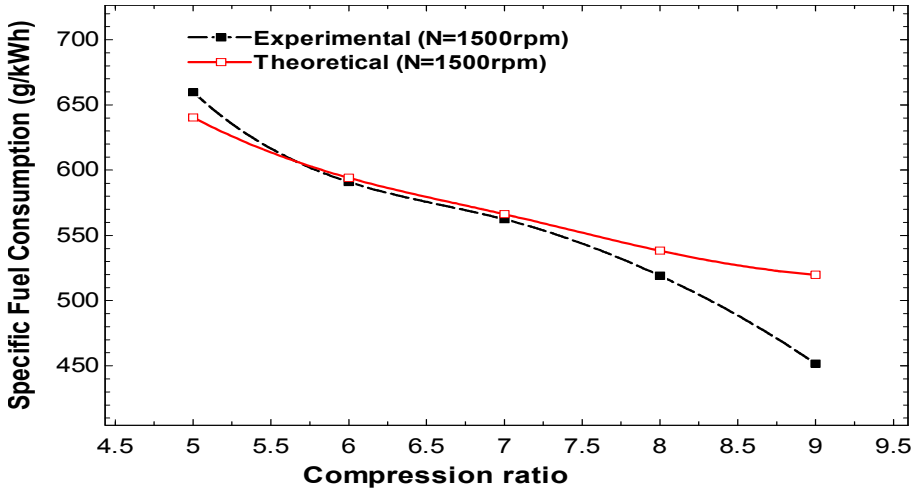



*Figure 4.26.Variation of thespecific fuel consumption with compression ratio at engine speed of 1500rpm.*

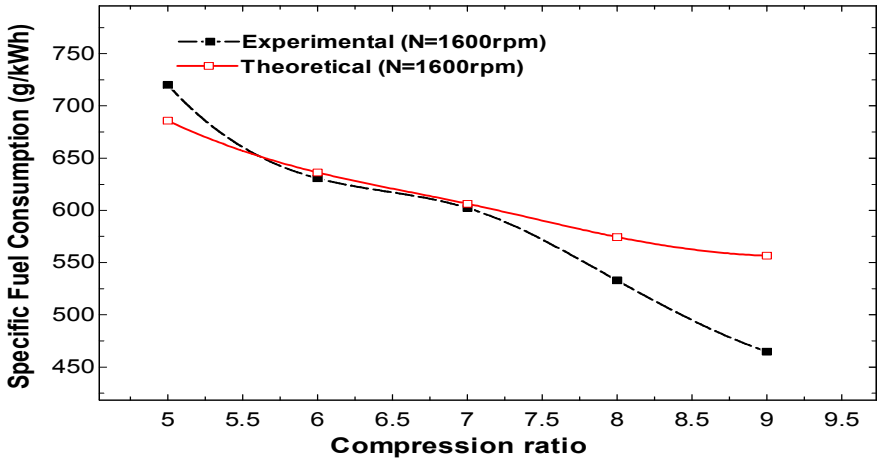



*Figure 4.27.Variation of thespecific fuel consumption with compression ratio at engine speed of 1600rpm.*

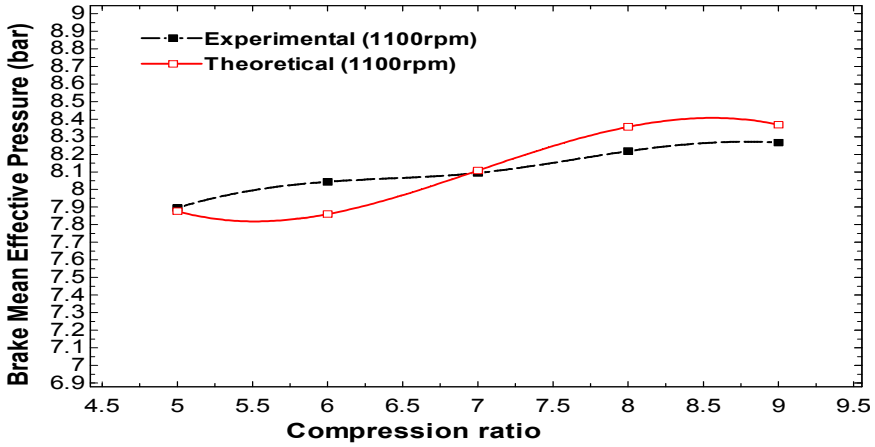



*Figure 4.28.Variation of brake mean effective pressure with compression ratio at engine speed of 1100rpm.*

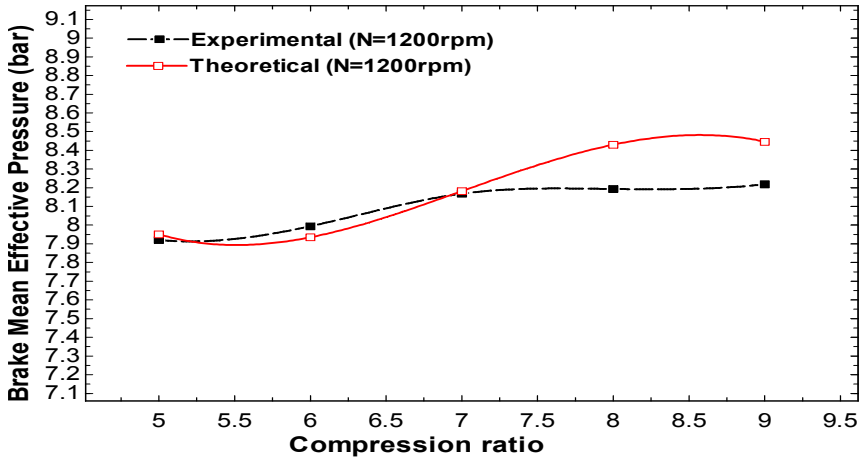



*Figure 4.29.Variation of brake mean effective pressure with compression ratio at engine speed of 1200rpm.*

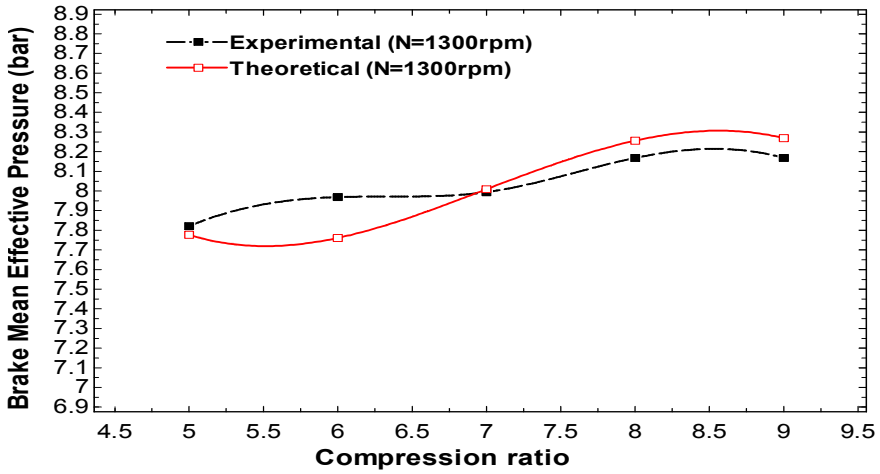



*Figure 4.30.Variation of brake mean effective pressure with compression ratio at engine speed of 1300rpm.*

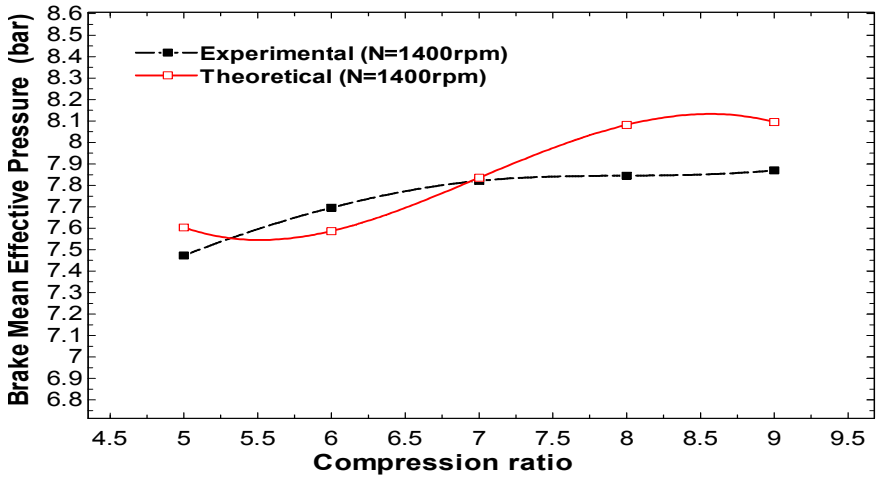



*Figure 4.31.Variation of brake mean effective pressure with compression ratio at engine speed of 1400rpm.*

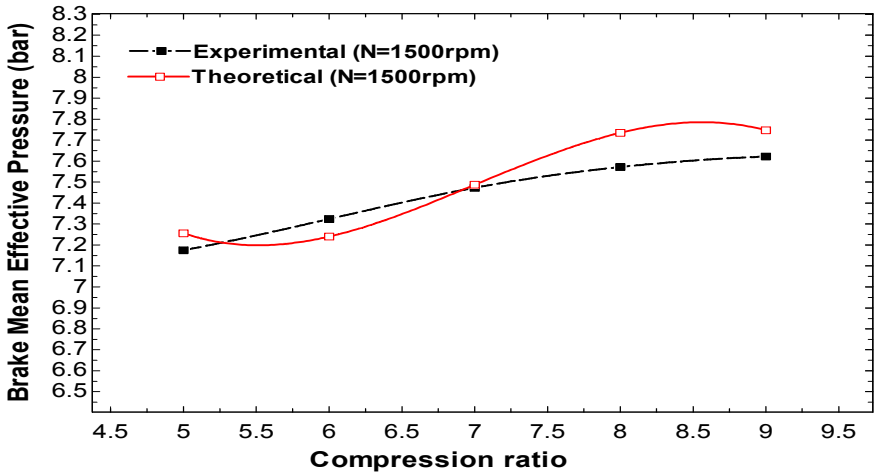



*Figure 4.32.Variation of brake mean effective pressure with compression ratio at engine speed of 1500rpm.*

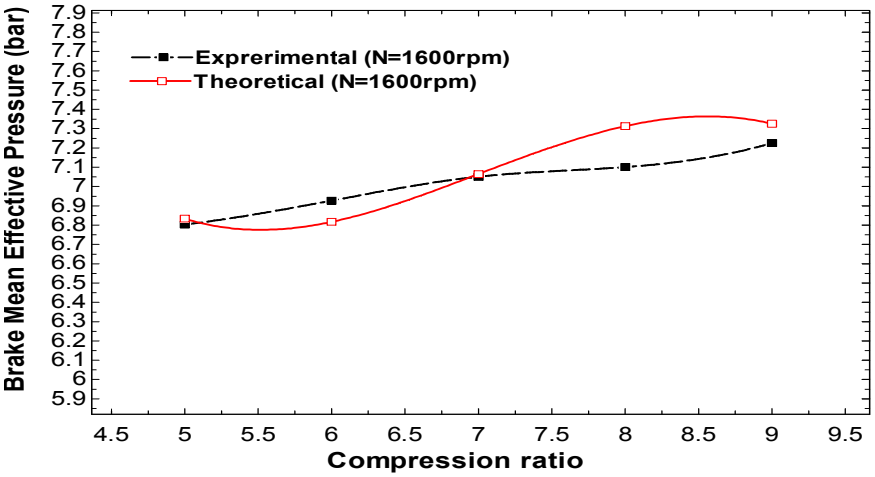



*Figure 4.33.Variation of brake mean effective pressure with compression ratio at engine speed of 1600rpm.*

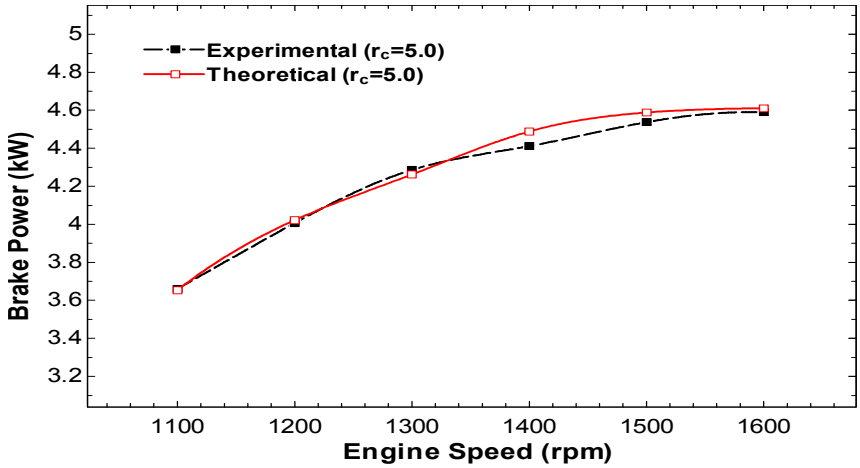



*Figure 4.34. Variation of brake power with engine speed at compression ratio of 5*

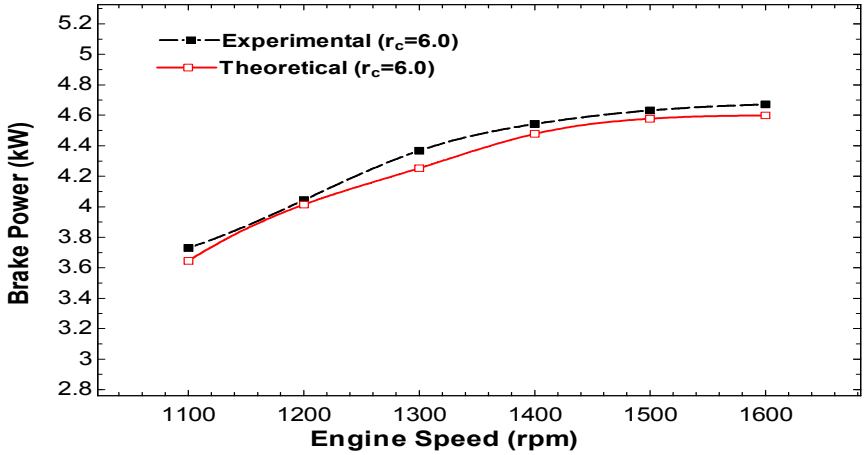



*Figure 4.35.Variation of brake power with engine speed at compression ratio of 6*

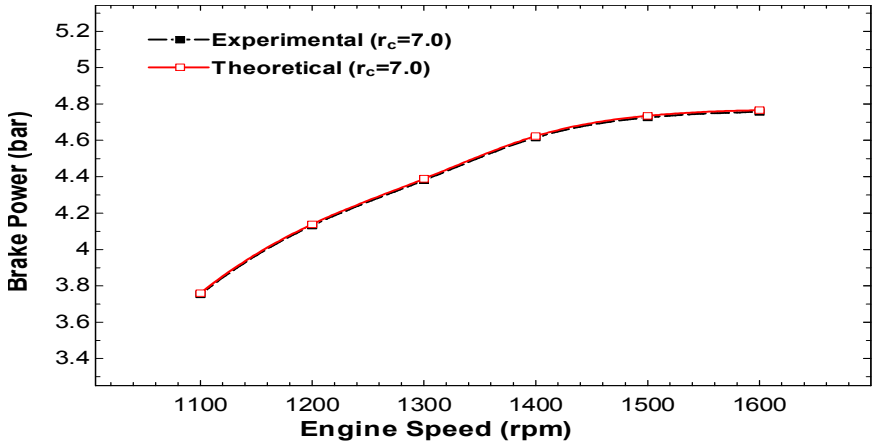



*Figure 4.36.Variation of brake power with engine speed at compression ratio of 7*

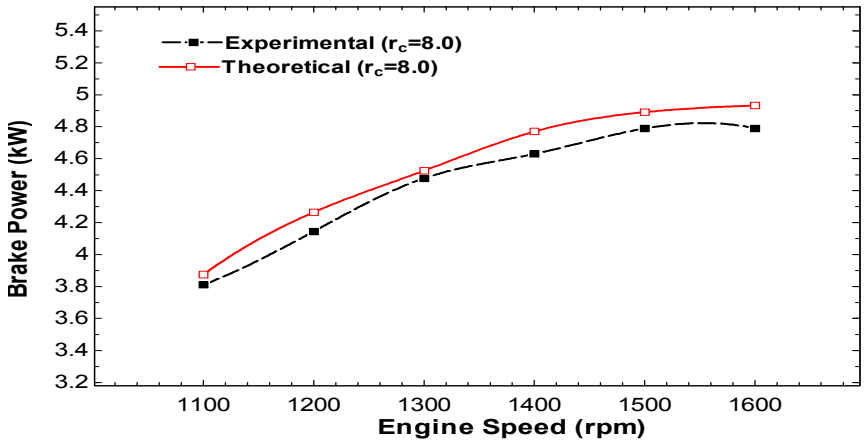



*Figure 4.37. Variation of brake power with engine speed at compression ratio of 8*

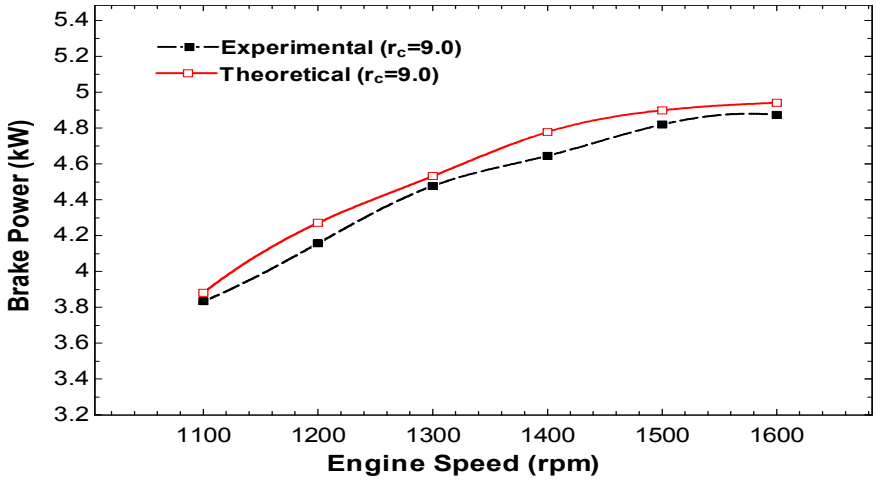



*Figure 4.38.Variation of brake power with engine speed at compression ratio of 9*

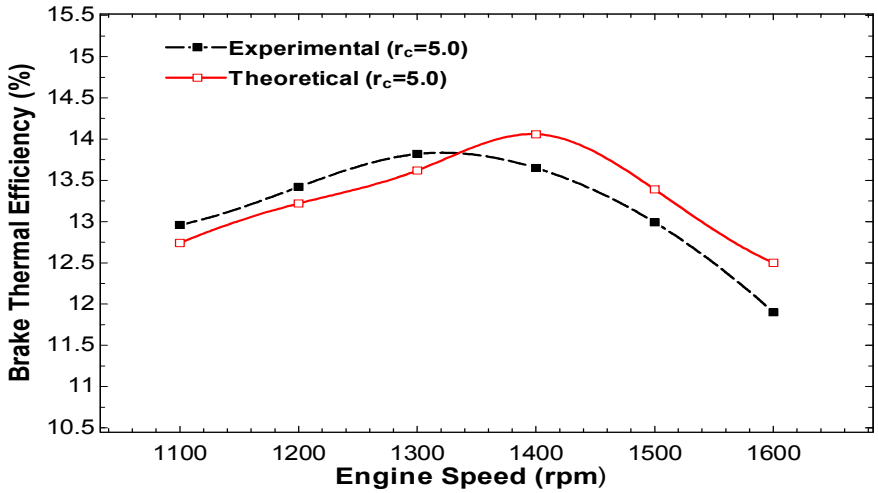



*Figure 4.39.Variation of brake thermal efficiency with engine speed at compression of 5*

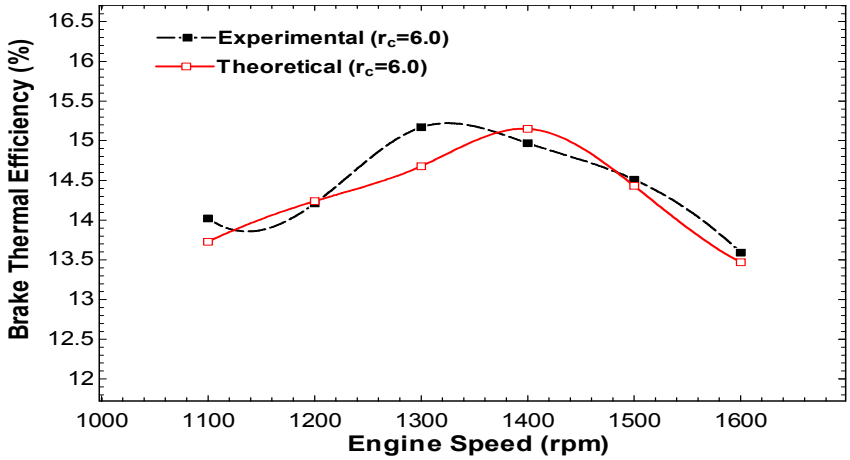



*Figure 4.40.Variation of brake thermal efficiency with engine speed at compression ratio of 6*

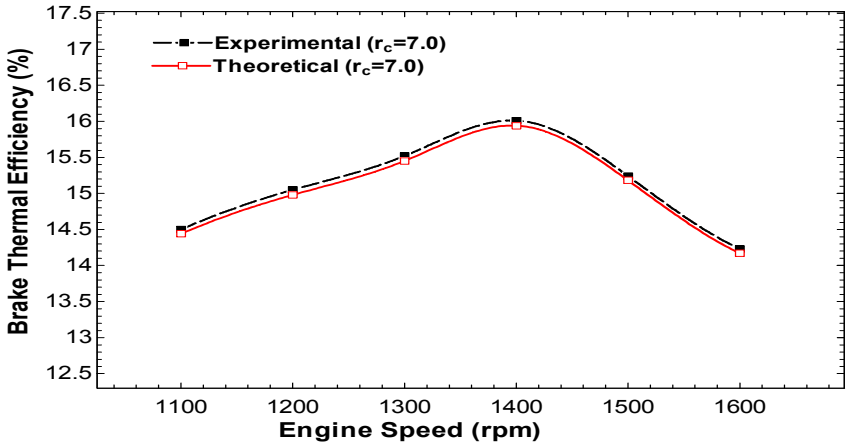



*Figure 4.41. Variation of brake thermal efficiency with engine speed at compression ratio of 7*

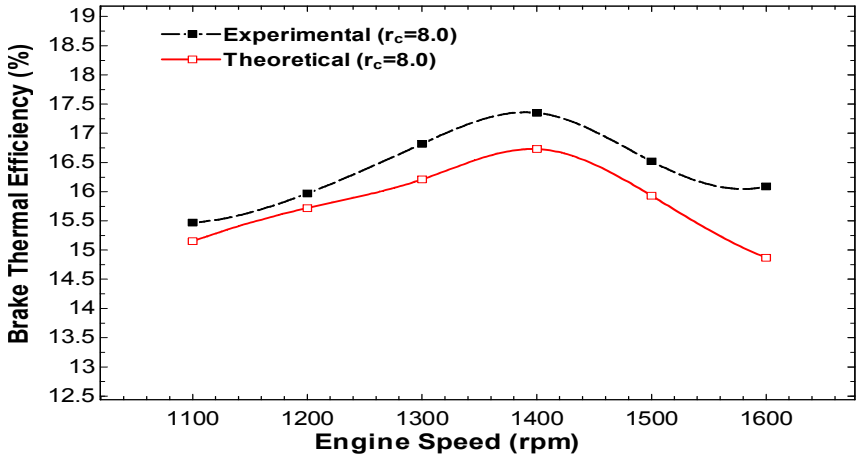



*Figure 4.42. Variation of brake thermal efficiency with engine speed at compression ratio of 8*

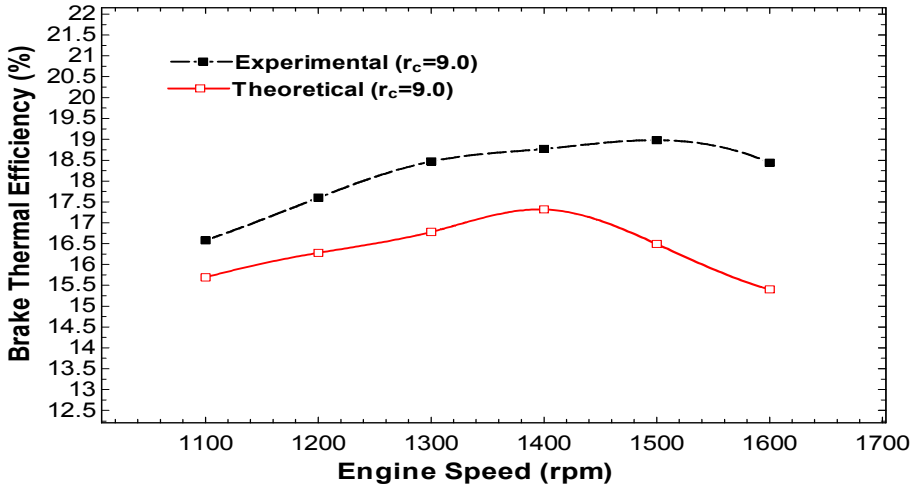



*Figure 4.43. Variation of brake thermal efficiency with engine speed at compression ratio of 9*

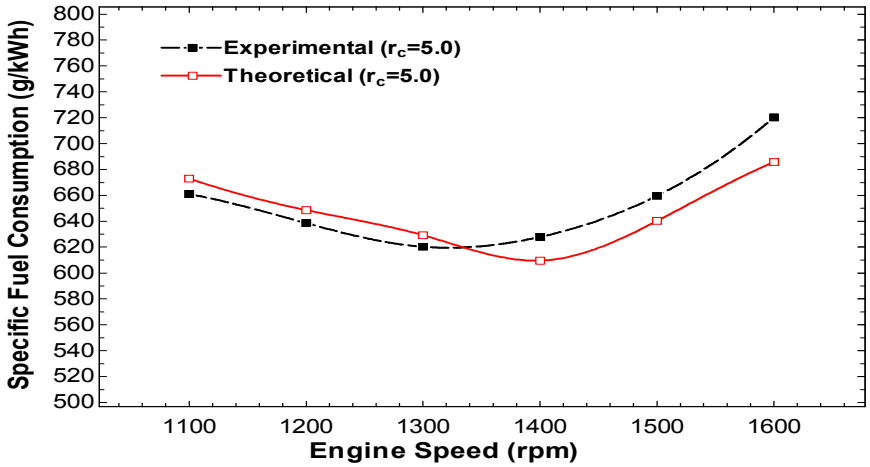



*Figure 4.44. Variation of brake specific fuel consumption with engine speed atcompression ratio of 5*

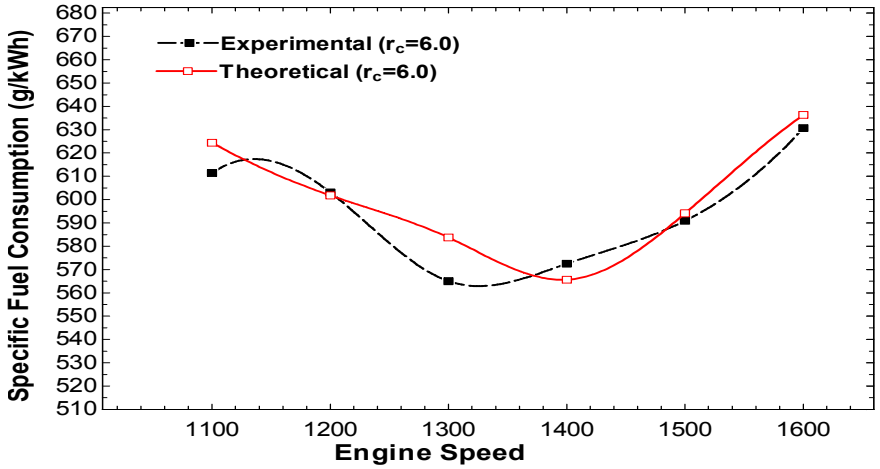



*Figure 4.45.Variation of brake specific fuel consumption with engine speed atcompression ratio of 6*

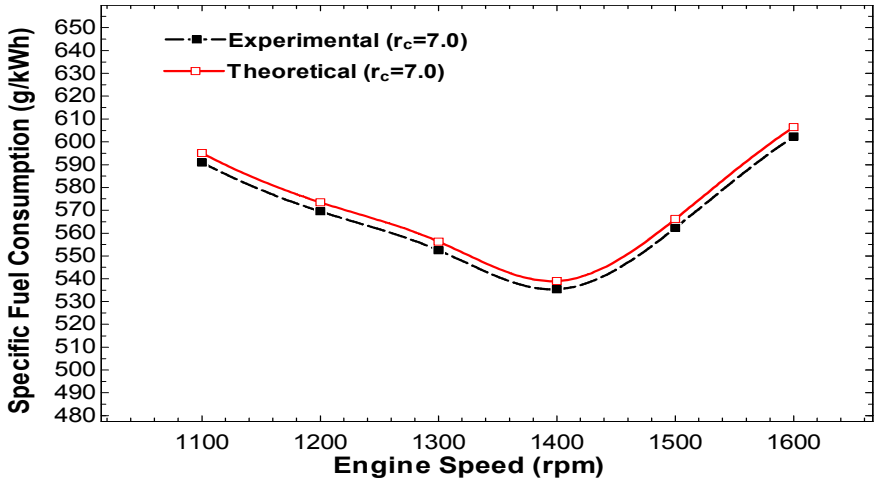



*Figure 4.46. Variation of brake specific fuel consumption with engine speed atcompression ratio of 7*

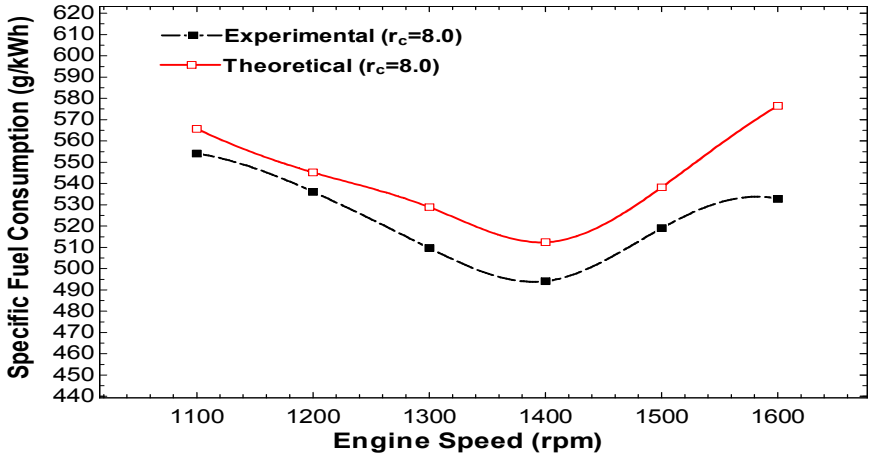



*Figure 4.47.Variation of brake specific fuel consumption with engine speed atcompression ratio of 8*

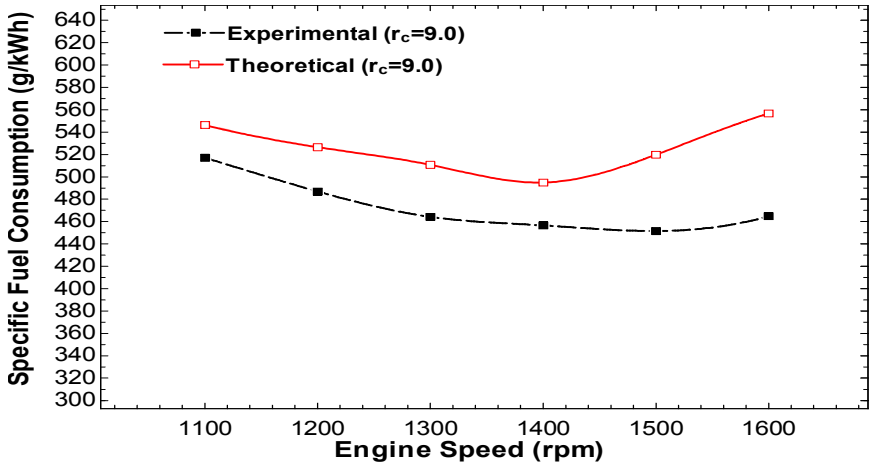



*Figure 4.48. Variation of brake specific fuel consumption with engine speed atcompression ratio of 9*

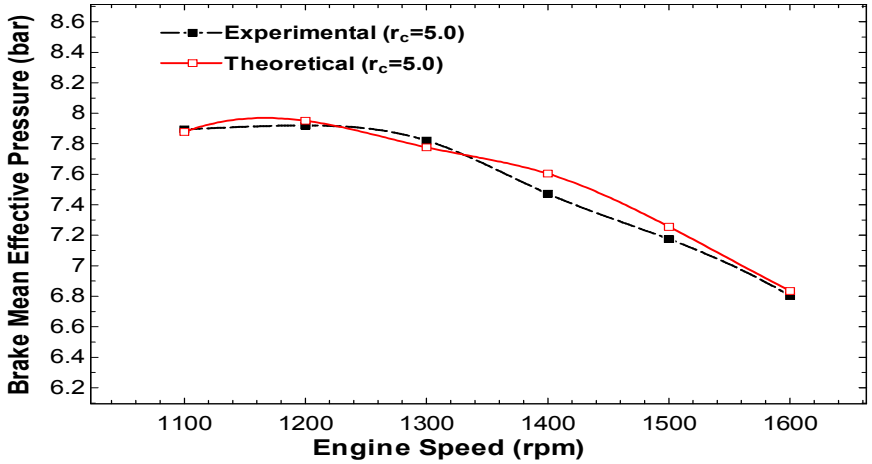



*Figure 4.49.Variation of brake mean effective pressure with engine speed atcompression ratio of 5*

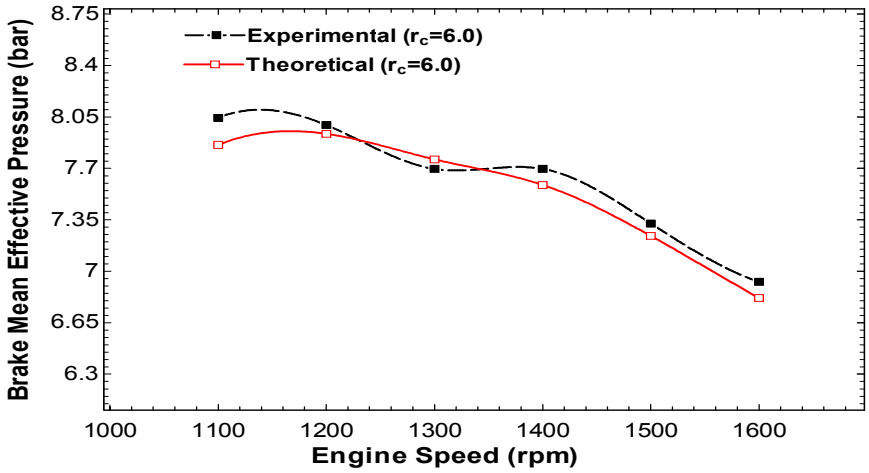



*Figure 4.50.Variation of brake mean effective pressure with engine speed atcompression ratio of 6*

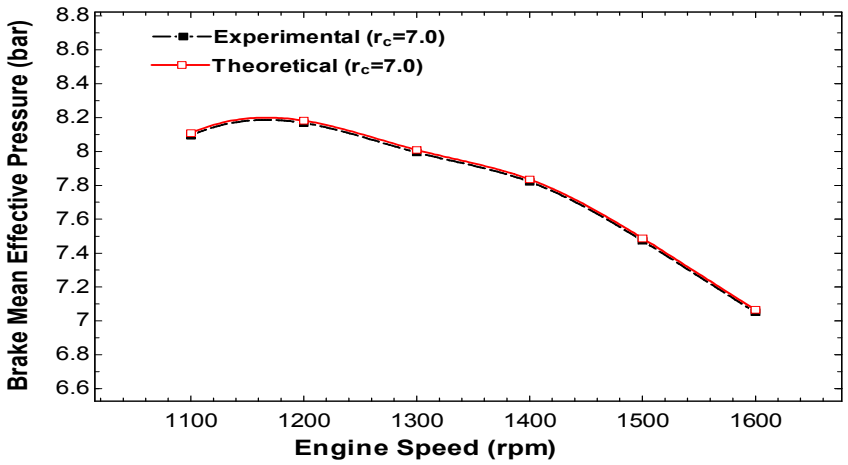



*Figure 4.51.Variation of brake mean effective pressure with engine speed atcompression ratio of 7*

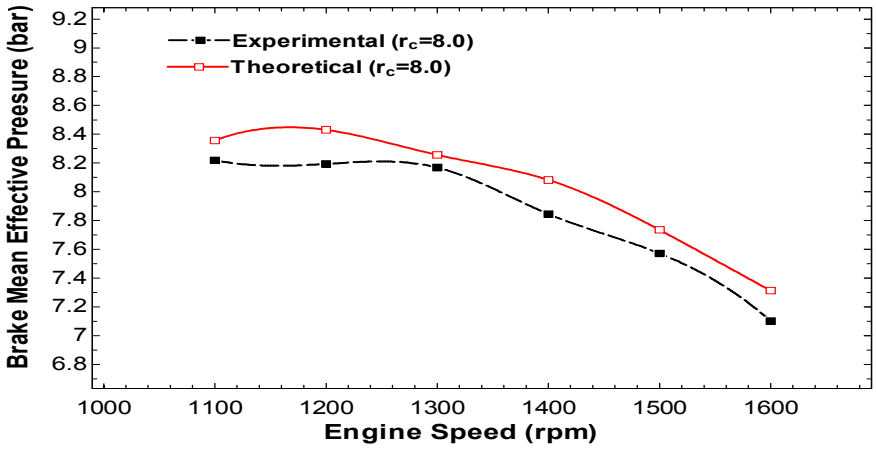



*Figure 4.52.Variation of brake mean effective pressure with engine speed atcompression ratio of 8*

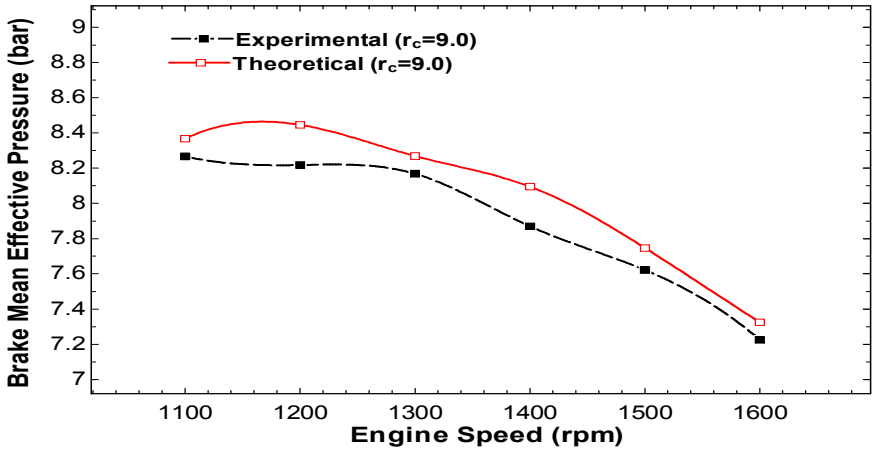



*Figure 4.53.Variation of brake mean effective pressure with engine speed at compression ratio of 9*

## 4.4 Comparison between Experimental and Theoretical Performance Characteristics

**4.4.1Brake power–**Figures 4.10 to 4.15 shows the relation of the brake power with compression ratio for both experimental and theoretical values. At low compression ratios of 5 and 6, theoretical values are lower than experimental values.As the compression ratio increases to 8 and 9, the theoretical brake power increases beyond the experimental values. This is because actual efficiency, and hence the brake power, is substantially below theoretical efficiency. Compression and expansion of gases is not adiabatic, there are friction losses in the engine. Complete combustion does not occur and work is required to draw in and exhaust gases.

Figures 4.34 to 4.38 also show the variation of brake power with engine speed at various compression ratios. At low compression ratios ( =5, =6), theoretical values are marginally lower than experimental values. It also appears that as the speed increases with compression ratio, the theoretical values increase more than the experimental values. It would then appears that equation 3.9 overestimates the torque gainfor >6.

At compression ratio of 7, the theoretical and experimental values are almost equal. This is because the values of *K* used in the theoretical analysis were obtained experimentally with reference compression ratio of 7.

Tables 4.21 to 4.25, gives the percentage error between the experimental and theoretical values. From the tables, the percentage error in the brake power tends to increase with increase in compression ratio. At compression ratio of 7 (the reference compression ratio), the minimum percentage error of 0.18% was obtained.

**4.4.2Brake thermal efficiency–**Figures 4.16 to 4.21shows the variation of the brake thermal efficiency with compression ratio at various engine speeds. As the compression ratio increases from 5 to 8, theoretical brake thermal efficiency is higher than experimental at 5 and 6, but decreases at 8 and 9.In Figures 4.39 to 4.43 also, it appears that as the compression ratio increases, the theoretical thermal efficiency decreases below the experimental value. It means that the theoretical thermal efficiency was underestimated for compression ratio beyond 7.

From Tables 4.26 to 4.30, it is shown thatthe percentage error in the brake thermal efficiency also tends to increase with increase in the compression ratio. At =5, the percentage error is 2.13%, while at =8 and 9, the percentage error is 3.67% and 9.89% respectively. The minimum error of 0.43% occurred at =7.

**4.4.3Specific fuel consumption -** In Figures 4.22 to 4.27, the theoretical specific fuel consumption shows similar trend with that of the experimentalvalues. Theoretical specific fuel consumption is higher than the experimental at all points of the compression ratios. This is due to the lower values of the theoretical brake thermal efficiency which makes the fuel consumption to rise theoretically. Equation 2.9 also supports this; specific fuel consumption is inversely proportional to thermal efficiency. In Figures 4.44 to 4.48 also, the general trend is that the calculated theoretical specific fuel consumption is higher than the experimental value.

Tables 4.26 to 4.30 showsthat the percentage error in the specific fuel consumption decreases with increase in compression ratio from 5 to 7. The error rose with >7 as shown. At =5, the average percentage error in the specific fuel consumption is 2.57%. At =8 and 9, the percentage error is 3.86% and 11.17% respectively. This shows that the average percentage

error in the theoretical specific fuel consumption increases with increase in the compression ratio.

**4.4.4 Brake mean effective pressure–**Figures 4.28 to 4.33shows the variation in brake mean effective pressure with compression ratio. The trend is similar to those of other parameters making the theoretical values higher than the experimental values at high compression ratios of 8 and 9.

The percentage error in the brake mean effective pressure tends to slightly increase with increase in the compression ratio. At =5 and 6, we have the error as 0.75% and 1.63% respectively, while at = 8 and 9, the error rose slightly to 2.3% and 1.85% respectively. The minimum errorlike in the other parameters occurred at the reference compression ratio of 7as 0.21%.

# CHAPTER FIVE

# SUMMARY, CONCLUSIONSAND RECOMMENDATIONS

## 5.1 Summary

Thisresearch work can be summarised as follows:

1. Investigation of the effect of increase in compression ratio of a Ricardo four stroke single cylinder petrol engine was conducted. A range of compression ratios of 5, 6, 7, 8 and 9, and engine speeds of 1100 to 1600 rpm in increments of 100 rpm were utilised. The basic parameters that were measured directly from the engine are the torque arm, brake load, time taken for the engine to consume 50ml of the fuel and the manometer readings for the air flow rate. The experimental values for the engine torque, brake power, brake mean effective pressure, brake thermal efficiency and specific fuel consumption were calculated. Improvements in the brake power, brake thermal efficiency, brake mean effective pressure and specific fuel consumption were evaluated when the compression ratio is increased from 5 to 6, 6 to 7, 7 to 8 and 8 to 9. The results shows that the brake power improves by 1.34%, brake thermal efficiency improves by 8.49%, brake mean effective pressure improves by 1.29% and the actual fuel consumption reduces by 7.75% averagely. The performance characteristics graphs for variation of the experimental brake power, brake thermal efficiency, brake mean effective pressure and specific fuel consumption with compression ratio were obtained.
2. Theoretical performance characteristics of the engine were obtained. Errors in the performance characteristics were evaluated and recorded.

Table 5.1.Grand averages ofthe percentage error

| | (%) | (%) | *SFC* (%) | *BMEP* (%) |
|---|---|---|---|---|
| 5 | 0.75 | 2.13 | 2.57 | 0.75 |
| 6 | 1.64 | 1.36 | 1.38 | 1.63 |
| 7 | 0.18 | 0.43 | 0.69 | 0.21 |
| 8 | 2.29 | 3.67 | 3.86 | 2.30 |
| 9 | 1.85 | 9.89 | 11.17 | 1.85 |

The theoretical values were compared with experimental values. The grand averages of the percentage error between the two values ranges from 0.18 to 2.29 % for the brake power, 0.43 to 9.89 % for the brake thermal efficiency, 0.69 to 11.17 % for the specific fuel consumption and 0.21 to 2.3 % for the brake mean effective pressure, as shown in Table 5.1. The discrepancies between the theoretical and experimental values for all the parameters were due to the values of *K* which was obtained experimentally. *K* varies with compression ratio and the engine speed.

## 5.2 Conclusions

The general conclusions drawn from the results of this research work are as follows:

1. Increase in compression ratio on the Ricardo variable compression ratio engine increases the brake power, brake thermal efficiency, brake mean effective pressure and reduction in the specific fuel consumption. It means that higher compression ratios make it possible to improve the performance characteristics of spark ignition engines.
2. Increase in the engine speed affects the volumetric efficiency more than when the compression ratio is increased. Thus, compression ratio has minimal effect on the volumetric efficiency.
3. The optimum compression ratio corresponding to the maximum brake thermal efficiency and brake power is 9.
4. The small values of the percentage errors between the theoretical and experimental values show that there is agreement between the theoretical and experimental performance characteristics of the engine.

## 5.3 Recommendations

The performance characteristics of a four stroke variable compression ratio engine in terms of the brake power, brake thermal efficiency, brake mean effective pressure and specific fuel consumption have been investigated with increase in thecompression ratio. Further research should be conducted to include a numerical modeling of combustion in a spark ignition variable compression ratio engine.

## REFERENCES


Abdel Rahman, A.A. and Osman, M.M.(1997). Experimental investigation of varying compression ratio of spark ignition engine working under different Ethanol-Gasoline fuel blends, International Journal of Energy Research, Kuwait University. Vol. 21, issue 1, pp. 31-40.

Andreas, B. (2003). Torque Modeling and Control of a Variable Compression Engine. Performed in Vehicular System.Reg nr: LITH-ISY-EX-3421

Asif, A.M., Jandool, K., Saeed, A.S. and Ali, A.C. (2008).Performance Evaluation of a Single Cylinder Four Stroke Petrol Engine.Farm machinery institute, National Agricultural Research Centre, Islamabad, Pakistan.

Chaiyot, D. and Somrat, K. (2005). Experimental Influence of Compression Ratio on to Performance and Emission of Compressed Natural Gas Retrofit Engine, King Mongkut's Institute of Technology North Bangkok.

Eastop, T.D. and McConkey, A. (1995).Applied Thermodynamics For Engineering Technologists.ELBS with Longman, 5th Edition pp. 420-439.

Haresh, K. and Swagatam.(2008). Comparison of Spark Ignition (SI) and Compression Ignition (CI) Engines. 2011 Bright Hub Inc. http://www.brighthub.com/engineering/mechanical/articles/1547.

Heywood J. B. (1988). Internal combustion Engines Fundamentals. McGraw Hill Book Company.

Hillier, V.A.W. and Pittuck, F.W. (1978).Fundamentals of Motor Vehicle Technology. Hutchinson and Co (Publisher) Ltd, London. pp. 44.

Jan-Ola, O., Per, T. and Bengt, J. (2002).Compression Ratio Influence on Maximum Fuelled HCCL Engine, Lund Institute of Technology, Society of Automotive Engineers, Inc. pp.147.

Jehad, A.A and Mohammad, H.D. (2003).Performance Simulation of a four-stroke engine with variable stroke length and compression ratio, Department of Mechanical Engineering, Faculty of Engineering and Technology, University of Jordan, 11942, Jordan.

Mohit, S. and Lamar, S. (2010). Making more efficient combustion engines. www.brighthub.com/engineering/mechanical/article/90240.aspx

MechanicalEngineeringSystems Laboratory. (2011). (*www.**me**.metu.edu.tr/**me4**10/**ME4**10%20Labsheet)*

Owoade, M.K. (1971). Performance of the Variable Compression Ratio SI Engine at full throttle.Final year thesis, Ahmadu Bello University, Zaria.

Philip, H.S. and David, N.W.(1954).The Design and Tuning of Competition Engines. Bentley publisher, 6th edition. ISBN 0837601401

Piston Engine Power Plant.Battery and Energy Technologies, Wood bank Communication Ltd. United Kingdom. (2005).

Power Supply in Nigeria.(2011).A review of the Nigerian Energy Industry. www.sweetcrudereports.com/2011/power

Ratnakara, R, Ramachandra R.V. and Muralidhara, M. (2009).Optimising the ratio for a Mahua fuelled compression ignition engine, India College of Engineering. Vol.4, No. 3.

Reciprocating Internal Combustion Engines.(2004). Chapter 6.pp. 224.www.personal.utulsa.edu/kenneth-weston/chapter6.pdf

Reaz M. (2001). Internal Combustion Engines, Engine Classification, Advantages and Disadvantages. ME 267: Fundamental of Mechanical Engineering Department of Mechanical Engineering, BUET (teacher.buet.ac.bd/nusairh/res/default/iceth.pdf)

Singer, C.J. and Raper, R. (1999).The Internal Combustion Engine.Clarendom Press. pp. 157 - 176

Thermal Efficiency of Engines. (1998). The Japan Society of Mechanical Engineers. www.jsme.or.jp/English/jsme%20roadmap/No.7pdf

Yuh, M. and Tohru, G. (2005).The Effect of Higher Compression Ratio in Two-Stroke Engines. Yamaha Motor Co, Ltd.

## APPENDIX A

### Engineering equation solver (EES) computer programme:

```
{Modelled equations for experimental analysis}

{Known information}
Q_Lv=42000000;{lower calorific value of the fuel, (J/kgK)}
        B=0.0762; {Cylinder bore (m)}
        S=0.111; {Cylinder stroke (m)}
            V_s=p*B^2*S/4; {Swept volume (m^3)}
                V=0.00005; {m^3}{volume of the fuel consumed, 50ml}
n = 1.4 ;{specific heat ratios}
S_g=0.740;  {specific gravity of the fuel}
          N_1=1100{rpm}; N_2=1200{rpm}; N_3=1300{rpm};
          N_4=1400{rpm}; N_5=1500{rpm}; N_6=1600{rpm}
P_atm=1239.9{milibar}{i.e atmospheric pressure of 930mmHg}
T_atm=305{K}; {ambient temperature}
denst_wat=1000; {water density}
denst_air=P_atm*100/(287*T_atm); {air density (kg/m^3)}
p=pi {3.142}



{ COMPRESSION RATIO,    r_c1 = 5.0}

{engine speed=1100rpm}
t_1=55.02; {fuel consumption time for 50 ml}
T_q1=31.8; {Torque}
  h_a1=3.3; {manometer reading, mm}
     m_f11=S_g*denst_wat*V/t_1; {fuel mass flow rate, kg/s}
    m_a11=(2.98*sqrt(P_atm*h_a1/T_atm))/3600;{air mass flow rate,
   AirFrat_11=m_a11/m_f11;    {air/fuel ratio}
  Voleff_a11=120*m_a11/(denst_air*V_s*N_1)*100; {volumetric
efficiency,(%)}
       b_p11=(2*3.14*N_1*T_q1/60);  {brake power, Watt}
      bmep_11=(120*b_p11)/(V_s*N_1); {brake mean effective
                                                  pressure,bar}
Thermaleff_11=b_p11/(q_Lv*m_f11)*100; {brake thermal
                                                  efficiency, (%)}
 sfc_11=3600*m_f11/(b_p11/1000); {specific fuel consumption}
```

```
{COMPRESSION RATIO,   r_c2 = 6.0}
{engine speed=1100rpm}
     t_21=58.4;
   T_q21=32.4;
     h_b1=3.4;
        m_f21=S_g*denst_wat*V/t_21;
         m_a21=(2.98*sqrt(P_atm*h_b1/T_atm))/3600;
          AirFrat_21=m_a21/m_f21;
           Voleff_b1=120*m_a21/(denst_air*V_s*N_1)*100
            b_p21=2*3.14*N_1*T_q21/60;
             bmep_21=(120*b_p21)/(V_s*N_1);
            Thermaleff_21=b_p21/(q_Lv*m_f21)*100;
             sfc_21=3600*m_f21/(b_p21/1000);

COMPRESSION RATIO}   r_c3=7.0
   {engine speed=1100rpm}
     t_31=60.05;
      T_q31=32.6;
      h_c1=3.5;
           m_f31=S_g*denst_wat*V/t_31;
           m_a31=(2.98*sqrt(P_atm*h_c1/T_atm))/3600;
           AirFrat_31=m_a31/m_f31;
           Voleff_c1=120*m_a31/(denst_air*V_s*N_1)*100;
          b_p31=2*3.14*N_1*T_q31/60;
         bmep_31=(120*b_p31)/(V_s*N_1);
        Thermaleff_31=b_p31/(q_Lv*m_f31)*100;
        sfc_31=3600*m_f31/(b_p31/1000);


{COMPRESSION RATIO   r_c4 = 8.0}

   {engine speed=1100rpm}
  t_41=63.08;
   T_q41=33.1;
   h_d1=3.4;
       m_f41=S_g*denst_wat*V/t_41;
       m_a41=(2.98*sqrt(P_atm*h_d1/T_atm))/3600;
        AirFrat_41=m_a41/m_f41;
        Voleff_d1=120*m_a41/(denst_air*V_s*N_1)*100
         b_p41=2*3.14*N_1*T_q41/60;
          bmep_41=(120*b_p41)/(V_s*N_1);
          Thermaleff_41=b_p41/(q_Lv*m_f41)*100;
           sfc_41=3600*m_f41/(b_p41/1000);
```

```
{COMPRESSION RATIO};  r_c5=9.0
    {engine speed=1100rpm}
 t_51=67.2;
  T_q51=33.3;
   h_e1=3.5;
       m_f51=S_g*denst_wat*V/t_51;
       m_a51=(2.98*sqrt(P_atm*h_e1/T_atm))/3600;
       AirFrat_51=m_a51/m_f51;
       Voleff_e1=120*m_a51/(denst_air*V_s*N_1)*100;
        b_p51=2*3.14*N_1*T_q51/60;
         bmep_51=(120*b_p51)/(V_s*N_1);
                          Thermaleff_51=b_p51/(q_Lv*m_f51)*100;
          sfc_51=3600*m_f51/(b_p51/1000);



{ COMPRESSION RATIO     r_c1 = 5.0}
    {engine speed=1200rpm}
                              t_2=52.06;
                              T_q2=31.9;
                              h_a2=4.1;
    m_f12=S_g*denst_wat*V/t_2;
     m_a12=(2.98*sqrt(P_atm*h_a2/T_atm))/3600;
      AirFrat_12=m_a12/m_f12;
       Voleff_a12=120*m_a12/(denst_air*V_s*N_2)*100;
        b_p12=2*3.14*N_2*T_q2/60;
    bmep_12=(120*b_p12)/(V_s*N_2);
     Thermaleff_12=b_p12/(q_Lv*m_f12)*100;
     sfc_12=3600*m_f12/(b_p12/1000);



{COMPRESSION RATIO   r_c2 = 6.0}
    {engine speed=1200rpm}
 t_22=54.61;
  T_q22=32.2;
   h_b2=4.2;
      m_f22=S_g*denst_wat*V/t_22;
     m_a22=(2.98*sqrt(P_atm*h_b2/T_atm))/3600;
      AirFrat_22=m_a22/m_f22;
    Voleff_b2=120*m_a22/(denst_air*V_s*N_2)*100
    b_p22=2*3.14*N_2*T_q22/60;
    bmep_22=(120*b_p22)/(V_s*N_2);
     Thermaleff_22=b_p22/(q_Lv*m_f22)*100;
    sfc_22=3600*m_f22/(b_p22/1000);
```

{COMPRESSION RATIO  r_c3=7.0}
{engine speed=1200rpm}
t_32=56.6;
T_q32=32.9;
h_c2=4.2;
m_f32=S_g*denst_wat*V/t_32;
m_a32=(2.98*sqrt(P_atm*h_c2/T_atm))/3600;
AirFrat_32=m_a32/m_f32;
Voleff_c2=120*m_a32/(denst_air*V_s*N_2)*100
b_p32=2*3.14*N_2*T_q32/60;
bmep_32=(120*b_p32)/(V_s*N_2);
Thermaleff_32=b_p32/(q_Lv*m_f32)*100;
sfc_32=3600*m_f32/(b_p32/1000);

{COMPRESSION RATIO  r_c4 = 8.0}
{engine speed=1200rpm}
t_42=59.89;
T_q42=33;
h_d2=3.9;
m_f42=S_g*denst_wat*V/t_42;
m_a42=(2.98*sqrt(P_atm*h_d2/T_atm))/3600;
AirFrat_42=m_a42/m_f42;
Voleff_d2=120*m_a42/(denst_air*V_s*N_2)*100
b_p42=2*3.14*N_2*T_q42/60;
bmep_42=(120*b_p42)/(V_s*N_2);
Thermaleff_42=b_p42/(q_Lv*m_f42)*100;
sfc_42=3600*m_f42/(b_p42/1000);

{COMPRESSION RATIO  r_c5=9.0}
{engine speed=1200rpm}
t_52=65.8;
T_q52=33.1;
h_e2=4.3;
m_f52=S_g*denst_wat*V/t_52;
m_a52=(2.98*sqrt(P_atm*h_e2/T_atm))/3600;
AirFrat_52=m_a52/m_f52;
Voleff_e2=120*m_a52/(denst_air*V_s*N_2)*100;
b_p52=2*3.14*N_2*T_q52/60;
bmep_52=(120*b_p52)/(V_s*N_2);
Thermaleff_52=b_p52/(q_Lv*m_f52)*100;

```
    sfc_52=3600*m_f52/(b_p52/1000);

{ COMPRESSION RATIO    r_c1 = 5.0}
    {engine speed=1300rpm}
 t_3=50.1;
                                T_q3=31.5;
h_a3=4.7;
     m_f13=S_g*denst_wat*V/t_3;
    m_a13=(2.98*sqrt(P_atm*h_a3/T_atm))/3600;
    AirFrat_13=m_a13/m_f13;
    Voleff_a13=120*m_a13/(denst_air*V_s*N_3)*100;
    b_p13=2*3.14*N_3*T_q3/60;
    bmep_13=(120*b_p13)/(V_s*N_3);
    Thermaleff_13=b_p13/(q_Lv*m_f13)*100;
    sfc_13=3600*m_f13/(b_p13/1000);



{COMPRESSION RATIO   r_c2 = 6.0}
    {engine speed=1300rpm}
t_23=53.98;
T_q23=32.1;
h_b3=4.9;
    m_f23=S_g*denst_wat*V/t_23;
    m_a23=(2.98*sqrt(P_atm*h_b3/T_atm))/3600;
    AirFrat_23=m_a23/m_f23;
    Voleff_b3=120*m_a23/(denst_air*V_s*N_3)*100
    b_p23=2*3.14*N_3*T_q23/60;
    bmep_23=(120*b_p23)/(V_s*N_3);
    Thermaleff_23=b_p23/(q_Lv*m_f23)*100;
    sfc_23=3600*m_f23/(b_p23/1000);



{COMPRESSION RATIO   r_c3=7.0}
    {engine speed=1300rpm}
t_33=55.03;
T_q33=32.2;
h_c3=4.9;
    m_f33=S_g*denst_wat*V/t_33;
    m_a33=(2.98*sqrt(P_atm*h_c3/T_atm))/3600;
    AirFrat_33=m_a33/m_f33;
    Voleff_c3=120*m_a33/(denst_air*V_s*N_3)*100
    b_p33=2*3.14*N_3*T_q33/60;
    bmep_33=(120*b_p33)/(V_s*N_3);
    Thermaleff_33=b_p33/(q_Lv*m_f33)*100;
    sfc_33=3600*m_f33/(b_p33/1000);
```

```
{COMPRESSION RATIO  r_c4 = 8.0}
    {engine speed=1300rpm}
   t_43=58.38;
    T_q43=32.9;
     h_d3=4.9;
                              m_f43=S_g*denst_wat*V/t_43;
                              m_a43=(2.98*sqrt(P_atm*h_d3/T_atm))/3600;
                              AirFrat_43=m_a43/m_f43;
                              Voleff_d3=120*m_a43/(denst_air*V_s*N_3)*100
                              b_p43=2*3.14*N_3*T_q43/60;
        bmep_43=(120*b_p43)/(V_s*N_3);
       Thermaleff_43=b_p43/(q_Lv*m_f43)*100;
      sfc_43=3600*m_f43/(b_p43/1000);



{COMPRESSION RATIO  r_c5=9.0}
    {engine speed=1300rpm}
  t_53=64.1;
   T_q53=32.9;
   h_e3=5.5;
       m_f53=S_g*denst_wat*V/t_53;
                              m_a53=(2.98*sqrt(P_atm*h_e3/T_atm))/3600;
                              AirFrat_53=m_a53/m_f53;
                              Voleff_e3=120*m_a53/(denst_air*V_s*N_3)*100;
                              b_p53=2*3.14*N_3*T_q53/60;
                              bmep_53=(120*b_p53)/(V_s*N_3);
                              Thermaleff_53=b_p53/(q_Lv*m_f53)*100;
                              sfc_53=3600*m_f53/(b_p53/1000);



{ COMPRESSION RATIO    r_c1 = 5.0}
    {engine speed=1400rpm}
t_4=48.1;
T_q4=30.1;
                              h_a4=5.2;
    m_f14=S_g*denst_wat*V/t_4;
    m_a14=(2.98*sqrt(P_atm*h_a4/T_atm))/3600;
    AirFrat_14=m_a14/m_f14;
    Voleff_a14=120*m_a14/(denst_air*V_s*N_4)*100
    b_p14=2*3.14*N_4*T_q4/60;
                              bmep_14=(120*b_p14)/(V_s*N_4);
```

```
    Thermaleff_14=b_p14/(q_Lv*m_f14)*100;
    sfc_14=3600*m_f14/(b_p14/1000);

{COMPRESSION RATIO   r_c2 = 6.0}
    {engine speed=1400rpm}
                                t_24=51.22;
                               T_q24=31;
                                h_b4=5.3;
                               m_f24=S_g*denst_wat*V/t_24;
                               m_a24=(2.98*sqrt(P_atm*h_b4/T_atm))/3600;
                               AirFrat_24=m_a24/m_f24;
                               Voleff_b4=120*m_a24/(denst_air*V_s*N_4)*100
                               b_p24=2*3.14*N_4*T_q24/60;
                               bmep_24=(120*b_p24)/(V_s*N_4);
                               Thermaleff_24=b_p24/(q_Lv*m_f24)*100;
                               sfc_24=3600*m_f24/(b_p24/1000);



{COMPRESSION RATIO   r_c3=7.0}
    {engine speed=1400rpm}
                                t_34=53.9;
                                T_q34=31.5;
                                h_c4=5.3;
    m_f34=S_g*denst_wat*V/t_34;
    m_a34=(2.98*sqrt(P_atm*h_c4/T_atm))/3600;
    AirFrat_34=m_a34/m_f34;
    Voleff_c4=120*m_a34/(denst_air*V_s*N_4)*100
    b_p34=2*3.14*N_4*T_q34/60;
    bmep_34=(120*b_p34)/(V_s*N_4);
    Thermaleff_34=b_p34/(q_Lv*m_f34)*100;
    sfc_34=3600*m_f34/(b_p34/1000);



{COMPRESSION RATIO   r_c4 = 8.0}
{engine speed=1400rpm}
                                 t_44=58.22;
                                T_q44=31.6;
                                 h_d4=5.5;
                                m_f44=S_g*denst_wat*V/t_44;
                                m_a44=(2.98*sqrt(P_atm*h_d4/T_atm))/3600;
    AirFrat_44=m_a44/m_f44;
     Voleff_d4=120*m_a44/(denst_air*V_s*N_4)*100
      b_p44=2*3.14*N_4*T_q44/60;
       bmep_44=(120*b_p44)/(V_s*N_4);
        Thermaleff_44=b_p44/(q_Lv*m_f44)*100;
```

```
    sfc_44=3600*m_f44/(b_p44/1000);


{COMPRESSION RATIO  r_c5=9.0}
    {engine speed=1400rpm}
                                t_54=62.8;
                                T_q54=31.7;
                                h_e4=5.7;
     m_f54=S_g*denst_wat*V/t_54;
    m_a54=(2.98*sqrt(P_atm*h_e4/T_atm))/3600;
    AirFrat_54=m_a54/m_f54;
    Voleff_e4=120*m_a54/(denst_air*V_s*N_4)*100;
    b_p54=2*3.14*N_4*T_q54/60;
    bmep_54=(120*b_p54)/(V_s*N_4);
     Thermaleff_54=b_p54/(q_Lv*m_f54)*100;
    sfc_54=3600*m_f54/(b_p54/1000);



{ COMPRESSION RATIO     r_c1 = 5.0}
    {engine speed=1500rpm}
  t_5=44.5;
 T_q5=28.9;
h_a5=5.5;
    m_f15=S_g*denst_wat*V/t_5;
    m_a15=(2.98*sqrt(P_atm*h_a5/T_atm))/3600;
    AirFrat_15=m_a15/m_f15;
    Voleff_a15=120*m_a15/(denst_air*V_s*N_5)*100
    b_p15=2*3.14*N_5*T_q5/60;
    bmep_15=(120*b_p15)/(V_s*N_5);
    Thermaleff_15=b_p15/(q_Lv*m_f15)*100;
    sfc_15=3600*m_f15/(b_p15/1000);



{COMPRESSION RATIO   r_c2 = 6.0}
    {engine speed=1500rpm}
t_25=48.67;
T_q25=29.5;
h_b5=5.6;
    m_f25=S_g*denst_wat*V/t_25;
    m_a25 =(2.98*sqrt(P_atm*h_b5/T_atm))/3600;
    AirFrat_25=m_a25/m_f25;
    Voleff_b5=120*m_a25/(denst_air*V_s*N_5)*100
    b_p25=2*3.14*N_5*T_q25/60;
```

```
    bmep_25=(120*b_p25)/(V_s*N_5);
     Thermaleff_25=b_p25/(q_Lv*m_f25)*100;
      sfc_25=3600*m_f25/(b_p25/1000);

{COMPRESSION RATIO   r_c3=7.0}
    {engine speed=1500rpm}
                              t_35=50.13;
                              T_q35=30.1;
                              h_c5=5.8;
    m_f35=S_g*denst_wat*V/t_35;
    m_a35=(2.98*sqrt(P_atm*h_c5/T_atm))/3600;
                             AirFrat_35=m_a35/m_f35;
                             Voleff_c5=120*m_a35/(denst_air*V_s*N_5)*100
                             b_p35=2*3.14*N_5*T_q35/60;
                             bmep_35=(120*b_p35)/(V_s*N_5);
                             Thermaleff_35=b_p35/(q_Lv*m_f35)*100;
                             sfc_35=3600*m_f35/(b_p35/1000);




{COMPRESSION RATIO   r_c4 = 8.0}
    {engine speed=1500rpm}
                               t_45=53.6;
                               T_q45=30.5;
                                h_d5=6.0;
      m_f45=S_g*denst_wat*V/t_45;
     m_a45=(2.98*sqrt(P_atm*h_d5/T_atm))/3600;
    AirFrat_45=m_a45/m_f45;
    Voleff_d5=120*m_a45/(denst_air*V_s*N_5)*100
    b_p45=2*3.14*N_5*T_q45/60;
    bmep_45=(120*b_p45)/(V_s*N_5);
    Thermaleff_45=b_p45/(q_Lv*m_f45)*100;
    sfc_45=3600*m_f45/(b_p45/1000);



{COMPRESSION RATIO  r_c5=9.0}
    {engine speed=1500rpm}
  t_55=61.2
   T_q55=30.7;
    h_e5=6.1;
       m_f55=S_g*denst_wat*V/t_55;
      m_a55=(2.98*sqrt(P_atm*h_e5/T_atm))/3600;
     AirFrat_55=m_a55/m_f55;
     Voleff_e5=120*m_a55/(denst_air*V_s*N_5)*100;
                               b_p55=2*3.14*N_5*T_q55/60;
```

```
    bmep_55=(120*b_p55)/(V_s*N_5);
    Thermaleff_55=b_p55/(q_Lv*m_f55)*100;
    sfc_55=3600*m_f55/(b_p55/1000);

{COMPRESSION RATIO     r_c1 = 5.0}
    {engine speed=1600rpm}
                                t_6=40.3;
                                T_q6=27.4;
                                h_a6=5.7;
       m_f16=S_g*denst_wat*V/t_6;
      m_a16=(2.98*sqrt(P_atm*h_a6/T_atm))/3600;
     AirFrat_16=m_a16/m_f16;
    Voleff_a16=120*m_a16/(denst_air*V_s*N_6)*100
    b_p16=2*3.14*N_6*T_q6/60;
    bmep_16=(120*b_p16)/(V_s*N_6);
    Thermaleff_16=b_p16/(q_Lv*m_f16)*100;
    sfc_16=3600*m_f16/(b_p16/1000);



{COMPRESSION RATIO   r_c2 = 6.0}
    {engine speed=1600rpm}
                                t_26=45.2;
T_q26=27.9;
h_b6=5.9;
    m_f26=S_g*denst_wat*V/t_26;
    m_a26=(2.98*sqrt(P_atm*h_b6/T_atm))/3600;
    AirFrat_26=m_a26/m_f26;
    Voleff_b6=120*m_a26/(denst_air*V_s*N_6)*100
    b_p26=2*3.14*N_6*T_q26/60;
    bmep_26=(120*b_p26)/(V_s*N_6);
    Thermaleff_26=b_p26/(q_Lv*m_f26)*100;
     sfc_26=3600*m_f26/(b_p26/1000);



{COMPRESSION RATIO   r_c3=7.0}
    {engine speed=1600rpm}
                                t_36=46.5;
T_q36=28.4;
                                h_c6=6.1;
    m_f36=S_g*denst_wat*V/t_36;
    m_a36=(2.98*sqrt(P_atm*h_c6/T_atm))/3600;
    AirFrat_36=m_a36/m_f36;
    Voleff_c6=120*m_a36/(denst_air*V_s*N_6)*100
     b_p36=2*3.14*N_6*T_q36/60;
    bmep_36=(120*b_p36)/(V_s*N_6);
```

```
Thermaleff_36=b_p36/(q_Lv*m_f36)*100;
sfc_36=3600*m_f36/(b_p36/1000);

{COMPRESSION RATIO   r_c4 = 8.0}
{engine speed=1600rpm}
                        t_46=52.2;
  T_q46=28.6;
                        h_d6=6.2;

                        m_f46=S_g*denst_wat*V/t_46;
                        m_a46=(2.98*sqrt(P_atm*h_d6/T_atm))/3600;
 AirFrat_46=m_a46/m_f46;
Voleff_d6=120*m_a46/(denst_air*V_s*N_6)*100;
                        b_p46=2*3.14*N_6*T_q46/60;
bmep_46=(120*b_p46)/(V_s*N_6);
Thermaleff_46=b_p46/(q_Lv*m_f46)*100;
sfc_46=3600*m_f46/(b_p46/1000);



{COMPRESSION RATIO  r_c5=9.0}
   {engine speed=1600rpm}
 t_56=58.8;
                          T_q56=29.1;
                           h_e6=6.6;
                          m_f56=S_g*denst_wat*V/t_56;
                          m_a56=(2.98*sqrt(P_atm*h_e6/T_atm))/3600;
                          AirFrat_56=m_a56/m_f56;
                          Voleff_e6=120*m_a56/(denst_air*V_s*N_6)*100;
                          b_p56=2*3.14*N_6*T_q56/60;
                          bmep_56=(120*b_p56)/(V_s*N_6);
                          Thermaleff_56=b_p56/(q_Lv*m_f56)*100;
                          sfc_56=3600*m_f56/(b_p56/1000)

{Calculation of 'K' for the reference compression ratio of 7.0, usingequation 3.13}
  T_q31 = (K_1/(2*p))*(1-1/(r_c3^(n-1)))*(m_f31*Q_Lv/(N_1/60));

    T_q32 = (K_2/(2*p))*(1-1/(r_c3^(n-1)))*(m_f32*Q_Lv/(N_2/60));

 T_q33 = (K_3/(2*p))*(1-1/(r_c3^(n-1)))*(m_f33*Q_Lv/(N_3/60));

T_q34 = (K_4/(2*p))*(1-1/(r_c3^(n-1)))*(m_f34*Q_Lv/(N_4/60));

 T_q35 = (K_5/(2*p))*(1-1/(r_c3^(n-1)))*(m_f35*Q_Lv/(N_5/60));

  T_q36 = (K_36/(2*p))*(1-1/(r_c3^(n-1)))*(m_f36*Q_Lv/(N_6/60));
```

## APPENDIX B

### Engineering equation solver (EES) computer programme:

{**Modelled equations for theoretical analysis**}

{Reference $r_C$= 7.0}

{Known values}
Q_Lv=42000000; {lower calorific value of the fuel (J/kgK)}
B=0.0762; {Cylinder bore (m)}
S=0.111; {Cylinder stroke (m)}
V_s=p*B^2*S/4; {Swept volume (m^3)}
N_1=1100{rpm}; N_2=1200{rpm}; N_3=1300{rpm};
N_4=1400{rpm};
N_5=1500{rpm}; N_6=1600{rpm}; {engine speed
T_q1=32.6; T_q2=32.9; T_q3=32.2; T_q4=31.5; T_q5=30.1;
T_q6=28.4;{Brake torque from reference compression ratio of 7}

{COMPRESSION RATIO, r_c1=5.0}
{engine speed=1100rpm}
T_q11=T_q1-(5/7)^0.4;
B_p11=2*3.14*N_1*T_q11/60
T_q11=K_1/(2*3.14)*(1-(1/5^0.4))*60*m_f11*Q_Lv/N_1
BMEP_11=120*B_p11/(V_s*N_1)
THERMALEFF_11=B_p11/(Q_Lv*m_f11)
SFC_11=3600*m_f11/(B_p11/1000)

{COMPRESSION RATIO, r_c2=6.0}
{engine speed=1100rpm}
T_q21=T_q1-(6/7)^0.4;;
B_p21=2*3.14*N_1*T_q21/60
T_q21=K_1/(2*3.14)*(1-(1/6^0.4))*60*m_f21*Q_Lv/N_1
BMEP_21=120*B_p21/(V_s*N_1)
THERMALEFF_21=B_p21/(Q_Lv*m_f21)
SFC_21=3600*m_f21/(B_p21/1000)

```
{COMPRESSION RATIO, r_c3=8.0}
                    {engine speed=1100rpm}
                    T_q31=T_q1+(8/7)^0.4;
                    B_p31=2*3.14*N_1*T_q31/60
                    T_q31=K_1/(2*3.14)*(1-(1/8^0.4))*60*m_f31*Q_Lv/N_1
                    BMEP_31=120*B_p31/(V_s*N_1)
                    THERMALEFF_31=B_p31/(Q_Lv*m_f31)
                    SFC_31=3600*m_f31/(B_p31/1000)


{COMPRESSION RATIO, r_c4=9.0}
                    {engine speed=1100rpm}
                    T_q41=T_q1+(9/7)^0.4;
                    B_p41=2*3.14*N_1*T_q41/60
                    T_q41=K_1/(2*3.14)*(1-(1/9^0.4))*60*m_f41*Q_Lv/N_1
                    BMEP_41=120*B_p41/(V_s*N_1)
                    THERMALEFF_41=B_p41/(Q_Lv*m_f41)
                    SFC_41=3600*m_f41/(B_p41/1000)



                    {average between r_c1=8.0 and r_6c=6.0, for r_c5=7.0}

                    {COMPRESSION RATIO, r_c5 = 7.0}
                    {engine speed=1100rpm}
                    B_p51=(B_p31+B_p21)/2;
                    T_q51=(T_q31+T_q21)/2;
                    m_f51=(m_f31+m_f21)/2;
                    BMEP_51=(BMEP_31+BMEP_21)/2;
   THERMALEFF_51=(THERMALEFF_31+THERMALEFF_21)/2;
                    SFC_51=(SFC_31+SFC_21)/2;



{COMPRESSION RATIO, r_c1=5.0}
                    {engine speed=1200rpm}
                    T_q12=T_q2-(5/7)^0.4;
                    B_p12=2*3.14*N_2*T_q12/60
                    T_q12=K_2/(2*3.14)*(1-(1/5^0.4))*60*m_f12*Q_Lv/N_2
                    BMEP_12=120*B_p12/(V_s*N_2)
                    THERMALEFF_12=B_p12/(Q_Lv*m_f12)
                    SFC_12=3600*m_f12/(B_p12/1000)
```

```
{COMPRESSION RATIO, r_c2=6.0}
                {engine speed=1200rpm}
                T_q22=T_q2-(6/7)^0.4;;
                B_p22=2*3.14*N_2*T_q22/60
                T_q22=K_2/(2*3.14)*(1-(1/6^0.4))*60*m_f22*Q_Lv/N_2
                BMEP_22=120*B_p22/(V_s*N_2)
                THERMALEFF_22=B_p22/(Q_Lv*m_f22)
                SFC_22=3600*m_f22/(B_p22/1000)


                {COMPRESSION RATIO, r_c3=8.0}
                {engine speed=1200rpm}
                T_q32=T_q2+(8/7)^0.4;
                B_p32=2*3.14*N_2*T_q32/60
                T_q32=K_2/(2*3.14)*(1-(1/8^0.4))*60*m_f32*Q_Lv/N_2
                BMEP_32=120*B_p32/(V_s*N_2)
                THERMALEFF_32=B_p32/(Q_Lv*m_f32)
                SFC_32=3600*m_f32/(B_p32/1000)


                {COMPRESSION RATIO, r_c4=9.0}
                {engine speed=1200rpm}
                T_q42=T_q2+(9/7)^0.4;;
                B_p42=2*3.14*N_2*T_q42/60
                T_q42=K_2/(2*3.14)*(1-(1/9^0.4))*60*m_f42*Q_Lv/N_2
                BMEP_42=120*B_p42/(V_s*N_2)
                THERMALEFF_42=B_p42/(Q_Lv*m_f42)
                SFC_42=3600*m_f42/(B_p42/1000)



                {average between r_c3=8.0 and r_c2=6.0, for r_c5=7.0}

                {COMPRESSION RATIO, r_c5 = 7.0}
                {engine speed=1200rpm}
                B_p52=(B_p32+B_p22)/2;
                T_q52=(T_q32+T_q22)/2;
                m_f52=(m_f32+m_f22)/2;
                BMEP_52=(BMEP_32+BMEP_22)/2;
                THERMALEFF_52=(THERMALEFF_32+THERMALEFF_22)/2;
                SFC_52=(SFC_32+SFC_22)/2;
```

{COMPRESSION RATIO, r_c1=5.0}

{engine speed=1300rpm}

T_q13=T_q3-(5/7)^0.4;

B_p13=2*3.14*N_3*T_q13/60

T_q13=K_3/(2*3.14)*(1-(1/5^0.4))*60*m_f13*Q_Lv/N_3

BMEP_13=120*B_p13/(V_s*N_3)

THERMALEFF_13=B_p13/(Q_Lv*m_f13)

SFC_13=3600*m_f13/(B_p13/1000)

{COMPRESSION RATIO, r_c2=6.0}

{engine speed=1300rpm}

T_q23=T_q3-(6/7)^0.4;;

B_p23=2*3.14*N_3*T_q23/60

T_q23=K_3/(2*3.14)*(1-(1/6^0.4))*60*m_f23*Q_Lv/N_3

BMEP_23=120*B_p23/(V_s*N_3)

THERMALEFF_23=B_p23/(Q_Lv*m_f23)

SFC_23=3600*m_f23/(B_p23/1000)

{COMPRESSION RATIO, r_c3=8.0}

{engine speed=1300rpm}

T_q33=T_q3+(8/7)^0.4;

B_p33=2*3.14*N_3*T_q33/60

T_q33=K_3/(2*3.14)*(1-(1/8^0.4))*60*m_f33*Q_Lv/N_3

BMEP_33=120*B_p33/(V_s*N_3)

THERMALEFF_33=B_p33/(Q_Lv*m_f33)

SFC_33=3600*m_f33/(B_p33/1000)

{COMPRESSION RATIO, r_c4=9.0}

{engine speed=1300rpm}

T_q43=T_q3+(9/7)^0.4;;

B_p43=2*3.14*N_3*T_q43/60

T_q43=K_3/(2*3.14)*(1-(1/9^0.4))*60*m_f43*Q_Lv/N_3

BMEP_43=120*B_p43/(V_s*N_3)

THERMALEFF_43=B_p43/(Q_Lv*m_f43)

SFC_43=3600*m_f43/(B_p43/1000)

{average between rc3=8.0 and rc2=6.0, for rc5=7.0}

{COMPRESSION RATIO, r_c5 = 7.0}
{engine speed=1300rpm}
B_p53=(B_p33+B_p23)/2;
T_q53=(T_q33+T_q23)/2;
m_f53=(m_f33+m_f23)/2;
BMEP_53=(BMEP_33+BMEP_23)/2;
THERMALEFF_53=(THERMALEFF_33+THERMALEFF_23)/2;
SFC_53=(SFC_33+SFC_23)/2;

{COMPRESSION RATIO, r_c1=5.0}
{engine speed=1400rpm}
T_q14=T_q4-(5/7)^0.4;
B_p14=2*3.14*N_4*T_q14/60
T_q14=K_4/(2*3.14)*(1-(1/5^0.4))*60*m_f14*Q_Lv/N_4
BMEP_14=120*B_p14/(V_s*N_4)
THERMALEFF_14=B_p14/(Q_Lv*m_f14)
SFC_14=3600*m_f14/(B_p14/1000)

{COMPRESSION RATIO, r_c2=6.0}
{engine speed=1400rpm}
T_q24=T_q4-(6/7)^0.4;;
B_p24=2*3.14*N_4*T_q24/60
T_q24=K_4/(2*3.14)*(1-(1/6^0.4))*60*m_f24*Q_Lv/N_4
BMEP_24=120*B_p24/(V_s*N_4)
THERMALEFF_24=B_p24/(Q_Lv*m_f24)
SFC_24=3600*m_f24/(B_p24/1000)

{COMPRESSION RATIO, r_c3=8.0}
{engine speed=1400rpm}
T_q34=T_q4+(8/7)^0.4;
B_p34=2*3.14*N_4*T_q34/60
T_q34=K_4/(2*3.14)*(1-(1/8^0.4))*60*m_f34*Q_Lv/N_4
BMEP_34=120*B_p34/(V_s*N_4)
THERMALEFF_34=B_p34/(Q_Lv*m_f34)
SFC_34=3600*m_f34/(B_p34/1000)

{COMPRESSION RATIO, r_c4=9.0}

{engine speed=1400rpm}
T_q44=T_q4+(9/7)^0.4;
B_p44=2*3.14*N_4*T_q44/60
T_q44=K_4/(2*3.14)*(1-(1/9^0.4))*60*m_f44*Q_Lv/N_4
BMEP_44=120*B_p44/(V_s*N_4)
THERMALEFF_44=B_p44/(Q_Lv*m_f44)
SFC_44=3600*m_f44/(B_p44/1000)

{average between rc3=8.0 and rc2=6.0, for rc5=7.0}

{COMPRESSION RATIO, r_c5 = 7.0}
{engine speed=1400rpm}
B_p54=(B_p34+B_p24)/2;
T_q54=(T_q34+T_q24)/2;
m_f54=(m_f34+m_f24)/2;
BMEP_54=(BMEP_34+BMEP_24)/2;
THERMALEFF_54=(THERMALEFF_34+THERMALEFF_24)/2;
SFC_54=(SFC_34+SFC_24)/2;

{COMPRESSION RATIO, r_c1=5.0}
{engine speed=1500rpm}
T_q15=T_q5-(5/7)^0.4;
B_p15=2*3.14*N_5*T_q15/60
T_q15=K_5/(2*3.14)*(1-(1/5^0.4))*60*m_f15*Q_Lv/N_5
BMEP_15=120*B_p15/(V_s*N_5)
THERMALEFF_15=B_p15/(Q_Lv*m_f15)
SFC_15=3600*m_f15/(B_p15/1000)

{COMPRESSION RATIO, r_c2=6.0}
{engine speed=1500rpm}
T_q25=T_q5-(6/7)^0.4;;
B_p25=2*3.14*N_5*T_q25/60
T_q25=K_5/(2*3.14)*(1-(1/6^0.4))*60*m_f25*Q_Lv/N_5
BMEP_25=120*B_p25/(V_s*N_5)
THERMALEFF_25=B_p25/(Q_Lv*m_f25)
SFC_25=3600*m_f25/(B_p25/1000)

{COMPRESSION RATIO, r_c3=8.0}
{engine speed=1500rpm}
T_q35=T_q5+(8/7)^0.4;
B_p35=2*3.14*N_5*T_q35/60

T_q35=K_5/(2*3.14)*(1-(1/8^0.4))*60*m_f35*Q_Lv/N_5
BMEP_35=120*B_p35/(V_s*N_5)
THERMALEFF_35=B_p35/(Q_Lv*m_f35)
SFC_35=3600*m_f35/(B_p35/1000)

{COMPRESSION RATIO, r_c4=9.0}
{engine speed=1500rpm}
T_q45=T_q5+(9/7)^0.4;;
B_p45=2*3.14*N_5*T_q45/60
T_q45=K_5/(2*3.14)*(1-(1/9^0.4))*60*m_f45*Q_Lv/N_5
BMEP_45=120*B_p45/(V_s*N_5)
THERMALEFF_45=B_p45/(Q_Lv*m_f45)
SFC_45=3600*m_f45/(B_p45/1000)

{average between rc3=8.0 and rc2=6.0, for rc5=7.0}

{COMPRESSION RATIO, r_c5 = 7.0}
{engine speed=1500rpm}
B_p55=(B_p35+B_p25)/2;
T_q55=(T_q35+T_q25)/2;
m_f55=(m_f35+m_f25)/2;
BMEP_55=(BMEP_35+BMEP_25)/2;
THERMALEFF_55=(THERMALEFF_35+THERMALEFF_25)/2;
SFC_55=(SFC_35+SFC_25)/2;

{COMPRESSION RATIO, r_c1=5.0}
{engine speed=1600rpm}
T_q16=T_q6-(5/7)^0.4;
B_p16=2*3.14*N_6*T_q16/60
T_q16=K_6/(2*3.14)*(1-(1/5^0.4))*60*m_f16*Q_Lv/N_6
BMEP_16=120*B_p16/(V_s*N_6)
THERMALEFF_16=B_p16/(Q_Lv*m_f16)
SFC_16=3600*m_f16/(B_p16/1000)

{COMPRESSION RATIO, r_c2=6.0}
{engine speed=1600rpm}

T_q26=T_q6-(6/7)^0.4;
B_p26=2*3.14*N_6*T_q26/60
T_q26=K_6/(2*3.14)*(1-(1/6^0.4))*60*m_f26*Q_Lv/N_6
BMEP_26=120*B_p26/(V_s*N_6)
THERMALEFF_26=B_p26/(Q_Lv*m_f26)
SFC_26=3600*m_f26/(B_p26/1000)

{COMPRESSION RATIO, r_c3=8.0}
{engine speed=1600rpm}
T_q36=T_q6+(8/7)^0.4;
B_p36=2*3.14*N_6*T_q36/60
T_q36=K_6/(2*3.14)*(1-(1/8^0.4))*60*m_f36*Q_Lv/N_6
BMEP_36=120*B_p36/(V_s*N_6)
THERMALEFF_36=B_p36/(Q_Lv*m_f36)
SFC_36=3600*m_f36/(B_p36/1000)

{COMPRESSION RATIO, r_c4=9.0}
{engine speed=1500rpm}
T_q46=T_q6+(9/7)^0.4;
B_p46=2*3.14*N_6*T_q46/60
T_q46=K_6/(2*3.14)*(1-(1/9^0.4))*60*m_f46*Q_Lv/N_6
BMEP_46=120*B_p46/(V_s*N_6)
THERMALEFF_46=B_p46/(Q_Lv*m_f46)
SFC_46=3600*m_f46/(B_p46/1000)

{average between rc=8.0 and rc=6.0, for rc=7.0}

{COMPRESSION RATIO, r_c5 = 7.0}
{engine speed=1600rpm}
B_p56=(B_p36+B_p26)/2;
T_q56=(T_q36+T_q26)/2;
m_f56=(m_f36+m_f26)/2;
BMEP_56=(BMEP_36+BMEP_26)/2;
THERMALEFF_56=(THERMALEFF_36+THERMALEFF_26)/2;
SFC_56=(SFC_36+SFC_26)/2;

## APPENDIX C

**[Formatted equations for experimental analysis]**

$Q_{Lv} = 4.2 \times 10^{7}$

$B = 0.0762$

$S = 0.111$

$V_s = p \cdot B^{2} \cdot \frac{S}{4}$

$V = 0.00005$

$n = 1.4$

$S_g = 0.74$

$P_{atm} = 1239.9$

$T_{atm} = 305$

$denst_{wat} = 1000$

$$denst_{air} = P_{atm} \cdot \frac{100}{287 \cdot T_{atm}}$$

$r_c1 = 5$

$t_1 = 55.02$

$T_{q1} = 31.8$

$h_{a1} = 3.3$

$$m_{f11} = S_g \cdot denst_{wat} \cdot \frac{V}{t_1}$$

$$m_{a11} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{a1}}{T_{atm}}}}{3600}$$

$$AirFrat_{11} = \frac{m_{a11}}{m_{f11}}$$

$$Voleff_{a11} = 120 \cdot \frac{m_{a11}}{denst_{air} \cdot V_s \cdot N_1} \cdot 100$$

$$b_{p11} = 2 \cdot 3.14 \cdot N_1 \cdot \frac{T_{q1}}{60}$$

$$bmep_{11} = \frac{120 \cdot b_{p11}}{V_s \cdot N_1}$$

$$Thermaleff_{11} = \frac{b_{p11}}{Q_{Lv} \cdot m_{f11}} \cdot 100$$

$$sfc_{11} = 3600 \cdot \frac{m_{f11}}{\frac{b_{p11}}{1000}}$$

r_c2 = 6

$$t_{21} = 58.4$$

$$T_{q21} = 32.4$$

$$h_{b1} = 3.4$$

$$m_{f21} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{21}}$$

$$m_{a21} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{b1}}{T_{atm}}}}{3600}$$

$$AirFrat_{21} = \frac{m_{a21}}{m_{f21}}$$

$$Voleff_{b1} = 120 \cdot \frac{m_{a21}}{denst_{air} \cdot V_s \cdot N_1} \cdot 100$$

$$b_{p21} = 2 \cdot 3.14 \cdot N_1 \cdot \frac{T_{q21}}{60}$$

$$bmep_{21} = \frac{120 \cdot b_{p21}}{V_s \cdot N_1}$$

$$Thermaleff_{21} = \frac{b_{p21}}{Q_{Lv} \cdot m_{f21}} \cdot 100$$

$$sfc_{21} = 3600 \cdot \frac{m_{f21}}{\frac{b_{p21}}{1000}}$$

r_c3 = 7

$$t_{31} = 60.05$$

$$T_{q31} = 32.6$$

$$h_{c1} = 3.5$$

$$m_{f31} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{31}}$$

$$m_{a31} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{c1}}{T_{atm}}}}{3600}$$

$$AirFrat_{31} = \frac{m_{a31}}{m_{f31}}$$

$$Voleff_{c1} = 120 \cdot \frac{m_{a31}}{denst_{air} \cdot V_s \cdot N_1} \cdot 100$$

$$b_{p31} = 2 \cdot 3.14 \cdot N_1 \cdot \frac{T_{q31}}{60}$$

$$bmep_{31} = \frac{120 \cdot b_{p31}}{V_s \cdot N_1}$$

$$Thermaleff_{31} = \frac{b_{p31}}{Q_{Lv} \cdot m_{f31}} \cdot 100$$

$$sfc_{31} = 3600 \cdot \frac{m_{f31}}{\frac{b_{p31}}{1000}}$$

$r_c4 = 8$

$$t_{41} = 63.08$$

$$T_{q41} = 33.1$$

$$h_{d1} = 3.4$$

$$m_{f41} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{41}}$$

$$m_{a41} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{d1}}{T_{atm}}}}{3600}$$

$$AirFrat_{41} = \frac{m_{a41}}{m_{f41}}$$

$$Voleff_{d1} = 120 \cdot \frac{m_{a41}}{denst_{air} \cdot V_s \cdot N_1} \cdot 100$$

$$b_{p41} = 2 \cdot 3.14 \cdot N_1 \cdot \frac{T_{q41}}{60}$$

$$bmep_{41} = \frac{120 \cdot b_{p41}}{V_s \cdot N_1}$$

$$Thermaleff_{41} = \frac{b_{p41}}{Q_{Lv} \cdot m_{f41}} \cdot 100$$

$$sfc_{41} = 3600 \cdot \frac{m_{f41}}{\frac{b_{p41}}{1000}}$$

r_c5 = 9

$r_{c5} = 9$

$t_{51} = 67.2$

$T_{q51} = 33.3$

$h_{e1} = 3.5$

$$m_{f51} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{51}}$$

$$m_{a51} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{e1}}{T_{atm}}}}{3600}$$

$$AirFrat_{51} = \frac{m_{a51}}{m_{f51}}$$

$$Voleff_{e1} = 120 \cdot \frac{m_{a51}}{denst_{air} \cdot V_s \cdot N_1} \cdot 100$$

$$b_{p51} = 2 \cdot 3.14 \cdot N_1 \cdot \frac{T_{q51}}{60}$$

$$bmep_{51} = \frac{120 \cdot b_{p51}}{V_s \cdot N_1}$$

$$Thermaleff_{51} = \frac{b_{p51}}{Q_{Lv} \cdot m_{f51}} \cdot 100$$

$$sfc_{51} = 3600 \cdot \frac{m_{f51}}{\frac{b_{p51}}{1000}}$$

$r_c1 = 5$

$$t_2 = 52.06$$

$$T_{q2} = 31.9$$

$$h_{a2} = 4.1$$

$$m_{f12} = S_g \cdot denst_{wat} \cdot \frac{V}{t_2}$$

$$m_{a12} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{a2}}{T_{atm}}}}{3600}$$

$$AirFrat_{12} = \frac{m_{a12}}{m_{f12}}$$

$$Voleff_{a12} = 120 \cdot \frac{m_{a12}}{denst_{air} \cdot V_s \cdot N_2} \cdot 100$$

$$b_{p12} = 2 \cdot 3.14 \cdot N_2 \cdot \frac{T_{q2}}{60}$$

$$bmep_{12} = \frac{120 \cdot b_{p12}}{V_s \cdot N_2}$$

$$Thermaleff_{12} = \frac{b_{p12}}{Q_{Lv} \cdot m_{f12}} \cdot 100$$

$$sfc_{12} = 3600 \cdot \frac{m_{f12}}{\frac{b_{p12}}{1000}}$$

r_c2 = 6

$$t_{22} = 54.61$$

$$T_{q22} = 32.2$$

$$h_{b2} = 4.2$$

$$m_{f22} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{22}}$$

$$m_{a22} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{b2}}{T_{atm}}}}{3600}$$

$$AirFrat_{22} = \frac{m_{a22}}{m_{f22}}$$

$$Voleff_{b2} = 120 \cdot \frac{m_{a22}}{denst_{air} \cdot V_s \cdot N_2} \cdot 100$$

$$b_{p22} = 2 \cdot 3.14 \cdot N_2 \cdot \frac{T_{q22}}{60}$$

$$bmep_{22} = \frac{120 \cdot b_{p22}}{V_s \cdot N_2}$$

$$Thermaleff_{22} = \frac{b_{p22}}{Q_{Lv} \cdot m_{f22}} \cdot 100$$

$$sfc_{22} = 3600 \cdot \frac{m_{f22}}{\frac{b_{p22}}{1000}}$$

r_c3 = 7

$$t_{32} = 56.6$$

$$T_{q32} = 32.9$$

$$h_{c2} = 4.2$$

$$m_{f32} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{32}}$$

$$m_{a32} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{c2}}{T_{atm}}}}{3600}$$

$$AirFrat_{32} = \frac{m_{a32}}{m_{f32}}$$

$$Voleff_{c2} = 120 \cdot \frac{m_{a32}}{denst_{air} \cdot V_s \cdot N_2} \cdot 100$$

$$b_{p32} = 2 \cdot 3.14 \cdot N_2 \cdot \frac{T_{q32}}{60}$$

$$bmep_{32} = \frac{120 \cdot b_{p32}}{V_s \cdot N_2}$$

$$Thermaleff_{32} = \frac{b_{p32}}{Q_{Lv} \cdot m_{f32}} \cdot 100$$

$$sfc_{32} = 3600 \cdot \frac{m_{f32}}{\frac{b_{p32}}{1000}}$$

r_c4 = 8

$$t_{42} = 59.89$$

$$T_{q42} = 33$$

$$h_{d2} = 3.9$$

$$m_{f42} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{42}}$$

$$m_{a42} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{d2}}{T_{atm}}}}{3600}$$

$$AirFrat_{42} = \frac{m_{a42}}{m_{f42}}$$

$$Voleff_{d2} = 120 \cdot \frac{m_{a42}}{denst_{air} \cdot V_s \cdot N_2} \cdot 100$$

$$b_{p42} = 2 \cdot 3.14 \cdot N_2 \cdot \frac{T_{q42}}{60}$$

$$bmep_{42} = \frac{120 \cdot b_{p42}}{V_s \cdot N_2}$$

$$Thermaleff_{42} = \frac{b_{p42}}{Q_{Lv} \cdot m_{f42}} \cdot 100$$

$$sfc_{42} = 3600 \cdot \frac{m_{f42}}{\frac{b_{p42}}{1000}}$$

r_c5 = 9

$$t_{52} = 65.8$$

$$T_{q52} = 33.1$$

$$h_{e2} = 4.3$$

$$m_{f52} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{52}}$$

$$m_{a52} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{e2}}{T_{atm}}}}{3600}$$

$$AirFrat_{52} = \frac{m_{a52}}{m_{f52}}$$

$$Voleff_{e2} = 120 \cdot \frac{m_{a52}}{denst_{air} \cdot V_s \cdot N_2} \cdot 100$$

$$b_{p52} = 2 \cdot 3.14 \cdot N_2 \cdot \frac{T_{q52}}{60}$$

$$bmep_{52} = \frac{120 \cdot b_{p52}}{V_s \cdot N_2}$$

$$Thermaleff_{52} = \frac{b_{p52}}{Q_{Lv} \cdot m_{f52}} \cdot 100$$

$$sfc_{52} = 3600 \cdot \frac{m_{f52}}{\frac{b_{p52}}{1000}}$$

r_c1= 5

$$t_3 = 50.1$$

$$T_{q3} = 31.5$$

$$h_{a3} = 4.7$$

$$m_{f13} = S_g \cdot denst_{wat} \cdot \frac{V}{t_3}$$

$$m_{a13} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{a3}}{T_{atm}}}}{3600}$$

$$AirFrat_{13} = \frac{m_{a13}}{m_{f13}}$$

$$Voleff_{a13} = 120 \cdot \frac{m_{a13}}{denst_{air} \cdot V_s \cdot N_3} \cdot 100$$

$$b_{p13} = 2 \cdot 3.14 \cdot N_3 \cdot \frac{T_{q3}}{60}$$

$$bmep_{13} = \frac{120 \cdot b_{p13}}{V_s \cdot N_3}$$

$$Thermaleff_{13} = \frac{b_{p13}}{Q_{Lv} \cdot m_{f13}} \cdot 100$$

$$sfc_{13} = 3600 \cdot \frac{m_{f13}}{\frac{b_{p13}}{1000}}$$

r_c2 = 6

$$t_{23} = 53.98$$

$$T_{q23} = 32.1$$

$$h_{b3} = 4.9$$

$$m_{f23} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{23}}$$

$$m_{a23} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{b3}}{T_{atm}}}}{3600}$$

$$AirFrat_{23} = \frac{m_{a23}}{m_{f23}}$$

$$Voleff_{b3} = 120 \cdot \frac{m_{a23}}{denst_{air} \cdot V_s \cdot N_3} \cdot 100$$

$$b_{p23} = 2 \cdot 3.14 \cdot N_3 \cdot \frac{T_{q23}}{60}$$

$$bmep_{23} = \frac{120 \cdot b_{p23}}{V_s \cdot N_3}$$

$$Thermaleff_{23} = \frac{b_{p23}}{Q_{Lv} \cdot m_{f23}} \cdot 100$$

$$sfc_{23} = 3600 \cdot \frac{m_{f23}}{\frac{b_{p23}}{1000}}$$

r_c3 = 7

$$t_{33} = 55.03$$

$$T_{q33} = 32.2$$

$$h_{c3} = 4.9$$

$$m_{f33} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{33}}$$

$$m_{a33} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{c3}}{T_{atm}}}}{3600}$$

$$AirFrat_{33} = \frac{m_{a33}}{m_{f33}}$$

$$Voleff_{c3} = 120 \cdot \frac{m_{a33}}{denst_{air} \cdot V_s \cdot N_3} \cdot 100$$

$$b_{p33} = 2 \cdot 3.14 \cdot N_3 \cdot \frac{T_{q33}}{60}$$

$$bmep_{33} = \frac{120 \cdot b_{p33}}{V_s \cdot N_3}$$

$$Thermaleff_{33} = \frac{b_{p33}}{Q_{Lv} \cdot m_{f33}} \cdot 100$$

$$sfc_{33} = 3600 \cdot \frac{m_{f33}}{\frac{b_{p33}}{1000}}$$

r_c4 = 8

$$t_{43} = 58.38$$

$$T_{q43} = 32.9$$

$$h_{d3} = 4.9$$

$$m_{f43} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{43}}$$

$$m_{a43} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{d3}}{T_{atm}}}}{3600}$$

$$AirFrat_{43} = \frac{m_{a43}}{m_{f43}}$$

$$Voleff_{d3} = 120 \cdot \frac{m_{a43}}{denst_{air} \cdot V_s \cdot N_3} \cdot 100$$

$$b_{p43} = 2 \cdot 3.14 \cdot N_3 \cdot \frac{T_{q43}}{60}$$

$$bmep_{43} = \frac{120 \cdot b_{p43}}{V_s \cdot N_3}$$

$$Thermaleff_{43} = \frac{b_{p43}}{Q_{Lv} \cdot m_{f43}} \cdot 100$$

$$sfc_{43} = 3600 \cdot \frac{m_{f43}}{\frac{b_{p43}}{1000}}$$

r_c5 = 9

$$t_{53} = 64.1$$

$$T_{q53} = 32.9$$

$$h_{e3} = 5.5$$

$$m_{f53} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{53}}$$

$$m_{a53} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{e3}}{T_{atm}}}}{3600}$$

$$AirFrat_{53} = \frac{m_{a53}}{m_{f53}}$$

$$Voleff_{e3} = 120 \cdot \frac{m_{a53}}{denst_{air} \cdot V_s \cdot N_3} \cdot 100$$

$$b_{p53} = 2 \cdot 3.14 \cdot N_3 \cdot \frac{T_{q53}}{60}$$

$$bmep_{53} = \frac{120 \cdot b_{p53}}{V_s \cdot N_3}$$

$$Thermaleff_{53} = \frac{b_{p53}}{Q_{Lv} \cdot m_{f53}} \cdot 100$$

$$sfc_{53} = 3600 \cdot \frac{m_{f53}}{\frac{b_{p53}}{1000}}$$

r_c1 = 5

$$t_4 = 48.1$$

$$T_{q4} = 30.1$$

$$h_{a4} = 5.2$$

$$m_{f14} = S_g \cdot denst_{wat} \cdot \frac{V}{t_4}$$

$$m_{a14} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{a4}}{T_{atm}}}}{3600}$$

$$AirFrat_{14} = \frac{m_{a14}}{m_{f14}}$$

$$Voleff_{a14} = 120 \cdot \frac{m_{a14}}{denst_{air} \cdot V_s \cdot N_4} \cdot 100$$

$$b_{p14} = 2 \cdot 3.14 \cdot N_4 \cdot \frac{T_{q4}}{60}$$

$$bmep_{14} = \frac{120 \cdot b_{p14}}{V_s \cdot N_4}$$

$$Thermaleff_{14} = \frac{b_{p14}}{Q_{Lv} \cdot m_{f14}} \cdot 100$$

$$sfc_{14} = 3600 \cdot \frac{m_{f14}}{\frac{b_{p14}}{1000}}$$

r_c2 = 6

$$t_{24} = 51.22$$

$$T_{q24} = 31$$

$$h_{b4} = 5.3$$

$$m_{f24} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{24}}$$

$$m_{a24} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{b4}}{T_{atm}}}}{3600}$$

$$AirFrat_{24} = \frac{m_{a24}}{m_{f24}}$$

$$Voleff_{b4} = 120 \cdot \frac{m_{a24}}{denst_{air} \cdot V_s \cdot N_4} \cdot 100$$

$$b_{p24} = 2 \cdot 3.14 \cdot N_4 \cdot \frac{T_{q24}}{60}$$

$$bmep_{24} = \frac{120 \cdot b_{p24}}{V_s \cdot N_4}$$

$$Thermaleff_{24} = \frac{b_{p24}}{Q_{Lv} \cdot m_{f24}} \cdot 100$$

$$sfc_{24} = 3600 \cdot \frac{m_{f24}}{\frac{b_{p24}}{1000}}$$

r_c3 = 7

$$t_{34} = 53.9$$

$$T_{q34} = 31.5$$

$$h_{c4} = 5.3$$

$$m_{f34} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{34}}$$

$$m_{a34} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{c4}}{T_{atm}}}}{3600}$$

$$AirFrat_{34} = \frac{m_{a34}}{m_{f34}}$$

$$Voleff_{c4} = 120 \cdot \frac{m_{a34}}{denst_{air} \cdot V_s \cdot N_4} \cdot 100$$

$$b_{p34} = 2 \cdot 3.14 \cdot N_4 \cdot \frac{T_{q34}}{60}$$

$$bmep_{34} = \frac{120 \cdot b_{p34}}{V_s \cdot N_4}$$

$$Thermaleff_{34} = \frac{b_{p34}}{Q_{Lv} \cdot m_{f34}} \cdot 100$$

$$sfc_{34} = 3600 \cdot \frac{m_{f34}}{\frac{b_{p34}}{1000}}$$

r_c4 = 8

$$t_{44} = 58.22$$

$$T_{q44} = 31.6$$

$$h_{d4} = 5.5$$

$$m_{f44} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{44}}$$

$$m_{a44} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{d4}}{T_{atm}}}}{3600}$$

$$AirFrat_{44} = \frac{m_{a44}}{m_{f44}}$$

$$Voleff_{d4} = 120 \cdot \frac{m_{a44}}{denst_{air} \cdot V_s \cdot N_4} \cdot 100$$

$$b_{p44} = 2 \cdot 3.14 \cdot N_4 \cdot \frac{T_{q44}}{60}$$

$$bmep_{44} = \frac{120 \cdot b_{p44}}{V_s \cdot N_4}$$

$$Thermaleff_{44} = \frac{b_{p44}}{Q_{Lv} \cdot m_{f44}} \cdot 100$$

$$sfc_{44} = 3600 \cdot \frac{m_{f44}}{\frac{b_{p44}}{1000}}$$

r_c5 = 9

$$t_{54} = 62.8$$

$$T_{q54} = 31.7$$

$$h_{e4} = 5.7$$

$$m_{f54} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{54}}$$

$$m_{a54} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{e4}}{T_{atm}}}}{3600}$$

$$AirFrat_{54} = \frac{m_{a54}}{m_{f54}}$$

$$Voleff_{e4} = 120 \cdot \frac{m_{a54}}{denst_{air} \cdot V_s \cdot N_4} \cdot 100$$

$$b_{p54} = 2 \cdot 3.14 \cdot N_4 \cdot \frac{T_{q54}}{60}$$

$$bmep_{54} = \frac{120 \cdot b_{p54}}{V_s \cdot N_4}$$

$$Thermaleff_{54} = \frac{b_{p54}}{Q_{Lv} \cdot m_{f54}} \cdot 100$$

$$sfc_{54} = 3600 \cdot \frac{m_{f54}}{\frac{b_{p54}}{1000}}$$

r_c1 = 5

$$t_5 = 44.5$$

$$T_{q5} = 28.9$$

$$h_{a5} = 5.5$$

$$m_{f15} = S_g \cdot denst_{wat} \cdot \frac{V}{t_5}$$

$$m_{a15} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{a5}}{T_{atm}}}}{3600}$$

$$AirFrat_{15} = \frac{m_{a15}}{m_{f15}}$$

$$Voleff_{a15} = 120 \cdot \frac{m_{a15}}{denst_{air} \cdot V_s \cdot N_5} \cdot 100$$

$$b_{p15} = 2 \cdot 3.14 \cdot N_5 \cdot \frac{T_{q5}}{60}$$

$$bmep_{15} = \frac{120 \cdot b_{p15}}{V_s \cdot N_5}$$

$$Thermaleff_{15} = \frac{b_{p15}}{Q_{Lv} \cdot m_{f15}} \cdot 100$$

$$sfc_{15} = 3600 \cdot \frac{m_{f15}}{\frac{b_{p15}}{1000}}$$

r_c2 = 6

$$t_{25} = 48.67$$

$$T_{q25} = 29.5$$

$$h_{b5} = 5.6$$

$$m_{f25} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{25}}$$

$$m_{a25} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{b5}}{T_{atm}}}}{3600}$$

$$AirFrat_{25} = \frac{m_{a25}}{m_{f25}}$$

$$Voleff_{b5} = 120 \cdot \frac{m_{a25}}{denst_{air} \cdot V_s \cdot N_5} \cdot 100$$

$$b_{p25} = 2 \cdot 3.14 \cdot N_5 \cdot \frac{T_{q25}}{60}$$

$$bmep_{25} = \frac{120 \cdot b_{p25}}{V_s \cdot N_5}$$

$$Thermaleff_{25} = \frac{b_{p25}}{Q_{Lv} \cdot m_{f25}} \cdot 100$$

$$sfc_{25} = 3600 \cdot \frac{m_{f25}}{\frac{b_{p25}}{1000}}$$

r_c = 3 = 7

$$t_{35} = 50.13$$

$$T_{q35} = 30.1$$

$$h_{c5} = 5.8$$

$$m_{f35} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{35}}$$

$$m_{a35} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{c5}}{T_{atm}}}}{3600}$$

$$AirFrat_{35} = \frac{m_{a35}}{m_{f35}}$$

$$Voleff_{c5} = 120 \cdot \frac{m_{a35}}{denst_{air} \cdot V_s \cdot N_5} \cdot 100$$

$$b_{p35} = 2 \cdot 3.14 \cdot N_5 \cdot \frac{T_{q35}}{60}$$

$$bmep_{35} = \frac{120 \cdot b_{p35}}{V_s \cdot N_5}$$

$$Thermaleff_{35} = \frac{b_{p35}}{Q_{Lv} \cdot m_{f35}} \cdot 100$$

$$sfc_{35} = 3600 \cdot \frac{m_{f35}}{\frac{b_{p35}}{1000}}$$

r_c4 = 8

$$t_{45} = 53.6$$

$$T_{q45} = 30.5$$

$$h_{d5} = 6$$

$$m_{f45} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{45}}$$

$$m_{a45} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{d5}}{T_{atm}}}}{3600}$$

$$AirFrat_{45} = \frac{m_{a45}}{m_{f45}}$$

$$Voleff_{d5} = 120 \cdot \frac{m_{a45}}{denst_{air} \cdot V_s \cdot N_5} \cdot 100$$

$$b_{p45} = 2 \cdot 3.14 \cdot N_5 \cdot \frac{T_{q45}}{60}$$

$$bmep_{45} = \frac{120 \cdot b_{p45}}{V_s \cdot N_5}$$

$$Thermaleff_{45} = \frac{b_{p45}}{Q_{Lv} \cdot m_{f45}} \cdot 100$$

$$sfc_{45} = 3600 \cdot \frac{m_{f45}}{\frac{b_{p45}}{1000}}$$

r_c5 = 9

$$t_{55} = 61.2$$

$$T_{q55} = 30.7$$

$$h_{e5} = 6.1$$

$$m_{f55} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{55}}$$

$$m_{a55} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{e5}}{T_{atm}}}}{3600}$$

$$AirFrat_{55} = \frac{m_{a55}}{m_{f55}}$$

$$Voleff_{e5} = 120 \cdot \frac{m_{a55}}{denst_{air} \cdot V_s \cdot N_5} \cdot 100$$

$$b_{p55} = 2 \cdot 3.14 \cdot N_5 \cdot \frac{T_{q55}}{60}$$

$$bmep_{55} = \frac{120 \cdot b_{p55}}{V_s \cdot N_5}$$

$$Thermaleff_{55} = \frac{b_{p55}}{Q_{Lv} \cdot m_{f55}} \cdot 100$$

$$sfc_{55} = 3600 \cdot \frac{m_{f55}}{\frac{b_{p55}}{1000}}$$

r_c1 = 5

$$t_6 = 40.3$$

$$T_{q6} = 27.4$$

$$h_{a6} = 5.7$$

$$m_{f16} = S_g \cdot denst_{wat} \cdot \frac{V}{t_6}$$

$$m_{a16} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{a6}}{T_{atm}}}}{3600}$$

$$AirFrat_{16} = \frac{m_{a16}}{m_{f16}}$$

$$Voleff_{a16} = 120 \cdot \frac{m_{a16}}{denst_{air} \cdot V_s \cdot N_6} \cdot 100$$

$$b_{p16} = 2 \cdot 3.14 \cdot N_6 \cdot \frac{T_{q6}}{60}$$

$$bmep_{16} = \frac{120 \cdot b_{p16}}{V_s \cdot N_6}$$

$$Thermaleff_{16} = \frac{b_{p16}}{Q_{Lv} \cdot m_{f16}} \cdot 100$$

$$sfc_{16} = 3600 \cdot \frac{m_{f16}}{\frac{b_{p16}}{1000}}$$

r_c2 = 6

$$t_{26} = 45.2$$

$$T_{q26} = 27.9$$

$$h_{b6} = 5.9$$

$$m_{f26} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{26}}$$

$$m_{a26} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{b6}}{T_{atm}}}}{3600}$$

$$AirFrat_{26} = \frac{m_{a26}}{m_{f26}}$$

$$Voleff_{b6} = 120 \cdot \frac{m_{a26}}{denst_{air} \cdot V_s \cdot N_6} \cdot 100$$

$$b_{p26} = 2 \cdot 3.14 \cdot N_6 \cdot \frac{T_{q26}}{60}$$

$$bmep_{26} = \frac{120 \cdot b_{p26}}{V_s \cdot N_6}$$

$$Thermaleff_{26} = \frac{b_{p26}}{Q_{Lv} \cdot m_{f26}} \cdot 100$$

$$sfc_{26} = 3600 \cdot \frac{m_{f26}}{\frac{b_{p26}}{1000}}$$

r_c3 = 7

$$t_{36} = 46.5$$

$$T_{q36} = 28.4$$

$$h_{c6} = 6.1$$

$$m_{f36} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{36}}$$

$$m_{a36} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{c6}}{T_{atm}}}}{3600}$$

$$AirFrat_{36} = \frac{m_{a36}}{m_{f36}}$$

$$Voleff_{c6} = 120 \cdot \frac{m_{a36}}{denst_{air} \cdot V_s \cdot N_6} \cdot 100$$

$$b_{p36} = 2 \cdot 3.14 \cdot N_6 \cdot \frac{T_{q36}}{60}$$

$$bmep_{36} = \frac{120 \cdot b_{p36}}{V_s \cdot N_6}$$

$$Thermaleff_{36} = \frac{b_{p36}}{Q_{Lv} \cdot m_{f36}} \cdot 100$$

$$sfc_{36} = 3600 \cdot \frac{m_{f36}}{\frac{b_{p36}}{1000}}$$

r_c4 = 8

$$t_{46} = 52.2$$

$$T_{q46} = 28.6$$

$$h_{d6} = 6.2$$

$$m_{f46} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{46}}$$

$$m_{a46} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{d6}}{T_{atm}}}}{3600}$$

$$AirFrat_{46} = \frac{m_{a46}}{m_{f46}}$$

$$Voleff_{d6} = 120 \cdot \frac{m_{a46}}{denst_{air} \cdot V_s \cdot N_6} \cdot 100$$

$$b_{p46} = 2 \cdot 3.14 \cdot N_6 \cdot \frac{T_{q46}}{60}$$

$$bmep_{46} = \frac{120 \cdot b_{p46}}{V_s \cdot N_6}$$

$$Thermaleff_{46} = \frac{b_{p46}}{Q_{Lv} \cdot m_{f46}} \cdot 100$$

$$sfc_{46} = 3600 \cdot \frac{m_{f46}}{\frac{b_{p46}}{1000}}$$

r_c5 = 9

$$t_{56} = 58.8$$

$$T_{q56} = 29.1$$

$$h_{e6} = 6.6$$

$$m_{f56} = S_g \cdot denst_{wat} \cdot \frac{V}{t_{56}}$$

$$m_{a56} = \frac{2.98 \cdot \sqrt{P_{atm} \cdot \frac{h_{e6}}{T_{atm}}}}{3600}$$

$$AirFrat_{56} = \frac{m_{a56}}{m_{f56}}$$

$$Voleff_{e6} = 120 \cdot \frac{m_{a56}}{denst_{air} \cdot V_s \cdot N_6} \cdot 100$$

$$b_{p56} = 2 \cdot 3.14 \cdot N_6 \cdot \frac{T_{q56}}{60}$$

$$bmep_{56} = \frac{120 \cdot b_{p56}}{V_s \cdot N_6}$$

$$Thermaleff_{56} = \frac{b_{p56}}{Q_{Lv} \cdot m_{f56}} \cdot 100$$

$$sfc_{56} = 3600 \cdot \frac{m_{f56}}{\frac{b_{p56}}{1000}}$$

$$T_{q31} = \frac{K_1}{2 \cdot p} \cdot \left[1 - \frac{1}{r_{c3}^{(n-1)}}\right] \cdot m_{f31} \cdot \frac{Q_{Lv}}{\frac{N_1}{60}}$$

$$T_{q32} = \frac{K_2}{2 \cdot p} \cdot \left[1 - \frac{1}{r_{c3}^{(n-1)}}\right] \cdot m_{f32} \cdot \frac{Q_{Lv}}{\frac{N_2}{60}}$$

$$T_{q33} = \frac{K_3}{2 \cdot p} \cdot \left[1 - \frac{1}{r_{c3}^{(n-1)}}\right] \cdot m_{f33} \cdot \frac{Q_{Lv}}{\frac{N_3}{60}}$$

$$T_{q34} = \frac{K_4}{2 \cdot p} \cdot \left[1 - \frac{1}{r_{c3}^{(n-1)}}\right] \cdot m_{f34} \cdot \frac{Q_{Lv}}{\frac{N_4}{60}}$$

$$T_{q35} = \frac{K_5}{2 \cdot p} \cdot \left[1 - \frac{1}{r_{c3}^{(n-1)}}\right] \cdot m_{f35} \cdot \frac{Q_{Lv}}{\frac{N_5}{60}}$$

$$T_{q36} = \frac{K_6}{2 \cdot p} \cdot \left[1 - \frac{1}{r_{c3}^{(n-1)}}\right] \cdot m_{f36} \cdot \frac{Q_{Lv}}{\frac{N_6}{60}}$$

## APPENDIX D

**[Formatted equations for theoretical analysis]**

$$T_{q1} = 32.6$$

$$T_{q2} = 32.9$$

$$T_{q3} = 32.2$$

$$T_{q4} = 31.5$$

$$T_{q6} = 28.4$$

$$r_c1 = 5$$

$$T_{q11} = T_{q1} - (5 / 7)^{0.4}$$

$$B_{p11} = 2 \cdot 3.14 \cdot N_1 \cdot \frac{T_{q11}}{60}$$

$$T_{q11} = \frac{K_1}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{5^{0.4}}\right] \cdot 60 \cdot m_{f11} \cdot \frac{Q_{Lv}}{N_1}$$

$$BMEP_{11} = 120 \cdot \frac{B_{p11}}{V_s \cdot N_1}$$

$$THERMALEFF_{11} = \frac{B_{p11}}{Q_{Lv} \cdot m_{f11}}$$

$$SFC_{11} = 3600 \cdot \frac{m_{f11}}{\frac{B_{p11}}{1000}}$$

r_c2 = 6

$$T_{q21} = T_{q1} - (6 / 7)^{0.4}$$

$$B_{p21} = 2 \cdot 3.14 \cdot N_1 \cdot \frac{T_{q21}}{60}$$

$$T_{q21} = \frac{K_1}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{6^{0.4}}\right] \cdot 60 \cdot m_{f21} \cdot \frac{Q_{Lv}}{N_1}$$

$$BMEP_{21} = 120 \cdot \frac{B_{p21}}{V_s \cdot N_1}$$

$$THERMALEFF_{21} = \frac{B_{p21}}{Q_{Lv} \cdot m_{f21}}$$

$$SFC_{21} = 3600 \cdot \frac{m_{f21}}{\frac{B_{p21}}{1000}}$$

r_c3 = 8

$$T_{q31} = T_{q1} + (8 / 7)^{0.4}$$

$$B_{p31} = 2 \cdot 3.14 \cdot N_1 \cdot \frac{T_{q31}}{60}$$

$$T_{q31} = \frac{K_1}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{8^{0.4}}\right] \cdot 60 \cdot m_{f31} \cdot \frac{Q_{Lv}}{N_1}$$

$$BMEP_{31} = 120 \cdot \frac{B_{p31}}{V_s \cdot N_1}$$

$$THERMALEFF_{31} = \frac{B_{p31}}{Q_{Lv} \cdot m_{f31}}$$

$$SFC_{31} = 3600 \cdot \frac{m_{f31}}{\frac{B_{p31}}{1000}}$$

r_c4 = 9

$$T_{q41} = T_{q1} + (9 / 7)^{0.4}$$

$$B_{p41} = 2 \cdot 3.14 \cdot N_1 \cdot \frac{T_{q41}}{60}$$

$$T_{q41} = \frac{K_1}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{9^{0.4}}\right] \cdot 60 \cdot m_{f41} \cdot \frac{Q_{Lv}}{N_1}$$

$$BMEP_{41} = 120 \cdot \frac{B_{p41}}{V_s \cdot N_1}$$

$$THERMALEFF_{41} = \frac{B_{p41}}{Q_{Lv} \cdot m_{f41}}$$

$$SFC_{41} = 3600 \cdot \frac{m_{f41}}{\frac{B_{p41}}{1000}}$$

r_c5 = 7

$$B_{p51} = \frac{B_{p31} + B_{p21}}{2}$$

$$T_{q51} = \frac{T_{q31} + T_{q21}}{2}$$

$$m_{f51} = \frac{m_{f31} + m_{f21}}{2}$$

$$BMEP_{51} = \frac{BMEP_{31} + BMEP_{21}}{2}$$

$$THERMALEFF_{51} = \frac{THERMALEFF_{31} + THERMALEFF_{21}}{2}$$

$$SFC_{51} = \frac{SFC_{31} + SFC_{21}}{2}$$

r_c1 = 5

$$T_{q12} = T_{q2} - (5 / 7)^{0.4}$$

$$B_{p12} = 2 \cdot 3.14 \cdot N_2 \cdot \frac{T_{q12}}{60}$$

$$T_{q12} = \frac{K_2}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{5^{0.4}}\right] \cdot 60 \cdot m_{f12} \cdot \frac{Q_{Lv}}{N_2}$$

$$BMEP_{12} = 120 \cdot \frac{B_{p12}}{V_s \cdot N_2}$$

$$THERMALEFF_{12} = \frac{B_{p12}}{Q_{Lv} \cdot m_{f12}}$$

$$SFC_{12} = 3600 \cdot \frac{m_{f12}}{\frac{B_{p12}}{1000}}$$

r_c2 = 6

$$T_{q22} = T_{q2} - (6 / 7)^{0.4}$$

$$B_{p22} = 2 \cdot 3.14 \cdot N_2 \cdot \frac{T_{q22}}{60}$$

$$T_{q22} = \frac{K_2}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{6^{0.4}}\right] \cdot 60 \cdot m_{f22} \cdot \frac{Q_{Lv}}{N_2}$$

$$BMEP_{22} = 120 \cdot \frac{B_{p22}}{V_s \cdot N_2}$$

$$THERMALEFF_{22} = \frac{B_{p22}}{Q_{Lv} \cdot m_{f22}}$$

$$SFC_{22} = 3600 \cdot \frac{m_{f22}}{\frac{B_{p22}}{1000}}$$

r_c3 = 8

$$T_{q32} = T_{q2} + (8 / 7)^{0.4}$$

$$B_{p32} = 2 \cdot 3.14 \cdot N_2 \cdot \frac{T_{q32}}{60}$$

$$T_{q32} = \frac{K_2}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{8^{0.4}}\right] \cdot 60 \cdot m_{f32} \cdot \frac{Q_{Lv}}{N_2}$$

$$BMEP_{32} = 120 \cdot \frac{B_{p32}}{V_s \cdot N_2}$$

$$THERMALEFF_{32} = \frac{B_{p32}}{Q_{Lv} \cdot m_{f32}}$$

$$SFC_{32} = 3600 \cdot \frac{m_{f32}}{\frac{B_{p32}}{1000}}$$

r_c4 = 9

$$T_{q42} = T_{q2} + (9 / 7)^{0.4}$$

$$B_{p42} = 2 \cdot 3.14 \cdot N_2 \cdot \frac{T_{q42}}{60}$$

$$T_{q42} = \frac{K_2}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{9^{0.4}}\right] \cdot 60 \cdot m_{f42} \cdot \frac{Q_{Lv}}{N_2}$$

$$BMEP_{42} = 120 \cdot \frac{B_{p42}}{V_s \cdot N_2}$$

$$THERMALEFF_{42} = \frac{B_{p42}}{Q_{Lv} \cdot m_{f42}}$$

$$SFC_{42} = 3600 \cdot \frac{m_{f42}}{\frac{B_{p42}}{1000}}$$

r_c5 = 7

$$B_{p52} = \frac{B_{p32} + B_{p22}}{2}$$

$$T_{q52} = \frac{T_{q32} + T_{q22}}{2}$$

$$m_{f52} = \frac{m_{f32} + m_{f22}}{2}$$

$$BMEP_{52} = \frac{BMEP_{32} + BMEP_{22}}{2}$$

$$THERMALEFF_{52} = \frac{THERMALEFF_{32} + THERMALEFF_{22}}{2}$$

$$SFC_{52} = \frac{SFC_{32} + SFC_{22}}{2}$$

r_c1 = 5

$$T_{q13} = T_{q3} - (5 / 7)^{0.4}$$

$$B_{p13} = 2 \cdot 3.14 \cdot N_3 \cdot \frac{T_{q13}}{60}$$

$$T_{q13} = \frac{K_3}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{5^{0.4}}\right] \cdot 60 \cdot m_{f13} \cdot \frac{Q_{Lv}}{N_3}$$

$$BMEP_{13} = 120 \cdot \frac{B_{p13}}{V_s \cdot N_3}$$

$$THERMALEFF_{13} = \frac{B_{p13}}{Q_{Lv} \cdot m_{f13}}$$

$$SFC_{13} = 3600 \cdot \frac{m_{f13}}{\frac{B_{p13}}{1000}}$$

r_c2 = 6

$$T_{q23} = T_{q3} - (6 / 7)^{0.4}$$

$$B_{p23} = 2 \cdot 3.14 \cdot N_3 \cdot \frac{T_{q23}}{60}$$

$$T_{q23} = \frac{K_3}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{6^{0.4}}\right] \cdot 60 \cdot m_{f23} \cdot \frac{Q_{Lv}}{N_3}$$

$$BMEP_{23} = 120 \cdot \frac{B_{p23}}{V_s \cdot N_3}$$

$$THERMALEFF_{23} = \frac{B_{p23}}{Q_{Lv} \cdot m_{f23}}$$

$$SFC_{23} = 3600 \cdot \frac{m_{f23}}{\frac{B_{p23}}{1000}}$$

r_c3 = 8

$$T_{q33} = T_{q3} + (8 / 7)^{0.4}$$

$$B_{p33} = 2 \cdot 3.14 \cdot N_3 \cdot \frac{T_{q33}}{60}$$

$$T_{q33} = \frac{K_3}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{8^{0.4}}\right] \cdot 60 \cdot m_{f33} \cdot \frac{Q_{Lv}}{N_3}$$

$$BMEP_{33} = 120 \cdot \frac{B_{p33}}{V_s \cdot N_3}$$

$$THERMALEFF_{33} = \frac{B_{p33}}{Q_{Lv} \cdot m_{f33}}$$

$$SFC_{33} = 3600 \cdot \frac{m_{f33}}{\frac{B_{p33}}{1000}}$$

r_c4 = 9

$$T_{q43} = T_{q3} + (9 / 7)^{0.4}$$

$$B_{p43} = 2 \cdot 3.14 \cdot N_3 \cdot \frac{T_{q43}}{60}$$

$$T_{q43} = \frac{K_3}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{9^{0.4}}\right] \cdot 60 \cdot m_{f43} \cdot \frac{Q_{Lv}}{N_3}$$

$$BMEP_{43} = 120 \cdot \frac{B_{p43}}{V_s \cdot N_3}$$

$$THERMALEFF_{43} = \frac{B_{p43}}{Q_{Lv} \cdot m_{f43}}$$

$$SFC_{43} = 3600 \cdot \frac{m_{f43}}{\frac{B_{p43}}{1000}}$$

r_c5 = 7

$$B_{p53} = \frac{B_{p33} + B_{p23}}{2}$$

$$T_{q53} = \frac{T_{q33} + T_{q23}}{2}$$

$$m_{f53} = \frac{m_{f33} + m_{f23}}{2}$$

$$BMEP_{53} = \frac{BMEP_{33} + BMEP_{23}}{2}$$

$$THERMALEFF_{53} = \frac{THERMALEFF_{33} + THERMALEFF_{23}}{2}$$

$$SFC_{53} = \frac{SFC_{33} + SFC_{23}}{2}$$

r_c1 = 5

$$T_{q14} = T_{q4} - (5 / 7)^{0.4}$$

$$B_{p14} = 2 \cdot 3.14 \cdot N_4 \cdot \frac{T_{q14}}{60}$$

$$T_{q14} = \frac{K_4}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{5^{0.4}}\right] \cdot 60 \cdot m_{f14} \cdot \frac{Q_{Lv}}{N_4}$$

$$BMEP_{14} = 120 \cdot \frac{B_{p14}}{V_s \cdot N_4}$$

$$THERMALEFF_{14} = \frac{B_{p14}}{Q_{Lv} \cdot m_{f14}}$$

$$SFC_{14} = 3600 \cdot \frac{m_{f14}}{\frac{B_{p14}}{1000}}$$

r_c2 = 6

$$T_{q24} = T_{q4} - (6 / 7)^{0.4}$$

$$B_{p24} = 2 \cdot 3.14 \cdot N_4 \cdot \frac{T_{q24}}{60}$$

$$T_{q24} = \frac{K_4}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{6^{0.4}}\right] \cdot 60 \cdot m_{f24} \cdot \frac{Q_{Lv}}{N_4}$$

$$BMEP_{24} = 120 \cdot \frac{B_{p24}}{V_s \cdot N_4}$$

$$THERMALEFF_{24} = \frac{B_{p24}}{Q_{Lv} \cdot m_{f24}}$$

$$SFC_{24} = 3600 \cdot \frac{m_{f24}}{\frac{B_{p24}}{1000}}$$

r_c3 = 8

$$T_{q34} = T_{q4} + (8 / 7)^{0.4}$$

$$B_{p34} = 2 \cdot 3.14 \cdot N_4 \cdot \frac{T_{q34}}{60}$$

$$T_{q34} = \frac{K_4}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{8^{0.4}}\right] \cdot 60 \cdot m_{f34} \cdot \frac{Q_{Lv}}{N_4}$$

$$BMEP_{34} = 120 \cdot \frac{B_{p34}}{V_s \cdot N_4}$$

$$THERMALEFF_{34} = \frac{B_{p34}}{Q_{Lv} \cdot m_{f34}}$$

$$SFC_{34} = 3600 \cdot \frac{m_{f34}}{\frac{B_{p34}}{1000}}$$

r_c4 = 9

$$T_{q44} = T_{q4} + (9 / 7)^{0.4}$$

$$B_{p44} = 2 \cdot 3.14 \cdot N_4 \cdot \frac{T_{q44}}{60}$$

$$T_{q44} = \frac{K_4}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{9^{0.4}}\right] \cdot 60 \cdot m_{f44} \cdot \frac{Q_{Lv}}{N_4}$$

$$BMEP_{44} = 120 \cdot \frac{B_{p44}}{V_s \cdot N_4}$$

$$THERMALEFF_{44} = \frac{B_{p44}}{Q_{Lv} \cdot m_{f44}}$$

$$SFC_{44} = 3600 \cdot \frac{m_{f44}}{\frac{B_{p44}}{1000}}$$

r_c5 = 7

$$B_{p54} = \frac{B_{p34} + B_{p24}}{2}$$

$$T_{q54} = \frac{T_{q34} + T_{q24}}{2}$$

$$m_{f54} = \frac{m_{f34} + m_{f24}}{2}$$

$$BMEP_{54} = \frac{BMEP_{34} + BMEP_{24}}{2}$$

$$THERMALEFF_{54} = \frac{THERMALEFF_{34} + THERMALEFF_{24}}{2}$$

$$SFC_{54} = \frac{SFC_{34} + SFC_{24}}{2}$$

r_c1 = 5

$$T_{q15} = T_{q5} - (5 / 7)^{0.4}$$

$$B_{p15} = 2 \cdot 3.14 \cdot N_5 \cdot \frac{T_{q15}}{60}$$

$$T_{q15} = \frac{K_5}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{5^{0.4}}\right] \cdot 60 \cdot m_{f15} \cdot \frac{Q_{Lv}}{N_5}$$

$$BMEP_{15} = 120 \cdot \frac{B_{p15}}{V_s \cdot N_5}$$

$$THERMALEFF_{15} = \frac{B_{p15}}{Q_{Lv} \cdot m_{f15}}$$

$$SFC_{15} = 3600 \cdot \frac{m_{f15}}{\frac{B_{p15}}{1000}}$$

r_c2 = 6

$$T_{q25} = T_{q5} - (6 / 7)^{0.4}$$

$$B_{p25} = 2 \cdot 3.14 \cdot N_5 \cdot \frac{T_{q25}}{60}$$

$$T_{q25} = \frac{K_5}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{6^{0.4}}\right] \cdot 60 \cdot m_{f25} \cdot \frac{Q_{Lv}}{N_5}$$

$$BMEP_{25} = 120 \cdot \frac{B_{p25}}{V_s \cdot N_5}$$

$$THERMALEFF_{25} = \frac{B_{p25}}{Q_{Lv} \cdot m_{f25}}$$

$$SFC_{25} = 3600 \cdot \frac{m_{f25}}{\frac{B_{p25}}{1000}}$$

r_c3 = 8

$$T_{q35} = T_{q5} + (8 / 7)^{0.4}$$

$$B_{p35} = 2 \cdot 3.14 \cdot N_5 \cdot \frac{T_{q35}}{60}$$

$$T_{q35} = \frac{K_5}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{8^{0.4}}\right] \cdot 60 \cdot m_{f35} \cdot \frac{Q_{Lv}}{N_5}$$

$$BMEP_{35} = 120 \cdot \frac{B_{p35}}{V_s \cdot N_5}$$

$$THERMALEFF_{35} = \frac{B_{p35}}{Q_{Lv} \cdot m_{f35}}$$

$$SFC_{35} = 3600 \cdot \frac{m_{f35}}{\frac{B_{p35}}{1000}}$$

r_c4 = 9

$$T_{q45} = T_{q5} + (9 / 7)^{0.4}$$

$$B_{p45} = 2 \cdot 3.14 \cdot N_5 \cdot \frac{T_{q45}}{60}$$

$$T_{q45} = \frac{K_5}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{9^{0.4}}\right] \cdot 60 \cdot m_{f45} \cdot \frac{Q_{Lv}}{N_5}$$

$$BMEP_{45} = 120 \cdot \frac{B_{p45}}{V_s \cdot N_5}$$

$$THERMALEFF_{45} = \frac{B_{p45}}{Q_{Lv} \cdot m_{f45}}$$

$$SFC_{45} = 3600 \cdot \frac{m_{f45}}{\frac{B_{p45}}{1000}}$$

r_c5 = 7

$$B_{p55} = \frac{B_{p35} + B_{p25}}{2}$$

$$T_{q55} = \frac{T_{q35} + T_{q25}}{2}$$

$$m_{f55} = \frac{m_{f35} + m_{f25}}{2}$$

$$BMEP_{55} = \frac{BMEP_{35} + BMEP_{25}}{2}$$

$$THERMALEFF_{55} = \frac{THERMALEFF_{35} + THERMALEFF_{25}}{2}$$

$$SFC_{55} = \frac{SFC_{35} + SFC_{25}}{2}$$

r_c1 = 5

$$T_{q16} = T_{q6} - (5 / 7)^{0.4}$$

$$B_{p16} = 2 \cdot 3.14 \cdot N_6 \cdot \frac{T_{q16}}{60}$$

$$T_{q16} = \frac{K_6}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{5^{0.4}}\right] \cdot 60 \cdot m_{f16} \cdot \frac{Q_{Lv}}{N_6}$$

$$BMEP_{16} = 120 \cdot \frac{B_{p16}}{V_s \cdot N_6}$$

$$THERMALEFF_{16} = \frac{B_{p16}}{Q_{Lv} \cdot m_{f16}}$$

$$SFC_{16} = 3600 \cdot \frac{m_{f16}}{\frac{B_{p16}}{1000}}$$

r_c2 = 6

$$T_{q26} = T_{q6} - (6 / 7)^{0.4}$$

$$B_{p26} = 2 \cdot 3.14 \cdot N_6 \cdot \frac{T_{q26}}{60}$$

$$T_{q26} = \frac{K_6}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{6^{0.4}}\right] \cdot 60 \cdot m_{f26} \cdot \frac{Q_{Lv}}{N_6}$$

$$BMEP_{26} = 120 \cdot \frac{B_{p26}}{V_s \cdot N_6}$$

$$THERMALEFF_{26} = \frac{B_{p26}}{Q_{Lv} \cdot m_{f26}}$$

$$SFC_{26} = 3600 \cdot \frac{m_{f26}}{\frac{B_{p26}}{1000}}$$

r_c3 = 8

$$T_{q36} = T_{q6} + (8 / 7)^{0.4}$$

$$B_{p36} = 2 \cdot 3.14 \cdot N_6 \cdot \frac{T_{q36}}{60}$$

$$T_{q36} = \frac{K_6}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{8^{0.4}}\right] \cdot 60 \cdot m_{f36} \cdot \frac{Q_{Lv}}{N_6}$$

$$BMEP_{36} = 120 \cdot \frac{B_{p36}}{V_s \cdot N_6}$$

$$THERMALEFF_{36} = \frac{B_{p36}}{Q_{Lv} \cdot m_{f36}}$$

$$SFC_{36} = 3600 \cdot \frac{m_{f36}}{\frac{B_{p36}}{1000}}$$

r_c4 = 9

$$T_{q46} = T_{q6} + (9 / 7)^{0.4}$$

$$B_{p46} = 2 \cdot 3.14 \cdot N_6 \cdot \frac{T_{q46}}{60}$$

$$T_{q46} = \frac{K_6}{2 \cdot 3.14} \cdot \left[1 - \frac{1}{9^{0.4}}\right] \cdot 60 \cdot m_{f46} \cdot \frac{Q_{Lv}}{N_6}$$

$$BMEP_{46} = 120 \cdot \frac{B_{p46}}{V_s \cdot N_6}$$

$$THERMALEFF_{46} = \frac{B_{p46}}{Q_{Lv} \cdot m_{f46}}$$

$$SFC_{46} = 3600 \cdot \frac{m_{f46}}{\frac{B_{p46}}{1000}}$$

r_c5 = 7

$$B_{p56} = \frac{B_{p36} + B_{p26}}{2}$$

$$T_{q56} = \frac{T_{q36} + T_{q26}}{2}$$

$$m_{f56} = \frac{m_{f36} + m_{f26}}{2}$$

$$BMEP_{56} = \frac{BMEP_{36} + BMEP_{26}}{2}$$

$$THERMALEFF_{56} = \frac{THERMALEFF_{36} + THERMALEFF_{26}}{2}$$

$$SFC_{56} = \frac{SFC_{36} + SFC_{26}}{2}$$

*Figure 3.1.Schematic diagram of the Ricardo variable compression ratio engine*

1. Air filter
2. Air filter drum
3. Cylinder head case
4. Crank lever
5. Engine block case (containing the cylinder bore)
6. Oil sump
7. Power shaft
9. Coupling between the motor and the engine crank shaft
10. Manometer system
11. Manometer tube housing
12. Dynamometer
13. Brake load meter
14. Drive belt
15. Tachometer
16. Switch gear box
17. Motoring switch
18. Field switch
19. Panel (Instrumentation unit)
20. Fuel system
21. Air hose to Orifice
22. Manometer fluid container
23. Switch gear
24. Switch gear

Flywheel cable