

Hydrogen Combustion Engine Model

Keith J. Wakeham 200316057

Lee Downer 200212025

Ron Ryan 200500767

Huai Wei Tang 200306215

Memorial University of Newfoundland and Labrador

February 1, 2009

Contents

Introduction	ii
I Background	1
1 Four Stroke Engine Operation	2
1.1 Losses	2
2 Existing Models	5
2.1 Otto Cycle	5
3 Further Work	7
II Model	8
4 Mark I	9
4.1 Crank Position	9
4.2 Piston Force	9
4.3 Piston Position	11
4.3.1 ‘S’ Solver	11
4.3.2 Phi Solver	11
4.3.3 Clearance Solver	13
4.3.4 Torque Resolver	13
4.3.5 Current Volume Solver	14
4.4 Thermodynamics	15
4.4.1 Isentropic Compression	15
4.4.2 Isentropic Expansion	17
4.4.3 Process Switch	17
5 Testing	18
5.1 Steady State Operation	18
5.2 Oscillation Test	18
5.3 Running The Model	20

Introduction

The main focus of the hydrogen combustion engine project is to determine the viability of running existing gasoline combustion engines on hydrogen through the development of a thermodynamic simulation model. This model is to be created through researching existing gasoline combustion engine models and developing a model tailored to the chemistry and combustion of hydrogen.

Part I

Background

Chapter 1

Four Stroke Engine Operation

The engine being modeled is a common four stroke engine. It has four major movements of the piston, each having a separate function. These strokes are:

1. Intake
2. Compression
3. Power / Expansion
4. Exhaust

During the intake stroke, the intake valve opens as shown in figure 1.1 while the piston moves down. This creates a lower pressure, resulting in air moving into the cylinder from the intake manifold. In a modern engine, the fuel injector will activate mixing fuel with the air. At the end of this stroke the intake valve closes and the piston starts compressing the air and fuel. Some time before top dead center the spark plug fires and causes the fuel to burn increasing pressure and temperature. This drives the piston down during the power stroke until it reaches bottom dead center where the exhaust valve opens and the momentum stored in the crank keeps the piston moving pushing the air out.

1.1 Losses

The entire process is a mix of mechanical movement, fluid losses, chemical reactions, and gas processes. During the intake stroke there are losses associated with piping which reduces the amount of air getting into the engine. As the piston compresses the air, the rate of change of volume, composition, and heat transfer affect the pressure and temperature rise of the working gases. This in turn affects the rate at which the reactions take place. The exhaust store has

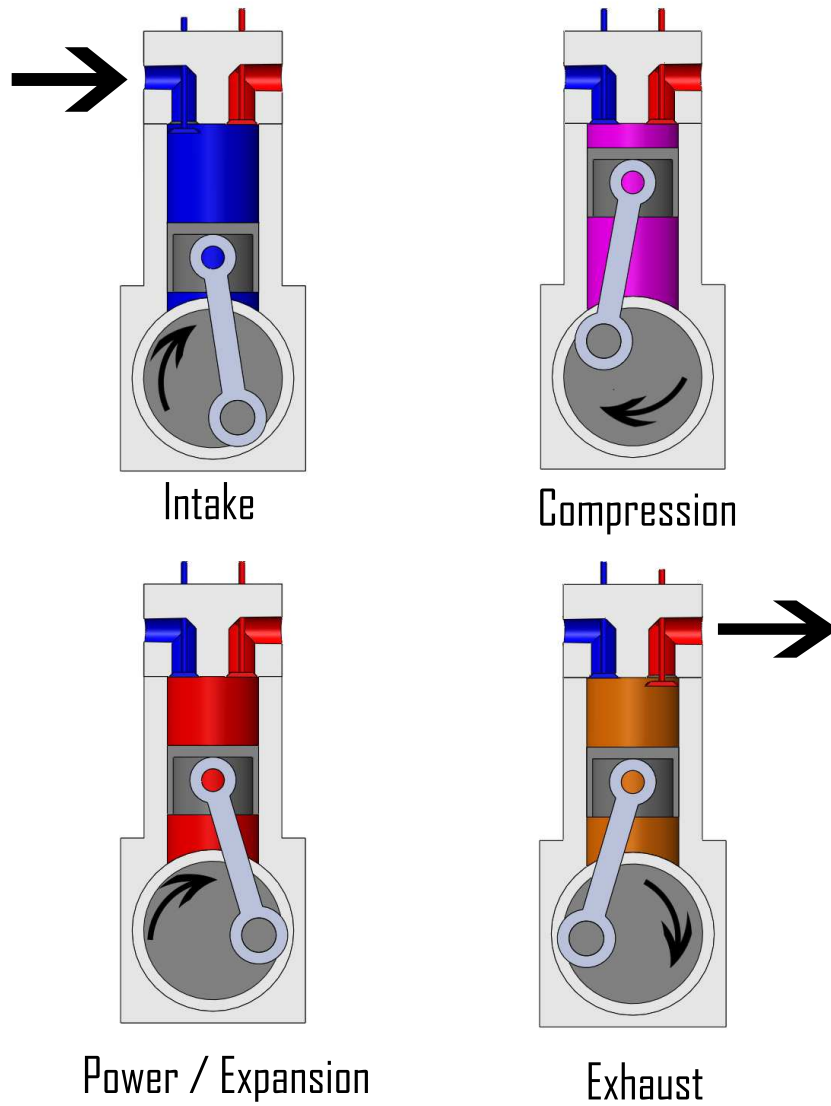


Figure 1.1: Four Stroke Engine

similar pumping losses associated with it and during the entire process there is frictional losses to be accounted for. The system is not accurately modelled by any single thermodynamic process but is best modelled through complex interdependent models relating the various aspects of the engine.

Chapter 2

Existing Models

The project initially looks at the most basic thermo dynamic model of engine operation which is the Otto cycle. Blair suggests modeling geometry, then gas flow, thermodynamics of combustion, gas scavenging, and finally friction[6]. The model being developed will focus more heavily on the thermodynamic model and therefore will follow a slightly different path of development. The thermodynamics model is considered more important for this application than gas flow and therefore will be conducted first.

2.1 Otto Cycle

The Otto Cycle[1] is the most basic model of a spark ignited combustion process. It ignores the intake and exhaust stroke and concentrates on the compression and power strokes. There are several major assumptions for this model.

- Isentropic process; no heat transfer
- Instantaneous heat addition at top dead center
- No intake or exhaust losses
- Working fluid is air even after combustion

State 1 in figure 2.1 is set at atmospheric pressure and the initial volume of the cylinder. The air is isentropically compresses to state 2 at top dead center where the $V=V_{clearance}$. Heat is instantaneously added increasing pressure and temperature to state 3. As the piston moves down, the gas isentropically expands to state 4 at a higher pressure and temperature. This energy is assumed to be lost instantly returning to state 1. The area enclosed by this process is the net work done. The area below state 1 to 2 is the work input, and area below state 3 to 4 is work extracted.

Movement from state 1 to state 5' and back is considered to be the exhaust and intake state at atmospheric pressure and included for reference.

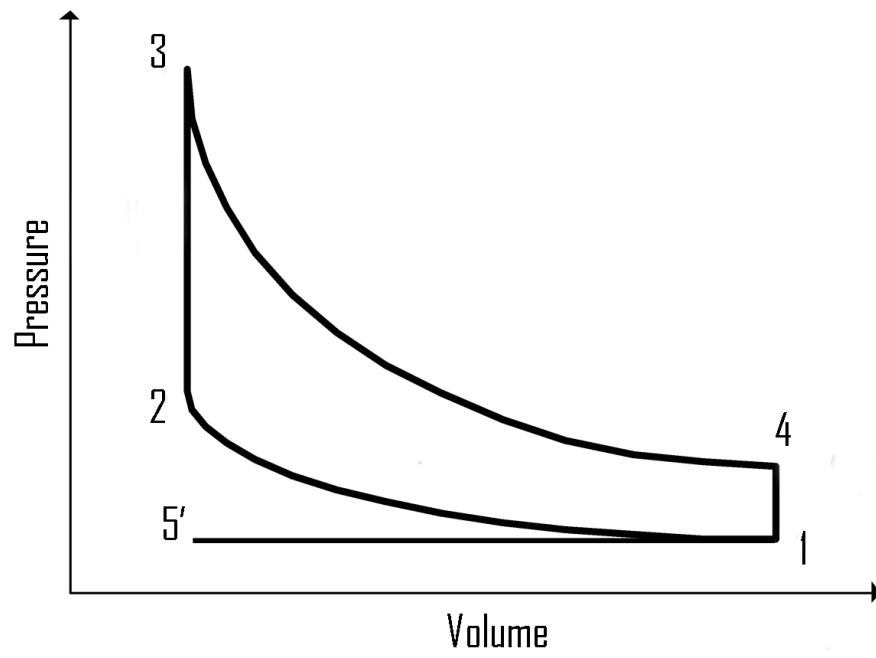


Figure 2.1: Otto Cycle Pressure Volume Graph

Chapter 3

Further Work

The next step in the development process is to incorporate an ability to add heat for the combustion process. This should cause a change in the internal temperature and pressure of the system which can be related to the heat release. In most simulations this is done through a simple Weibe function for burning of fuel. The model will start with this to relate heat input to empirical data but will move to a combustion reaction based process. It also opens the system to heat transfer due to cooling, more accurately model the system, which is targetted to be completed at a later time.

The combustion process can be modeled to determine the heat release rate through the system and then be used as an input into this model. Eventually a more accurate model of the compressibility of the gases based on the actual composition could be incorporated.

If time permits, the final stages will see development of intake and exhaust losses as well as engine friction models to add even more accuracy.

Part II
Model

Chapter 4

Mark I

The Mark I Simulink model is a model based on engine geometry and the air standard Otto cycle[1]. The model describes a single cylinder with massless parts except for the crank which has a defined mass moment of inertia. Forces from compressing the working gas will slow down the rotation of the crank while the expansion process will speed it up. Shown in figure 4.1 are the 4 major layout blocks with several graph displays and an X-Y plot.

4.1 Crank Position

Based on equation 4.1, input torque is equal to the mass moment of inertia multiplied by angular acceleration. This is shown in figure 4.2 where it is then integrated with an initial value set by an external constant for initial rotation speed. This is integrated again with an internal initial value of 0 with a reset at 4π based on a comparator and a reset input to the integrator. The integrator is reset so that there is an absolute position for the two revolutions required for a four stroke engine. $\theta=0$ is top dead center starting the intake stroke.

$$T = I_G \cdot \alpha \quad (4.1)$$

4.2 Piston Force

Piston pressure is resolved to a force on the piston through multiplying by the area as shown in figure 4.3. This area is calculated based on the piston diameter but the actual pressure on the piston is absolute. Therefore the crank case pressure must be subtracted before being multiplied to give the true piston force.

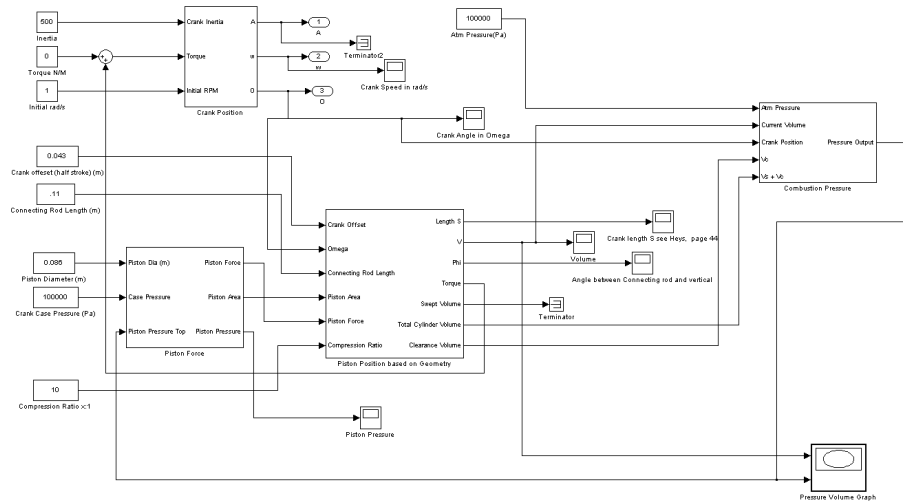


Figure 4.1: Mark I Simulink Model

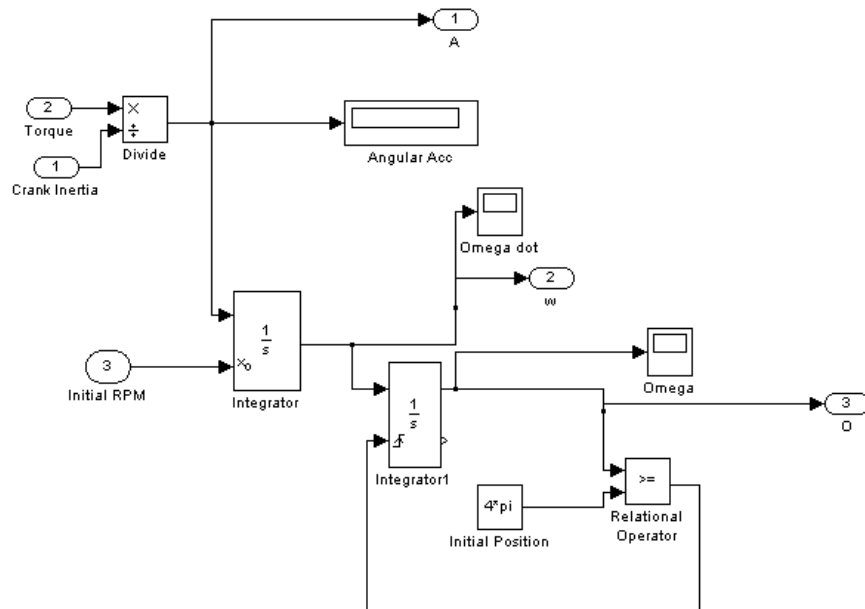


Figure 4.2: Crank Position Block

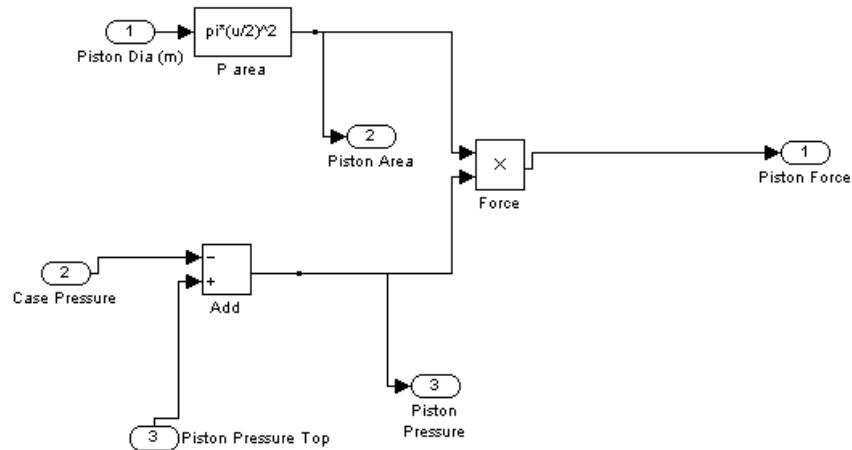


Figure 4.3: Piston Force Block

4.3 Piston Position

The piston position block is made up of several smaller blocks that develop solutions for the vectors from the crank center to the piston, the angle of the connecting rod compared to the vertical as well as piston force resolved to crank torque. It also performs some volume calculations.

4.3.1 ‘S’ Solver

The vector S is described as the vertical vector from the center of the crank to the position of the piston directly above. This vector is used to calculate the current volume[2] and is based on geometry. It is derived from equation 4.2 by Heywood and shown in simulink block form in figure 4.5. The inputs are crank position θ along with geometry crank arm length ‘ A ’ and connecting rod length ‘ L ’.

$$S = A \cos \theta + (L^2 - A^2 \cdot \sin^2 \theta)^{\frac{1}{2}} \quad (4.2)$$

4.3.2 Phi Solver

The angle between the connecting rod and the vertical is needed so that torque can be calculated at a later time. It is based on equation 4.3 and the Simulink block form is shown in figure 4.6. This block is based on current position and engine geometry.

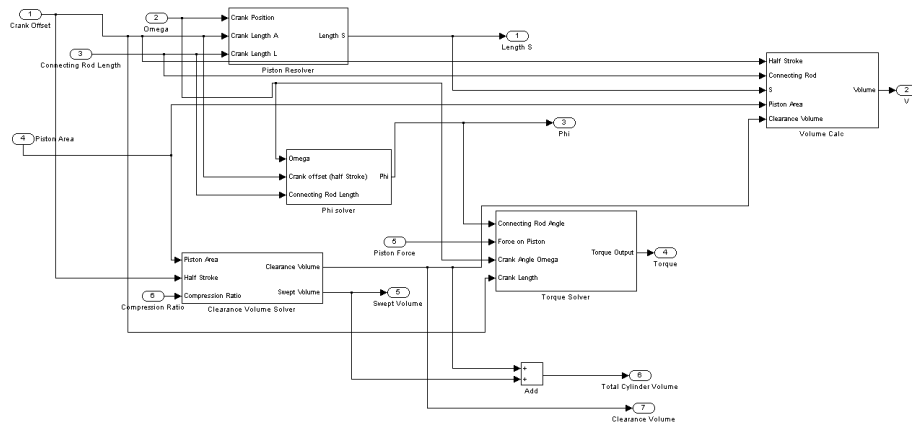


Figure 4.4: Piston Position Block

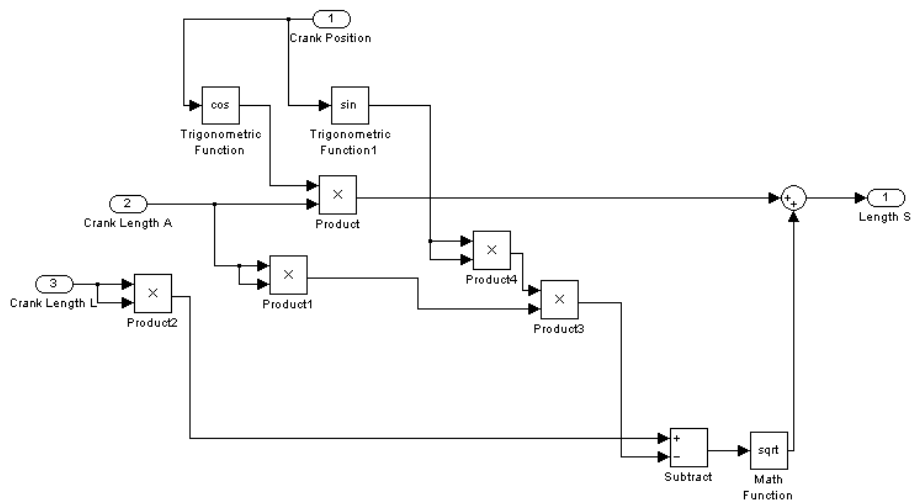


Figure 4.5: Piston Length 'S' calculator Block

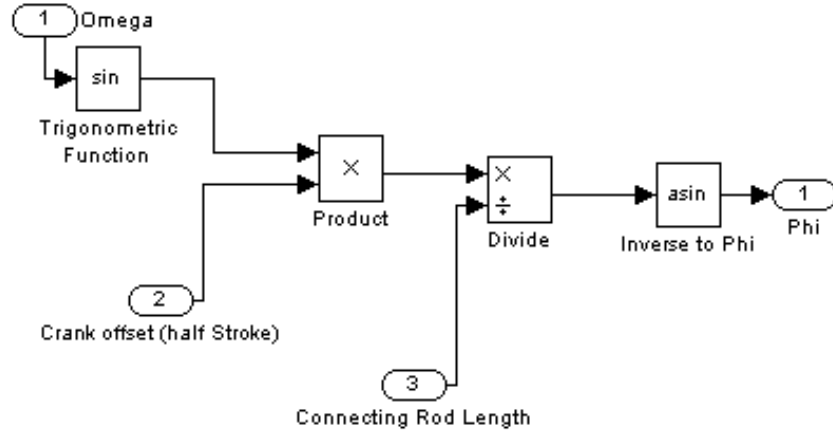


Figure 4.6: Phi Solver

$$\phi = \arcsin \frac{A \cdot \sin \theta}{L} \quad (4.3)$$

4.3.3 Clearance Solver

The clearance solver determines the swept volume and clearance volume based on the stroke, piston area, and compression ratio. Its Simulink block is shown in figure 4.7 and uses the following equations:

$$V_{swept} = 2 \cdot A_{halfstroke} \cdot A_{piston} \quad (4.4)$$

$$V_{clearance} = \frac{V_{swept}}{r - 1} \quad (4.5)$$

4.3.4 Torque Resolver

The torque resolver is a complex block that uses ϕ and ω along with engine geometry to determine the amount of torque on the crank. Its simulink block, which is shown in figure 4.8, is based on the following equations:

$$\beta = 90 - \omega - \phi \quad (4.6)$$

$$F_{cr} = \frac{F_p}{\cos \phi} \quad (4.7)$$

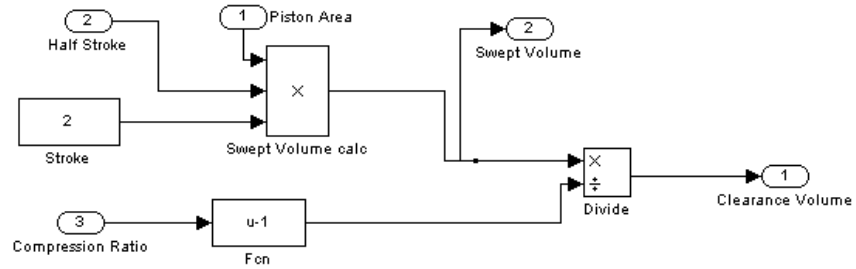


Figure 4.7: Clearance

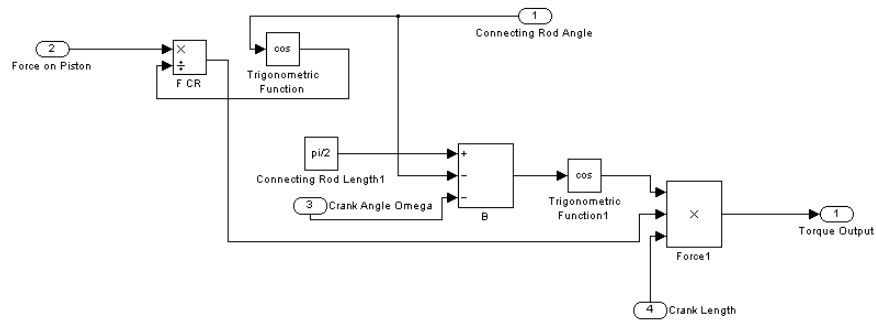


Figure 4.8: Torque resolver block

$$F_T = F_{CR} \cos \beta \quad (4.8)$$

4.3.5 Current Volume Solver

The maximum position of the piston is when the piston is at top dead center which corresponds to minimum volume. The current volume can then be given by equation 4.9. The Simulink block equivalent is shown in figure 4.9.

$$V = (L + A - S) \cdot A_{piston} + V_{clearance} \quad (4.9)$$

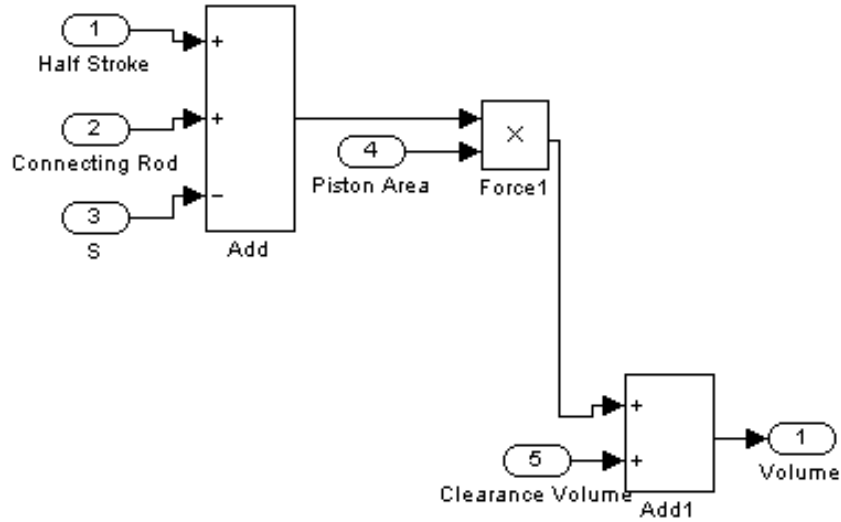


Figure 4.9: Current Volume Solver

4.4 Thermodynamics

The combustion process is modeled by isentropic expansion and compression connected to a mechanism that chooses which block to use shown in figure 4.10.

4.4.1 Isentropic Compression

Isentropic compression starts by solving for V_{r1} through an interpolated equation based on gas properties of air and initial temperature which is equation 4.10. From equation 4.11 V_{r2} can be solved for. A second interpolation to calculate output temperature based on V_{r2} is developed into equation 4.12.

$$V_{r1} = 9 \cdot 10^9 \cdot T_1^{-2.856} \quad (4.10)$$

$$V_{r1} = V/V_{total} \cdot V_{r1} \quad (4.11)$$

$$T = 2994.6 \cdot V_{r1}^{-0.349} \quad (4.12)$$

$$P = P_1 \cdot \frac{T}{T_1} \cdot \frac{V_{total}}{V} \quad (4.13)$$

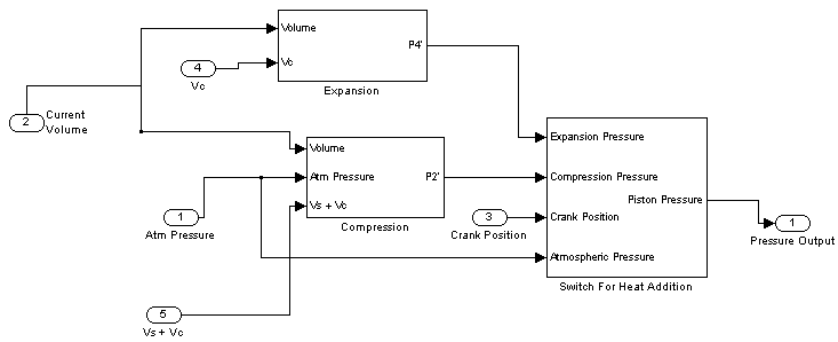


Figure 4.10: Combustion Block

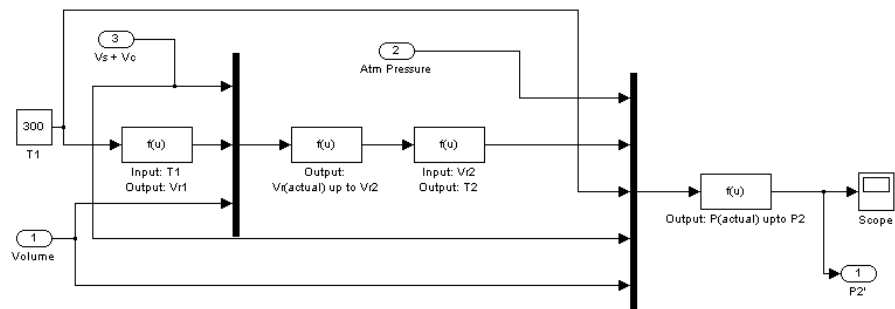


Figure 4.11: Isentropic Compression Block

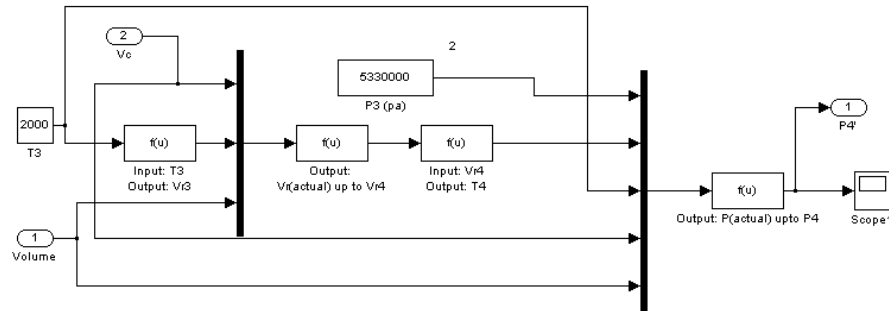


Figure 4.12: Isentropic Expansion Block

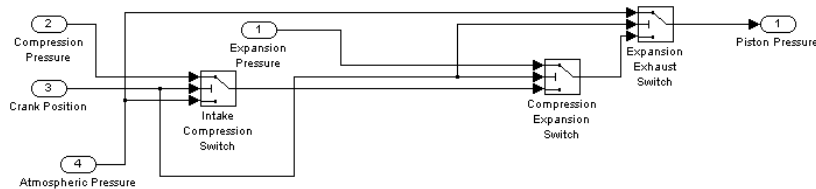


Figure 4.13: Process Switcher Block

4.4.2 Isentropic Expansion

The expansion block is identical to the compression block but because there is a marked discontinuity in the pressure, temperature, and volume, there are new initial value inputs. The changes include replacing total volume with clearance volume, and pressure and temperature is defined at higher values based on calculations found in Moran and Shapiro’s Fundamentals of Engineering Thermodynamics. These can be seen in figure 4.12.

4.4.3 Process Switch

The process switch has several inputs for pressure and an output for the correct current pressure depending on the crank angle. There is an input for the compression pressure, the expansion pressure, as well as the atmospheric pressure which is used for intake and exhaust place holders. The crank starts off at $\theta=0$ on the intake stroke. The switch selects atmospheric for this process. Once the crank is at position $\theta=\pi$ it switches to the compression model until $\theta=2\pi$. It then switches to an expansion model until $\theta=3\pi$ where it goes back to atmospheric for the exhaust stroke. The crank position resets when $\theta=4\pi$ so that the process of selecting will automatically repeat.

Chapter 5

Testing

The model must be tested throughout the development process to ensure each individual block works as predicted, as well as working correctly when combined together. Each block is tested for individual function but when connected to another block there may be unforeseen issues resulting in unpredictable results. This creates a need for higher level tests to ensure that the model is working correctly.

5.1 Steady State Operation

The first step in testing the geometry as a large block is to ensure that at a constant speed with no torque the mechanism calculates the appropriate live values such as volume and crank position repeatedly. Since provisions for setting an initial ω are incorporated, values for torque and pressure can be disconnected to give the position graph shown in fig 5.1. The ω was set to 1 rad/s and resets after $4\cdot\pi$ radians. According to the volume graph shown in figure 5.2 with the same time on the x-axis it is seen that the piston cycles from top dead center to bottom dead center twice before the position resets. This indicates a working volume calculator.

5.2 Oscillation Test

Testing the dynamics of the model can be facilitated through determining if the piston will oscillate. Setting the initial ω to 0 and applying a constant force to the piston with an initial θ equal to some value between 0 and π should cause the piston to rotate to the identical position at the upstroke and then fall back down repeatedly. If this occurs it means that the model accurately models the mass parts and the torque resolver is working correctly.

For this test an initial value was set to 0.1 in the integrator with a resolved pressure of 100kpa on the piston. Figure 5.3 shows that the predicted result of oscillation does occur and therefore the geometry model is accurate.

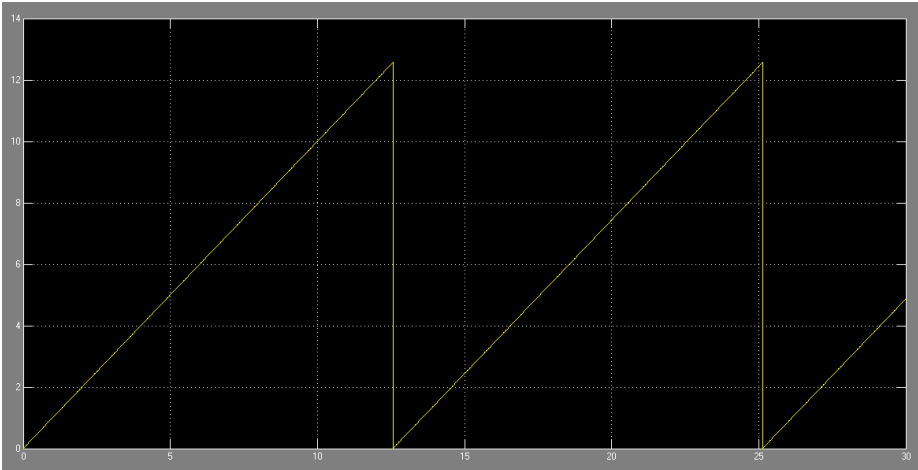


Figure 5.1: steady state position

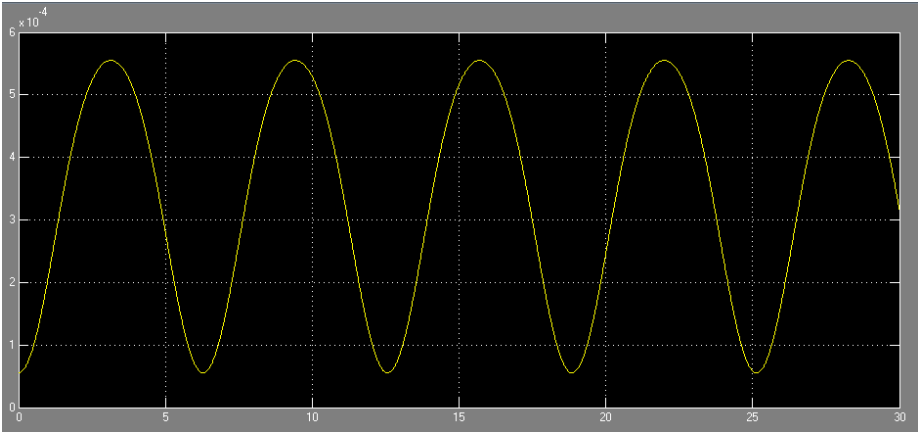


Figure 5.2: steady state volume

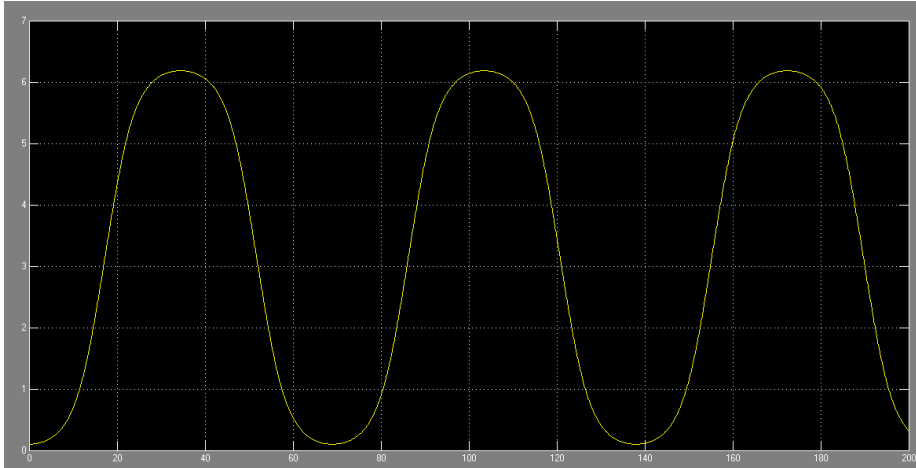


Figure 5.3: Oscillation Test

5.3 Running The Model

At the completion of the Mark I model the results need to fall within the expected operation since it is well documented and easy to predict. While the specific energy input is based on example calculations[1], they appear close to expected values upon comparison to real engines in both Heywood's[2] and Blair's[6] books respectively.

Shown in figure 5.4 is the crank speed ω in radians/second and coincides with the expected results. During the intake stroke, until $\theta=\pi$, the speed is constant because crank pressure and atmospheric pressure are both 100kpa resulting in no net force on the piston. When $\theta=\pi$ the compression process is started and pressure increase causing the speed to slow down. When $\theta=2\pi$ there is a jump in pressure and this causes increased torque speeding up the rotation. During the exhaust stroke starting when $\theta=3\pi$ the force is again 0 and there is no speed change since crank case pressure and atmospheric pressure are the same. The x-axis is against time so as the engine speeds up, the time it takes for this process to occur is shorter which can also be seen in the figure.

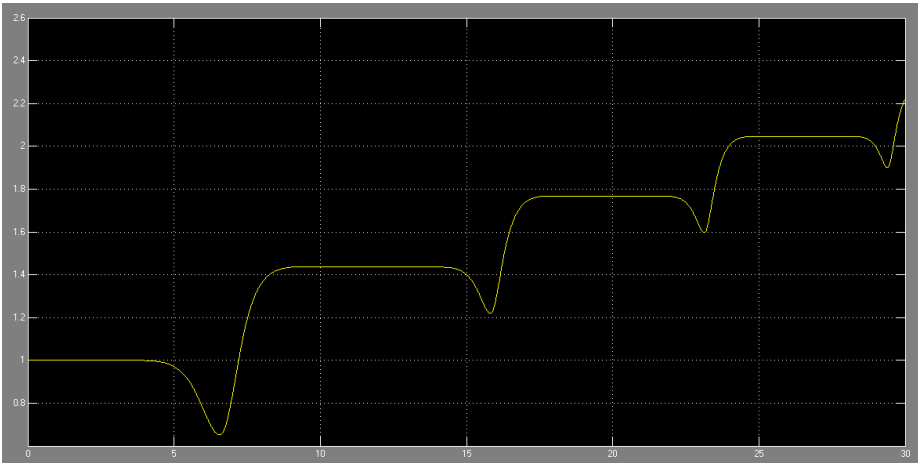


Figure 5.4: Model Results

Bibliography

- [1] Moran, Michael J. and Shapiro, Howard N., *Fundamentals of Engineering Thermodynamics*, John Wiley and Sons, Inc, Hoboken/New Jersey-U.S.A., 5th edition, 2004
- [2] Heywood, John B., *Internal Combustion Engine Fundamentals*, McGraw-Hill Book Company, New York-U.S.A., 1988
- [3] Annamalai, Kalyan and Puri, Ishwar K., *Advanced Thermodynamics Engineering*, CRC Press LLC, Boca Raton/Florida-U.S.A., 2002
- [4] Ferguson, Colin R. and Kirkpatrick, Allan T., *Internal Combustion Engines Applied Thermosciences*, John Wiley and Sons, Inc, New York/New York-U.S.A., 2nd edition, 2000
- [5] Memurry, John and Fay, Robert *Chemistry*, Prentice Hall, New York/New York-U.S.A., 4th edition, 2000, Check this
- [6] Blair, Gordon P. *Design and Simulation of Four-Stroke Engines*, Society of Automotive Engineers, Inc., Warrendale/Pennsylvania-U.S.A., 2001