Stirling engine cycle efficiency

HAMK
UNIVERSITY OF APPLIED SCIENCES

Bachelor's thesis

Automation Engineering

Valkeakoski

Nasrollah Naddaf

HAMK
UNIVERSITY OF APPLIED SCIENCES

BACHELOR'S THESIS

Degree programme in Automation Engineering
Valkeakoski

Title	Stirling engine cycle efficiency
Author	Nasrollah Naddaf
Supervised by	Raine Lehto
Approved on	_____._____.20_____
Approved by	

ABSTRACT

Valkeakoski
Degree Program in Automation Engineering

Author Nasrollah Naddaf **Year** 2012

Subject of Bachelor's thesis Stirling engine cycle efficiency

ABSTRACT

This study strives to provide a clear explanation of the Stirling engine and its efficiency using new automation technology and the Lab View software. This heat engine was invented by Stirling, a Scottish in 1918. The engine's working principles are based on the laws of thermodynamics and ability of volume expansion of ideal gases at different temperatures. Basically there are three types of Stirling engines: the gamma, beta and alpha models.

The commissioner of the thesis was HAMK University of Applied Sciences under the direct supervision of the engineering physics unit. The study focuses on a beta type engine model (388-232), which is located in the Automation engineering laboratory. The engine is coupled with a small generator for transforming heat energy to electrical energy. The heating energy is provided by a special resistor inside the cylinder.

Lab View software and hardware conduct the measurements and control the station. Measureable variables are defined and their instantaneous values are transferred by suitable sensors to a hardware module which can communicate with the interface through a communication card which is located in the computer.

Measured values for: pressure, volume and other parameters are connected to the Lab View software through a communication card. The data is processed by a program consist of seven loops with each loop performing a certain function relative to the other loops. A friendly user interface has been designed so that the user can see the measured values either graphically or numerically on the screen. Main values include: input power, output power, efficiency, rpm and temperature as well as the PV diagram. Another tab shows analytical and detailed measurements.

All protective and security issues have been taken into account in the program through the use of automation functions and logics available in the Lab View environments. Automation system has a great impact on the process outcome. Using powerful interface software to monitor current conditions of the process equipment or their components enables users to analyse the behaviour of a variable from different points of view. It makes it easy to take the right decision based on the conditions in a system.

Keywords; Stirling engine, cycle efficiency and PV graph, data preparation, and Lab View programming

Pages 4p. +9p appendices

ACKNOWLEDGMENTS

I would like to sincerely thank my supervisor Mr. Raine Lehto who guided me to find a subject for the thesis and gave me a perfect description of the subject, which was a great help later finding my way to do my thesis. Again thanks to Mr. Raine Lehto for coming to school during summer holidays and observing the process of the study and giving me directions and recommendations.
I am also grateful to Mr. Antti Aimo the Head of the Automation department who gave me opportunity to do my thesis at HAMK automation laboratory in summer 2012.
Thanks to staff, teachers and assistants who were at school during holidays and helped me a lot, especially Mr. Osmo Leiniäinen, Assistant for the Automation department who is really dedicated to offering help to students.

All my acknowledgments and thanks are expressed to my teachers, colleagues and my family who were supportive and friendly and encouraged me in my bachelor’s studies.

Symbols

Symbol	Name	Unit name
A	Area	Square meter (m^2)
E	Energy	Joule (J)
I	Current	Ampere (A)
F	Force	Newton (N)
n	Molar quantity of gas	Mole (mol)
P	Power	Watt (W)
P	Pressure	Pascal (pa)
R	Gas constant	Joule/Kelvin*mole($JK^{-1}mol^{-1}$)
R	Resistance	Ohm (Ω)
Q	Heat	Joule (J)
QH	Hot side heat	Joule (J)
QC	Cool side heat	Joule (J)
T	Temperature	Kelvin (K)
TL	Low temperature	Kelvin (K)
TH	High temperature	Kelvin (K)
TC	Cooling temperature	Kelvin (K)
V	Volume	Cubic meter (m^3)
V	Voltage	Volt (v)
W	Work	Joule (J)
η	Efficiency	-
ρ	Density	kg/m^3

CONTENTS

1 INTRODUCTION

The aim of this thesis was to design a system for the beta Stirling engine which can monitor the efficiency and PV diagram of the engine. The project includes installing suitable sensors, performing the power supply and connection circuit and software programming in Lab View environment. The engine is located in the HAMK automation laboratory. A small dynamo (3-4Watt) was coupled to the engine for the purpose of acting as a generator. At least four live values were needed: pressure, volume, temperature, and rpm in order to be able to reach the goal.

The machine and its current situation were examined at first. Secondly all the electrical circuits, the connection box, the BNC terminals, the power supply, and the sensors were made and installed into the station. The adjustment and calibration of variables was done according to manufacturer recommendations of the equipments. The provided information is connected to terminal BNC2110 where it is transferred to the communication card by a flat cable. The details can be found in related section.

The software programming is performed in the Lab View environment version 2010. The program consists of two panels: the user interface panel and the block diagram panel. The block diagram contains seven parts or loops. Two loops are data preparation loops where raw information is acquired and scaled for further usage, the rest of the loops are for data processing. All the loops are paralleled but have their individual timing functions. The user interface provides a variety of different information on the screen either graphically or numerically. It has two tabs: the user tab and the analytical tab. The analytical tab offers details and related data which are helpful for finding out the cause of failures.

Many pretests were carried out for finding problems. Each test included observing and solving problems, ultimately this led to fix the program and making it ready for the final measurements. During these tests it was revealed that one has to know the theoretical aspects of an engine in order to be able to design a perfect program, therefore at first mechanics of a Stirling engine are explained here.

The results were obtained through two final tests: an idle test and a load test. In both tests the gained efficiency was very close to the theoretical expectations, the obtained PV diagram was similar to the theoretical models and it supported the theoretical achievements fully. The measurements were conducted in almost stable conditions, when next to no noise was present.
Experiences showed when rotational speed of the engine was 210rpm in the idle test and 240in the load test it had the highest efficiency. The calculation of cycle power which is a base stone for obtaining efficiency was done by the polygon function of the Lab View. It calculates the area between the curves of the PV diagram, which is in fact an irregular polygon.

A friendly user interface is another benefit of using Lab View. It monitors information more sensibly in front of the user on the screen. The program writes recent data on a defined excel file or other files automatically if a failure has stopped the engine, or a user has pressed the write data button. Many improvements were done for securing and stabilizing the program, the details of these improvements can be found in the instructions.

2 STIRLING ENGINE

A Stirling engine is a heat engine which was invented by Robert Stirling in 1918. it is based on gas properties and thermodynamic laws and principles.
The engine uses an external heat source in contrast with combust engines so there is no explosion inside the cylinder while working. The gas is expanded and compressed cyclically and continuously to produce motion to transforming energy. Fluid gas remains inside the system and it is displaced from the hot side to the cool side and vice versa when the engine is operating. There is no exhaustion like normal petrol engine, the engine works very quietly.
The compressible gas can be air, hydrogen, helium, nitrogen or even vapor depending on the design of the engine. Any source of heat can power the engine, from solid coal to oil and solar energy, only the heat source must be adjusted to the engine. For example in a solar energy model the solar concentrator and absorber have to be integrated with the heating part of the cylinder. The Stirling engine was invented as a safer alternative for steam engines of the time, when steam engines had poor quality and often caused explosion because of uncontrollable pressure elevation and primitive technology.
This engine offers the possibility for having high efficiency with less exhaust emissions in comparison with the internal combustion engine.
The Stirling engine has high performance in many applications and is suitable where:

- multi-fueled characteristic is required;
- a very good cooling source is available;
- quiet operation is required;
- relatively low speed operation is permitted;
- constant power output operation is permitted;
- slow changing of engine power output is permitted;
- a long warm-up period is permitted.

Figure1 Modern Stirling engine

Modern models of Stirling engine have a relatively high efficiency and can be run even at low temperature, (figure1) shows a new modern engine which can be run by the heat of a cup of coffee. (Prof .T. Sundararajan, UT of Madras India.)

2.1 Operating principles of Stirling engine

In its simplest form a Stirling engine consists of a cylinder containing a gas, a piston and a displacer. The regenerator and a flywheel are other complimentary parts of the engine. When heat part of cylinder is heated up by an external heat source (figure2), the temperature rises and gas expands proportional in to the temperature of the heat side. Total volume is constant and limited by a piston thus expanded gas pushes the piston down, so the volume of the pressured gas is increased and the gas loses its pressure and temperature, then the piston backs to the heat side and compresses the gas by momentum force of the flywheel, when it reaches near its up limit the displacer also pushes the cooled gas to the heat side of the cylinder so that the gas is compressed and it can be prepared to do another cycle. The expanding gas pushes the piston down again to produce mechanical energy for doing work, this cycling will continue till an external heat source is available.

The flywheel and the regenerator have great roles in the engine's performance. the flywheel converts the linear movement of a working piston to rotary movement, it gives needed momentum for the cycle procedure. Regenerator takes heat from gas in the expansion phase and releases heat to the gas in the compression phase, improving the engine's efficiency considerably. A Stirling engine and its components are shown in (figure2) below.

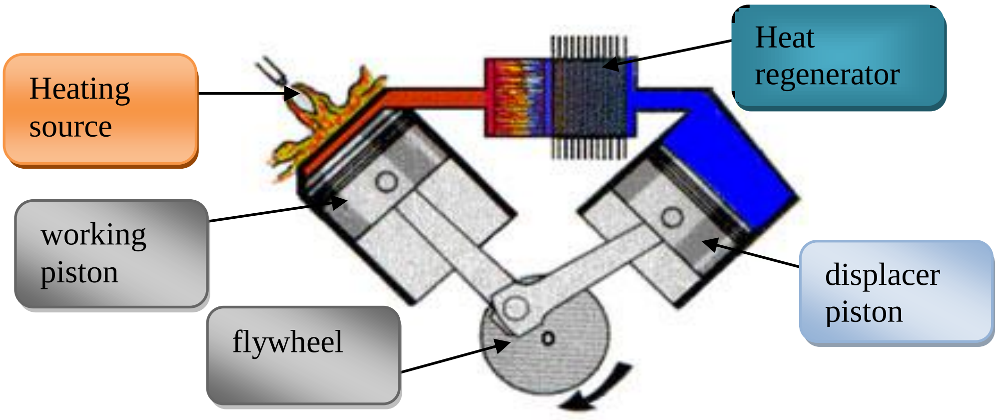


Figure 2 Stirling engine and its components

The cycle of a Stirling engine has four phases; heating, expansion, cooling and compression. Short explanation of each phase is given in the following:

- Heating: Heat source provides thermal energy to the engine so that it raises pressure and temperature of gas.
- Expansion: in this phase the volume increases, but the pressure and temperature decrease, mechanical energy is produced from heat energy during this phase of cycle only.
- Cooling: the gas is cooled and temperature and pressure decrease, so the gas is prepared to be compressed during this cycle.
- Compression: the pressure of gas increases whereas its volume decreases; a part of produced mechanical energy is used for processing of this phase, because it needs an amount of work to be done.

Illustrations of different phases are shown in (figure 3) below.

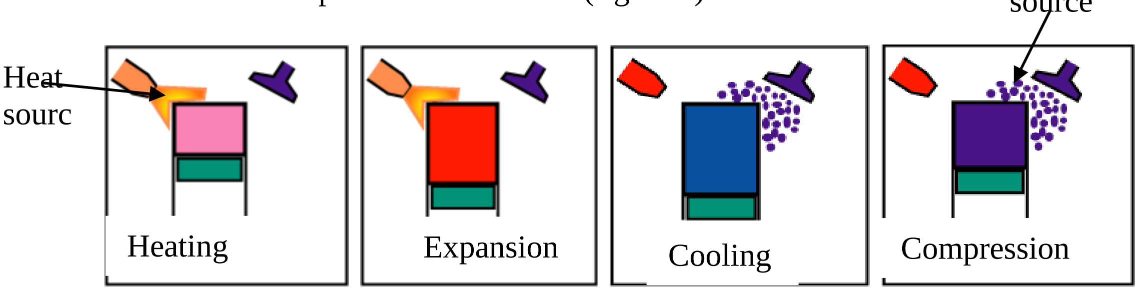


Figure 3 phases of Stirling cycle

The procedure of phase can be illustrated graphically in a PV diagram as it is shown in (figure 4)

Looking at the graph (figure 4) of Stirling cycle one can see that, the volume is constant in heating phase (1-2) and cooling phase (3-4) while during Expansion (2-3) and Compression (4-1) volume is varying but temperature is constant. (Pierre Gras, January 07, 2009)

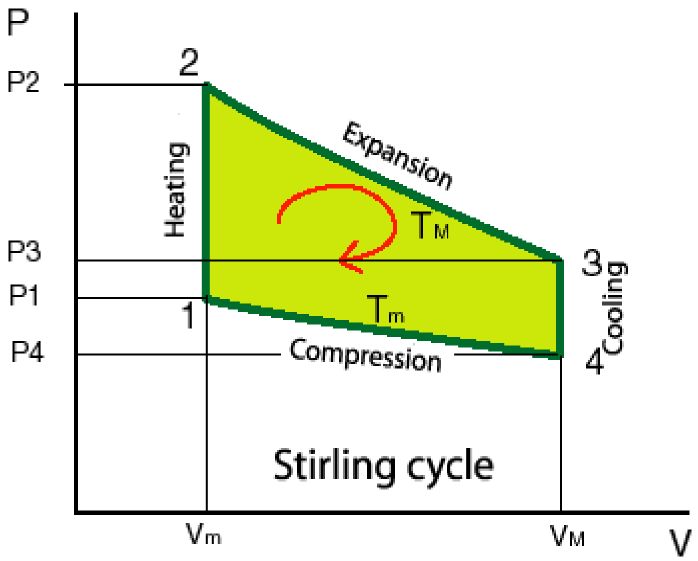


Figure 4 PV graph of Stirling cycle

Engine's working principles derived from thermodynamic laws, following formulas introduces related parameters. Stirling cycle' energy (ability to do work produced by a thermodynamic system) is equal to;

$$E = PV = nRT = constant. \quad (2.1)$$

$$P = \frac{V}{nRT}. \quad (2.2)$$

Where;

E= Energy (J),

P= Pressure (pa),

V=Volume (m^3),

n=Molar quantity of gas (mol),

R= universal gas constant ($JK^{-1}mol^{-1}$),

T= Temperature (K),

As formula shows energy of a cycle depends on pressure and volume, so any changes in these two main parameters changes output power of engine. In simple words it can be said, temperature of hot side of engine causes pressure to rise and pushes the piston move down, piston's moving down changes volume thus it makes ΔT *and* ΔP inside cylinder that forces engine to run. (Prof T Sundararajan, Madras UT, India.)

Early Stirling engines were inefficient compare to other heat engines. But now its sophisticated models are enough efficient and competitive with internal combustion engines, the new ones can be run at either high or low temperature heat in almost all circumstances.

2.2 Stirling engine classification

Several types of Stirling engines have been introduced for different purposes, the most known and practical models are Alpha, Beta and Gamma. The working mechanism of all the three is the same and based on gas expansion at higher temperature and thermodynamic laws, but each type has individual designation, short explanation for each one comes in the following.

The Alpha type is the simplest design (figure 5) of Stirling engine, easy to maintain and repair. It however does use more material to built, and efficiency may be lower. Hence, it is most useful for stationary or having large engines.

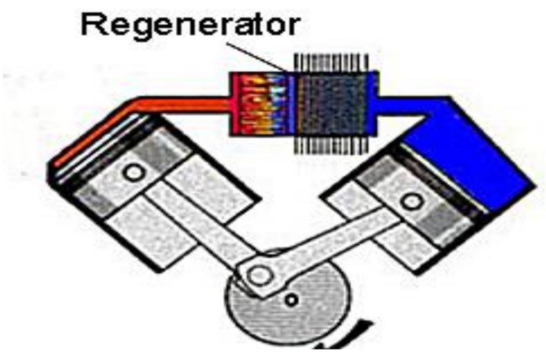


Figure 5 Alpha type of Stirling engine

The Beta type which this study is based on (figure 6) has more complicated design and more difficult to maintain or repair it, however it needs lees component to be built. Its efficiency is lightly higher than others. Hence, it is most useful for mobile or small application like laboratory works.

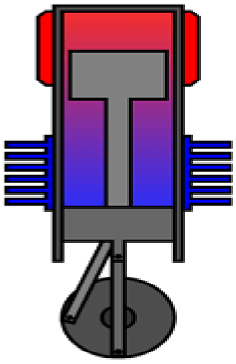


Figure 6 Beta type of Stirling engine

Gamma type (figure 7) engines have a displacer and power piston similar to Beta machines but in different cylinders. This model provides a convenient complete separation between the heat exchangers associated with the displacer cylinder and the compression and expansion work space associated with the piston. The gas in the two cylinders can flow freely between them and remains a single body. This designation produces a lower compression ratio but mechanically is simpler and often used in multi cylinder Stirling engines. (Van Dormael, 2010 Stirling LTD.)

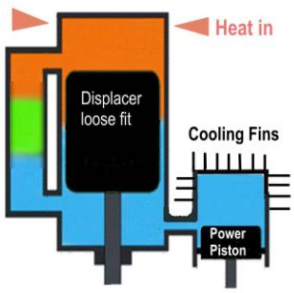


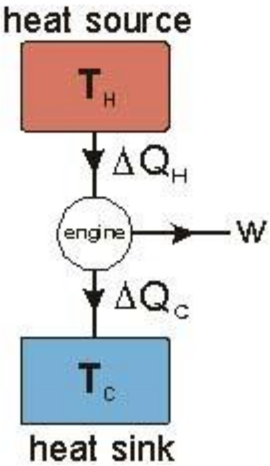
Figure 7 Gamma Stirling engine

2.3 Efficiency of Stirling cycle

Efficiency is the ratio of the energy delivered (or work done) by a machine to the energy needed (or work required) in operating the machine. In other word the ratio of effective or useful output to the total input in a system is efficiency and usually it is shown by this η symbol.

The efficiency is one of the most important decisive factors for every machine when choosing an appliance for an application. Efficiency always is less than 100%, because it is not possible to avoid lost energy when transforming it in practice.

Heat engines are often shown by diagrams like the one below.



During each cycle:

w is the net work done by the engine

ΔQ_H is the energy taken from the (hot) source

ΔQ_C is the energy given to the (cold) sink

Figure 8 Heat engine’s work procedure diagram

Thermodynamic efficiency (or just efficiency) of an engine is defined to be

$$\eta = \frac{Net\ work\ done\ by\ engine}{Enery\ taken\ from\ the\ source} = \frac{(\Delta Q_H - \Delta Q_C)}{\Delta Q_C}. \qquad (2.3)$$

This can be rearranged finally to:

$$\eta = 1 - \frac{\Delta Q_c}{\Delta Q_H}. \qquad (2.4)$$

If an engine is working with a constant heat $Q_H$and Q_C is the rejected heat from system then efficiency for working nominally will be:

$$\eta = \frac{(Q_H - Q_C)}{Q_H} = 1 - \frac{Q_C}{Q_H}. \qquad (2.5)$$

The above formula (2.5) calculates theoretical maximum possible efficiency of a heat engine. The equation does not much care about lost energy during process, so that in reality the efficiency of best engines is about half of what can be achieved by this for-mula.

Carnot formula is another way of calculating performance of heat engines. The method is derived from heat side and cool side temperatures TH and TC, details are shown on (figure 9) PV diagram of Carnot cycle.(Collin Broholm Dce 8, 1997.)

In fact TH is explosion temperature in internal combustion engines and TC is exhaustion temperature, following formula is formed accordingly.

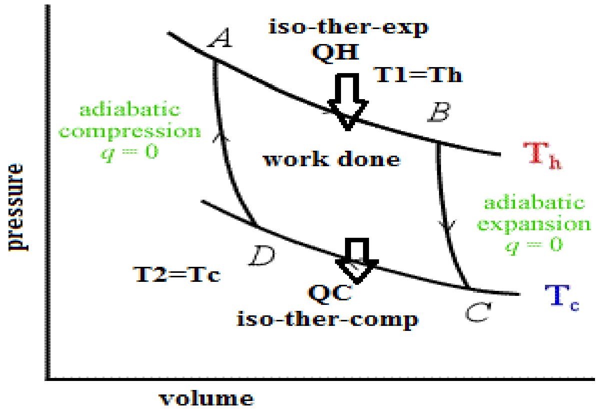


Figure 9 Carnot cycle procedure

$$\eta c = \frac{(T1 - T2)}{T1} = 1 - \frac{T2}{T1}.$$

(2.6) Where;

T1=input temperature in Kelvin

T2=output temperature in Kelvin

General known formula for calculating efficiency is obtained from dividing input power by output power of a system. This gives more accurate result, if it is possible to calculate power directly. Basic known formula for efficiency says:

$$efficiency = \frac{output\ power}{input\ power}, so\ \eta = \frac{P_{out}}{P_{in}}. \quad (2.7)$$

the above formula is used for calculations in this study.

2.4 Calculating power of cycle

When work is done for a period of time, we can calculate power as a rate of provided energy in a certain time. Stirling engine follows thermodynamic laws and principles, its power depends on pressure inside the cylinder, volume and temperature, thus power can be calculated from following formulas;

$$p = \frac{F}{A}. \quad (2.8)$$

As work is equal to force multiply by travelled distance the;

$$W = Fd. \quad (2.9)$$

when on the other hand we have;

$$F = PA. \quad (2.10)$$

By replacing pressure and area instead of force in the formula it becomes;

$$W = PAd. \quad (2.11)$$

When pressure is inserted on a constant area like cross section area of a piston the work will depend on distance travelled by piston directly, here volume is equal to;

$V = Ad$. (2.12)

So final obtained formula of instantaneous work in a cycle is;

$W = PV$. (2.13)

power as a rate of provided energy by Stirling cycle for doing work is equal to output energy or work in a cycle multiply by rotational speed of engine per second so;

$P = W(E)cyc.rp_{sec}$. (2.14)

Where:
P=pressure/pa
F=force/N
d=Distance travelled/m
A= Cross section area of a piston/m^2
W=work or energy/J
p=power/W
rpm_{sec}= rotational speed rounds/second
W_{cyc}= energy of a cycle

No matter what is the unit of time, it can be second or minute or hour and etc.., but the result will be power per a period of time. The formula (2.14) is applied by program in calculation procedure.

By having instantaneous pressure and volume it is possible to calculate the output energy or work done by machine. If instantaneous measured pressure and volume during a cycle be optimized on a XY coordinate, where Y is the pressure and X is the volume of the engine, the result will be an irregular polygon (figure 10) which its area is the output energy of cycle of Stirling engine.

Now power can be obtained by multiplying energy of a cycle by revolution/second of engine, at the end dividing it by input heating power gives efficiency of the engine. This job will be done by LABVIEW program in this experience. Mechanics of the procedure is explained later in related program sections.

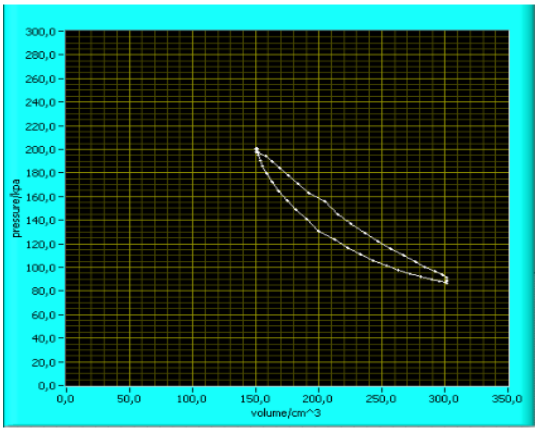


Figure 10 simulation of a PV diagram

3 PRELIMINARY INSTALLATIONS AND DATA PREPARATION

Selected engine model for this study is an old one. It does not have required information what are needed for programming. Values of pressure, volume, temperature and rpm are inevitable raw information for purpose of this study, therefore the old engine has been studied and suitable tools are selected to offer initiative data. Pressure, volume, temperature, rpm, input (heating) voltage values are captured by different sensors and tools. Sensors are mounted on body of engine in a fair possible location.

A power supply is made to provide working energy to sensors and other informative loads. It consists of a transformer, rectifier diodes, capacitors and two voltage regulators IC AN7805. Input voltage is 230VAC and outputs are 24VDC and two separated 5VDC, 5VDC, separation took place to remove experienced noises. Explanation of mounted equipments comes briefly in the following.

3.1 Magnetic sensor

This sensor (figure 11) is sensitive to magnetic field. If it be opposed to a magnetic field it sends a specified voltage (10v) out which can be used for acquiring data. In this case a piece of magnet has been glued on the flywheel of engine which has a permanent magnetic field. When engine is running and flywheel is turning the glued magnet activates magnetic sensor one time in each turn of flywheel which is equal to one cycle. Sensor sends 10V for each pass to the program where a counter edge DAQ max counts rise edges, then rpm loop calculates engine's rpm based on counted edge.

Figure 11 magnetic sensor

3.2 Position sensor (volume meter)

This sensor has a linear movement which causes changes of output voltage from low to high (0v to 10v) and vice versa, so the position of piston can be specified by reading output voltage of sensor. Instantaneous volume of cylinder can be acquired by scaling this voltage as changes in volume. It is connected with piston's rod in a way that covers full range of volume changes (150cm3) when engine is operating. Piston's Δd is 51mm but position meter Δd is 32mm, a transferor pulley (figure 13) is made to transfer the 51mm to 32mm physically

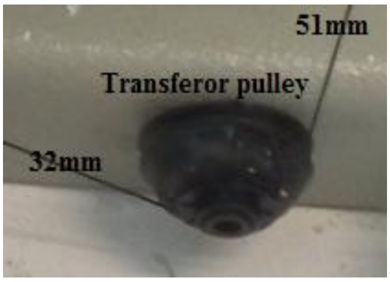


Figure 12 position meter sensor

Figure13 distance transferor pulley

Position sensor also has a transducer that translates sensed voltages by physical part to stable readable voltage for software and finally sends them to connection box.

3.3 Pressure sensor

The sensor is a piezoresistive transducer that includes silicon pressure sensor (figure 14) for a wide range of applications. The sensor ranged from 20kpa to 250kpa, its output varies from 0.2 to 4.9v respectively, thus reading and scaling the voltage gives the exact instantaneous pressure inside piston when it is working.

Pressure sensor has to be calibrated carefully. When piston is in lowest level the pressure in cylinder is equal to atmospheric pressure, no any extra pressure is inserted inside. Connection tube can be opened to the air at maximum volume when calibrating. Its sensitivity is 20mv per one kilo Pascal that means 1v change shows 50kpa change in pressure,

Figure 14 pressure sensor

3.4 Thermometer

Temperature has a significant role in engine's working. High temperature decreases engine's efficiency and damages almost all components inside cylinder. A temperature data is needed for controlling the engine when it is overheated. For this purpose a PTC thermistor has been stuck to the outside wall of cylinder, so that any changes in cylinder's temperature causes change in resistance of thermistor and acts as a thermometer in the system. Acquired voltage from thermistor is calibrated and monitored by the program as temperature of cooling water in cool side of engine. Its electrical circuit and connectivity is explained in connection box circuit.

Figure 15 Thermistor

3.5 Power supply& connection box

The power supply consists of a transformer, pole diodes, capacitors, resistors and an IC. Transformer takes 220AC as input and gives two separate voltages (12, 24vVAC) as outputs. Full wave rectification method is used to produce three different dc voltages (5, 12,24VDC) by the above components. 24 volt is connected to volume (position) transducer which powers position sensor, 12 volt goes to magnetic sensors and 5 volt dedicated to pressure sensor and thermal circuit. Connection box provides connections between sensors and connector terminal BNC2110. All inputs to this box are sensors' data which are connected through terminals to BNC connectors where ready information is transferring to BNC2110 by BNC cables. Two diode indicators on the box show availability of power supply (red) and generator (blue) output.

Two extra connection plugs are built on the box for load testing. Each plug has its own switch to be on or off. The box is shown in (figure 17). More details and sub circuits about this project can be found on electrical circuit drawing which is available in appendix documents.

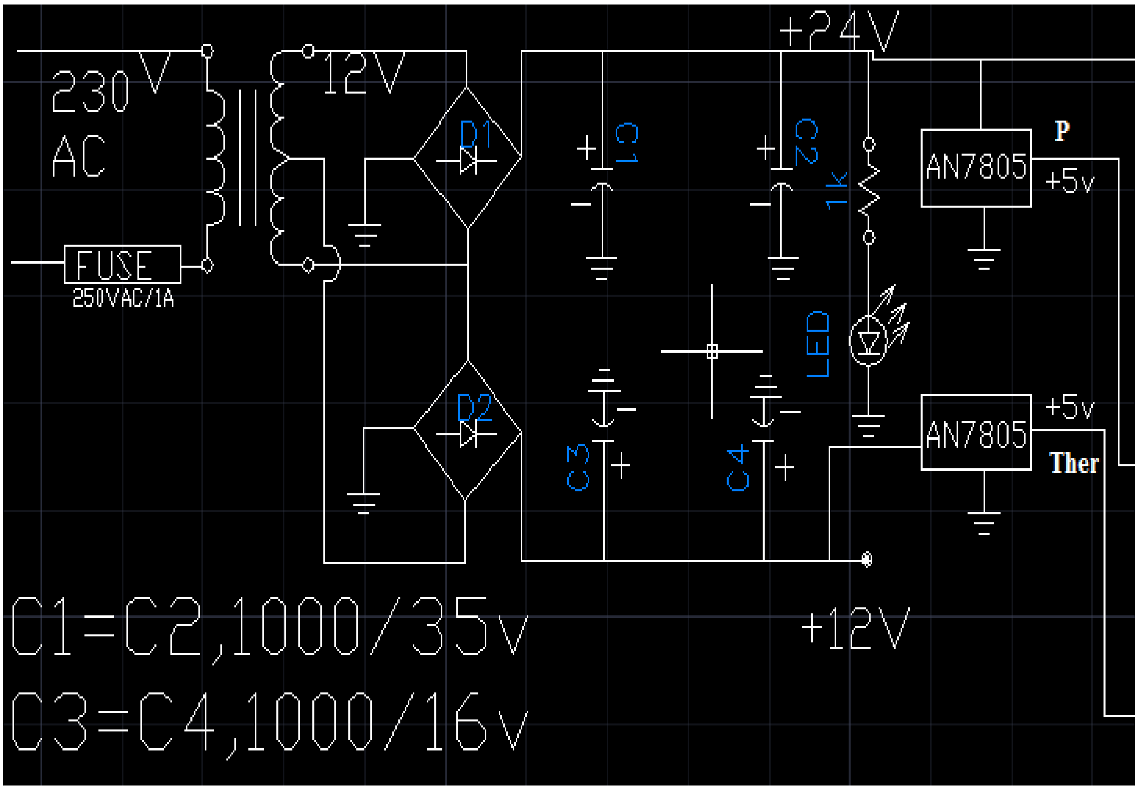


Figure 16 power supply circuit with three separated outputs

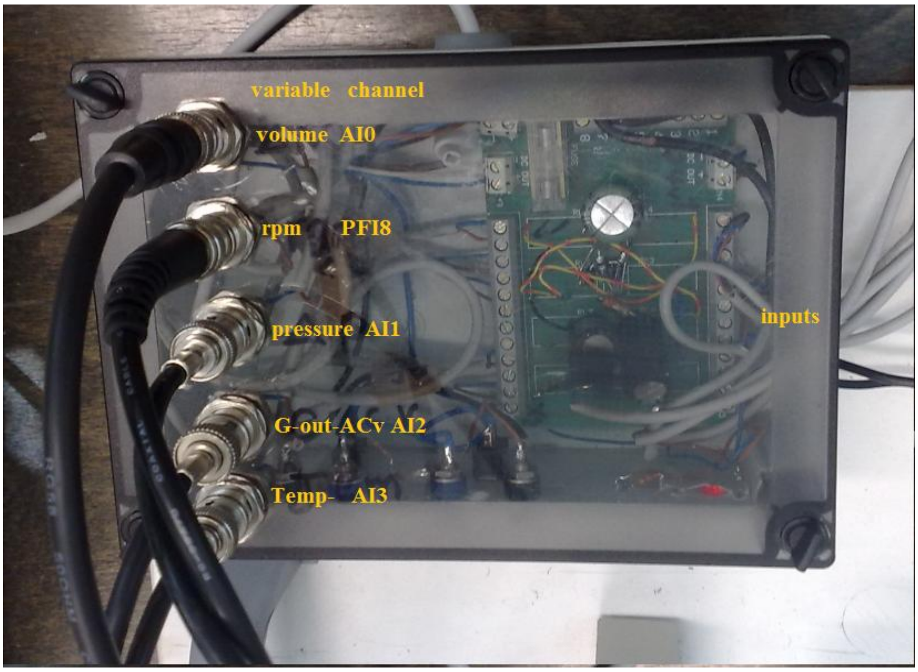


Figure 17 connection box with BNC connectors and cables

3.6 Testing and setting up I/O data table

In this step all sensors are powered and connected to connection box where their outputs are connected to BNC plugs for further usage. Manual tests were conducted using a digital multimeter and other calibrator tools then obtained results have been compared with sensors' specification and manufacturer's recommendations. After being sure that all criteria have been met, it is left for software programming.

The tests showed that it is not possible to send a direct reference of feeding voltage to BNC connector terminal, because the voltage is over high limit of BNC connector and its current more than 10 ampere. It can damage the hardware. This reference is needed in program for calculating efficiency.

An adaptor circuit (voltage divider) is made for this purpose, which sends out safe and accurate reference of feeding voltage to the program. It consists of two 100kΩ resistors which are connected in series to feeding power and transfer low voltage to BNC connector.

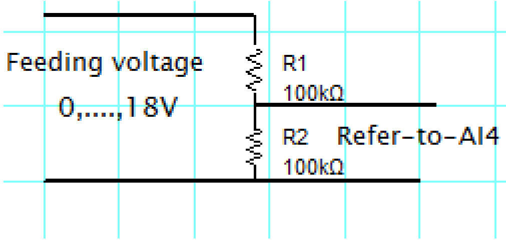


Figure 18 circuit adaptor (voltage divider)

Data table has been set up to show which I/O is dedicated to which variable. The table also is available as a clear guidance for further maintenance and developments; there are five Analog inputs, one analog out puts and one digital input in this table. Inputs are volume, pressure, generator voltage, heating voltage and temperature, the only analog output is control voltage to feeding transformer, rpm is considered as a digital input, details are shown (table 1) in the below.

Table1 I/O data table configured to BNC terminal 2110

No	Variable	I/O	connected to	type of connection
1	Volume	AI0	connection box ΔV	BNC cable
2	Pressure	AI1	connection box ΔP	BNC cable
3	Generator voltage	AI2	connection box G-v	BNC cable
4	Temperature	AI3	connection box Temp	BNC cable
5	Heating voltage	AI4	adaptor terminal	BNC cable+ wire
6	rpm	PFI8	connection box	BNC cable+ wire
7	Control voltage	AO1	transformer input socket	BNC+ socket

4. DATA PROCESSING AND SOFTWARE PROGRAMMING

Lab View software has been chosen for conducting measurements and documentation of data of this application. This powerful software produced by National Instrument Company for measurement, engineering, developing and automation which is widely used in the world. Program has high flexibility and different functions to establish configuration between different software and systems thus it helps to come close with standardization in automation area of work, where numerous systems and brands are used. Short explanations about it come in the following section.

4.1 LabView

Lab View is a graphical programming environment from National Instrument Company for design and engineering. The software used for developing measurement, test and control systems. It uses a graphical language named G, which is a dataflow programming language. Each program or vi (virtual instrument) has a front panel (user interface) and block diagram (source code). Execution is determined by the structure of a graphical block diagram (Lab View-source code) on which the programmer connects different function-nodes by drawing wires between them. The wires bring variables to the nodes and any nodes can execute as soon as all its input data are available. An example of vi is shown (figure 19) in the below.

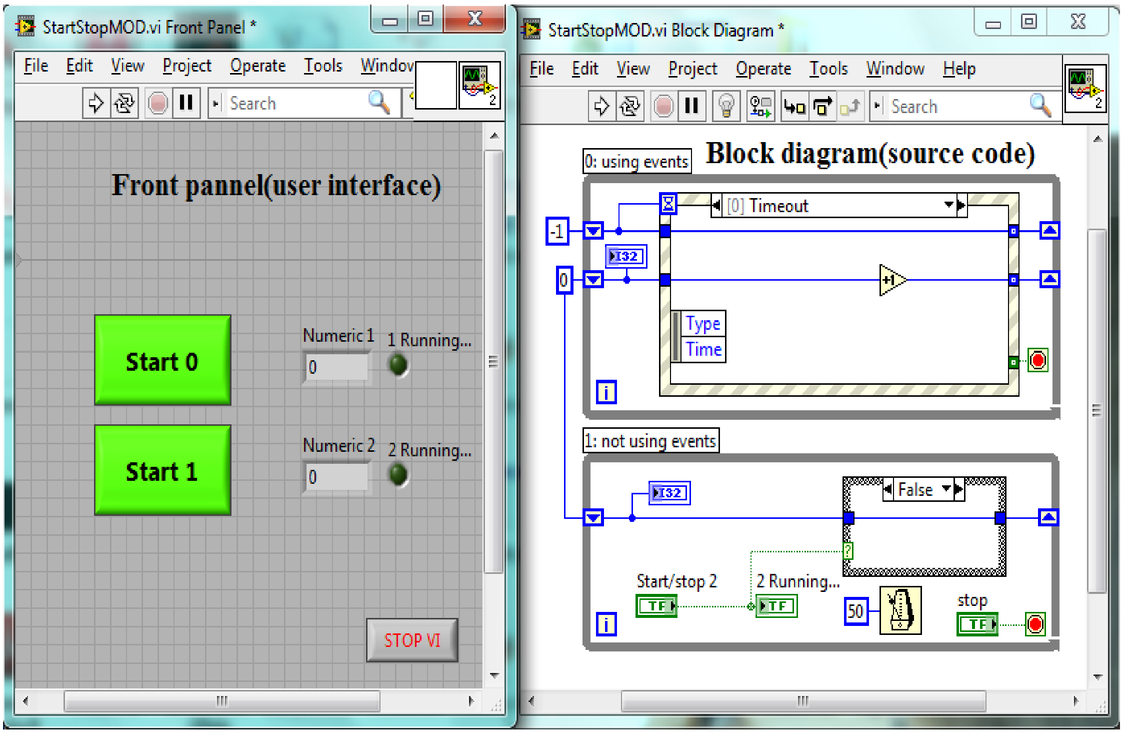


Figure 19 example of program, front panel and block diagram

4.2 Properties of Lab View library

As it is said in the above vi or let say a program in Labview environment consists of front panel and block diagram. By right clicking on each of these parts it shows a dialog box contains lists and symbols, which lead to sub symbols that represent all abilities and functions of the panel. In the front panel dialog box shows indicators and controls that stand for output and input in the block diagram when writing a code. One can chose a suitable symbol by clicking on the symbol and dragging it in to the front panel, the dragged symbols will be crated automatically on the block diagram simultaneously. The mentioned dialog boxes are shown in (figures 20, 21) in the following.

In block diagram there are functions that appear only on block diagram when writing a code, like mathematical nodes, Boolean nodes and etc.., these functions participated in processing data and don’t have representative on front panel. There is a search on dialog boxes one can write desired function in search box and a group of option will appear on dialog box that programmer can select the suitable ones.

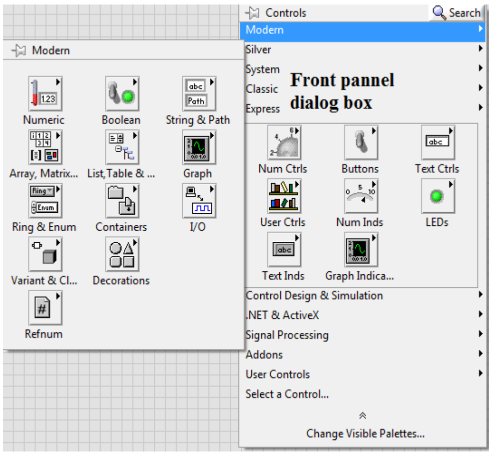


Figure 20 front panel dialog box

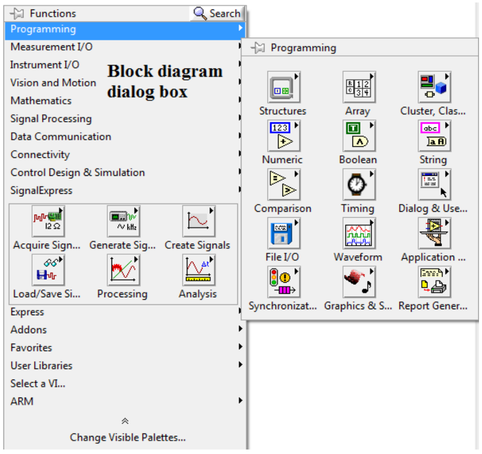


Figure 21 block diagram dialog box

Each symbol can be modified by right click on it and selecting property or other visible menus based on the purpose of programming. When an input or output is created on the block diagram, they are appeared automatically on the front panel too. All practical and applied functions are in block diagram dialog box, one can drag analyzer, processor or calculator nodes in to the block diagram and wire them together purposely to obtain the expected results. (measurement Automation HAMK, 2012)

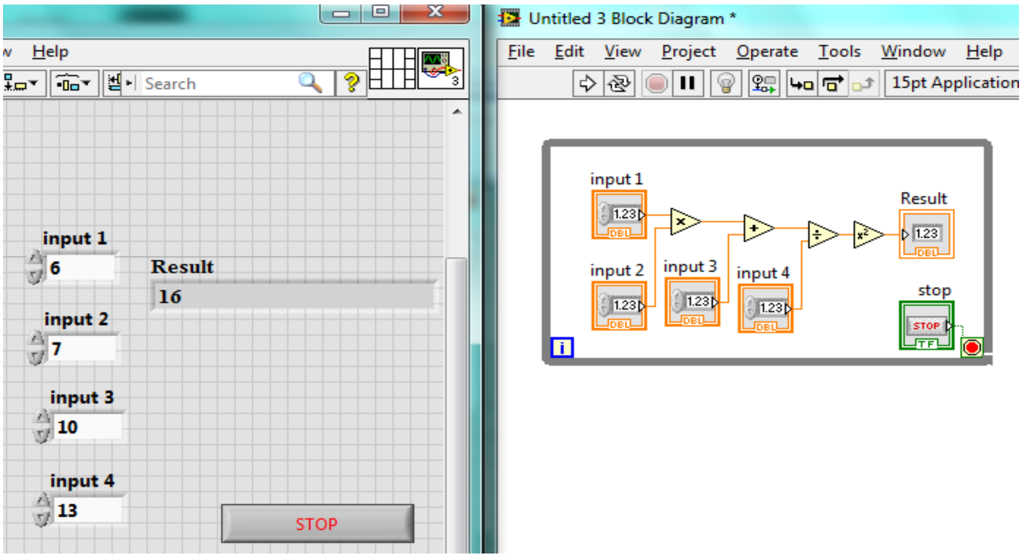


Figure 22 simple example mathematical program with while loop

For making a program the needed nodes have to be dragged in to block diagram and be wired then enclosed by a suitable loop from structure menu, there are different loops with different properties which can be used for catching the goal of a program. A simple

program is shown in (figure 22) that has four inputs and one output, if user changes the values of inputs the results changes respectively.
When it is wanted continuous measuring, the code have to be enclosed by while lop, if measuring is needed for certain times then for loop is a good option, however there are different loops for variety of usages in Lab View.

4.3 NI communication card and connector terminal

When a program is written in virtual environment of LabView it needs some special equipment for interpreting virtual inputs outputs to physical ones and providing communications with measurer instruments and hardware on the plant. Here the job is done by NI ….. M series card (figure 23), it is installed in the computer and is connected to the BNC terminal 2110 which is the final step towards physical I/O. The obtained data at connection box of engine station are brought to connector terminal by BNC cables, where a huge flat cable connects the BNC terminal to the NI card in a computer. The image of connector (figure 25) is shown in front of text.

Figure 24 BNC terminal 2110

Figure 23 communication card M series

Configuration and compatibility between the hard ware have to be considered very carefully; otherwise they may cause complicated problems and disturb obtained results.

Always it is beneficial to follow manufacturers' recommendation while they know better what are behind these virtual environments. In fact M card is like nerve system for software brain which without that nerve the program is paralyzed and no function is expected. (NI tutorial online.)

Figure 25 BNC 2110 connected to M card.

5 SOFTWARE PROGRAM

The program used to gather, calculate, control and display the data in Lab View front panel on the screen. The main purpose of this program is to draw PV diagram and calculating efficiency of the beta type of Stirling engine. Different types of data have been acquired for giving analytical ability to the program, using both numerical and graphical indicators help that data be more visible to users.

Front panel (figure 26) consists of two tabs; user tab and analytical tab. User tab contains controls and indicators which enable users manage engine's output, while analytical tab shows details data that are helpful for understanding cause of failures.

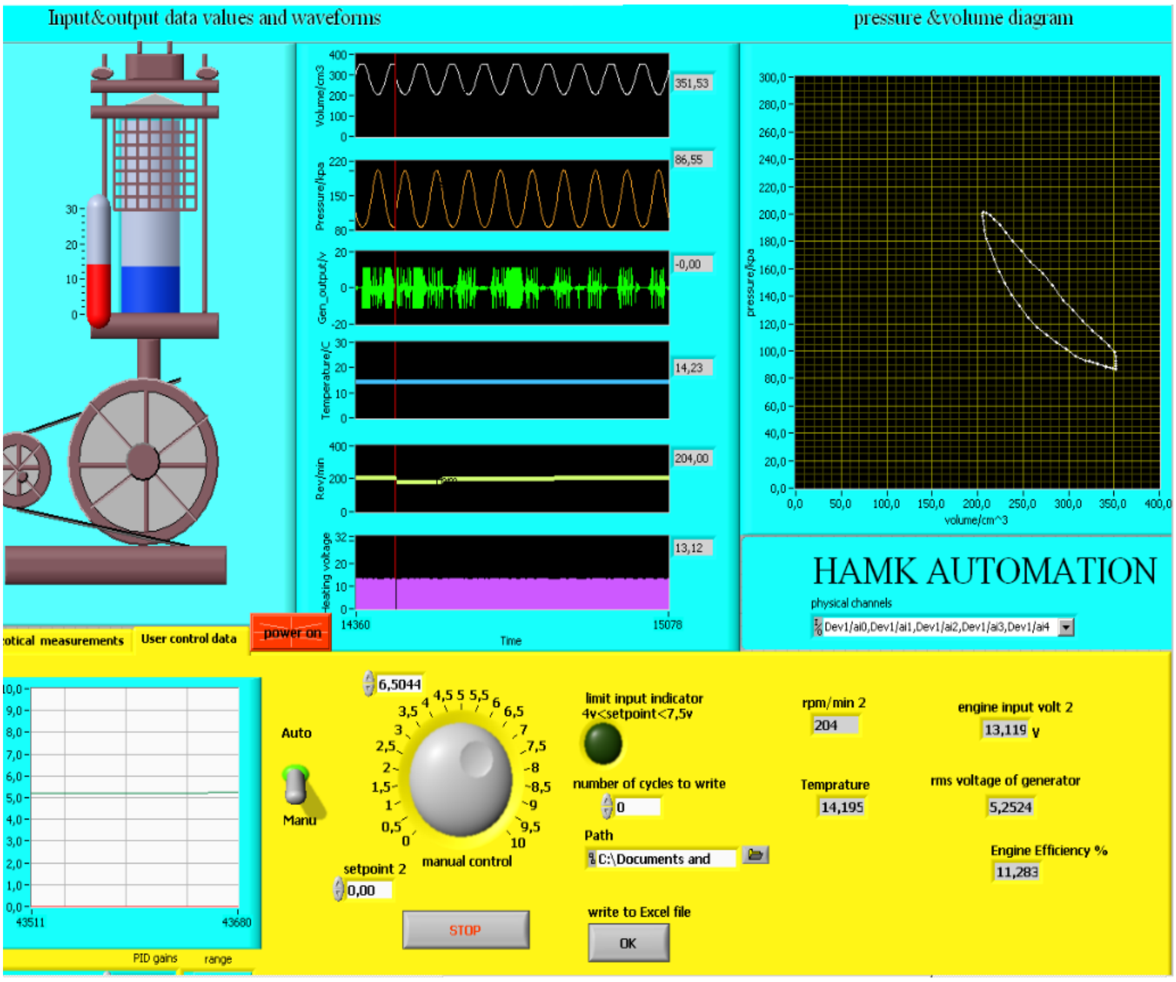


Figure 26 user interface (front panel) Stirling engine efficiency-PV diagram

A few numerical inputs and other types of controlling are designed for user tab in front panel to enable user to have on time and effective control on system. Graphical indicators are available in both tabs and represents instantaneous information of the station. It is tried to choose suitable font and color to make the user interface more friendly. Instantaneous pressure value inside cylinder and temperature is connected to image of beta type of Stirling engine on front panel, so that it moving up and down harmonically when engine is working.

Safety issues are considered when codes were writing. Operator is not able to make problematic changes to program from front panel, different limitations has been built up that prevents harmful changes.

Block diagram of the program is divided in to seven parts or let say loops for being easier to follow it. All loops are working parallel together but each one does certain tasks and has its own timing regulation. A text box on the loop explains the main targets of a loop. Two DAQmax are configured, one for anlog inputs (figure 28) another for digital input (figure 27) (counter). A DAQ assistant(figure 35) is configured for aquiring an output voltage (1...10V) for contolling feeding transformer. A DAQ can handle one types of data at a time. There are some loops inside maine loops which are used to process data. Scale notation or specicific function are explained in text boxes of each loop. Block diagram is the most important part at acquiring data process so that loops and their task are described one by one in the following.

5.1 The rpm loop

In the rpm loop DAQ max vi is configured to count the edge of coming pulse from magnetic sensor to PFI8 (programmable function input). A read DAQ max vi reads the acquired values inside loop. This loop is timed for one second, while flywheel sends one pulse per revolution by magnetic sensor to be read, so that read data during one second multiply by 60 gives rpm of engine. Cycle duration time and iteration time of PV diagram loop are derived from rpm by mathematical nodes in this loop, therefore rpm loop has base stone role in program. Image of loop is shown below.

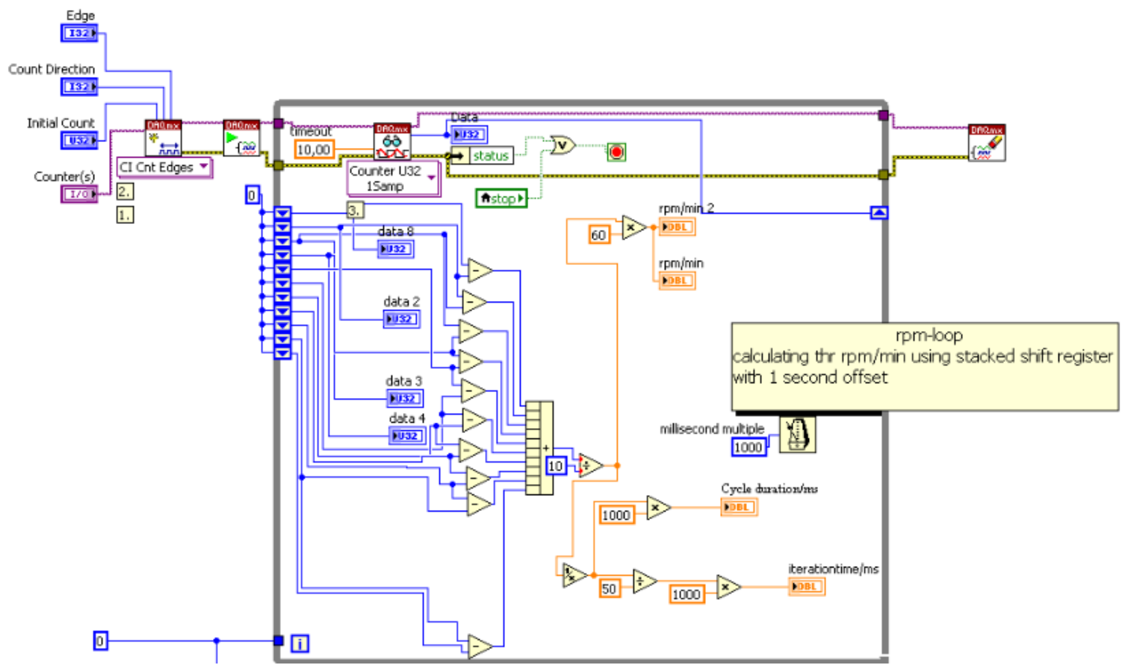


Figure 27 rpm loop (DAQmax configured to count edge)

Acquired data is connected to a staked shift register with ten elements then each element is compared to the next one and all differences are summed then divided by number of elements, so that the average and more accurate rpm is achieved.

It is decided to have at least 50 points in a cycle for illustration of PV diagram of engine, so that duration time of cycle which is derived from formula (15);

$$Cycle\ duration = T = \frac{1sec}{rp_{sec}}. \qquad (5.15)$$

Where;

rp_{sec}= revolution per second

Obtained cycle duration is divided by 50 and then it is multiplied by 1000 for having time in milliseconds, thus the result is considered as iteration time of (for loop) inside PV diagram loop. Final values are sent to other loops using local variable method.

5.2 Data loop

Data loop provides all analog data. A DAQ max vi is configured to measure multiple analog inputs simultaneously, another read DAQ max vi reads measured data inside loop and gives them out in an array of data then array is indexed to separate each individual measured voltage. Individual voltage is scaled and compensated precisely, before sending to other loops through local variable function. See (figure 28)

For example total volume of cylinder is 350cm^3 and total change in volume ΔV is 150cm^3 and measured voltage varies from almost (0…10v), therefore multiplying by 15 and then adding 200 gives instantaneous volume of cylinder. The method is applied to pressure too. Pressure sensor output varies from (0…5v) while its full range is 250kpa, thus value from pressure sensor multiplied by 50 gives real pressure inside cylinder, nothing else is needed because pressure at V max is atmospheric pressure.

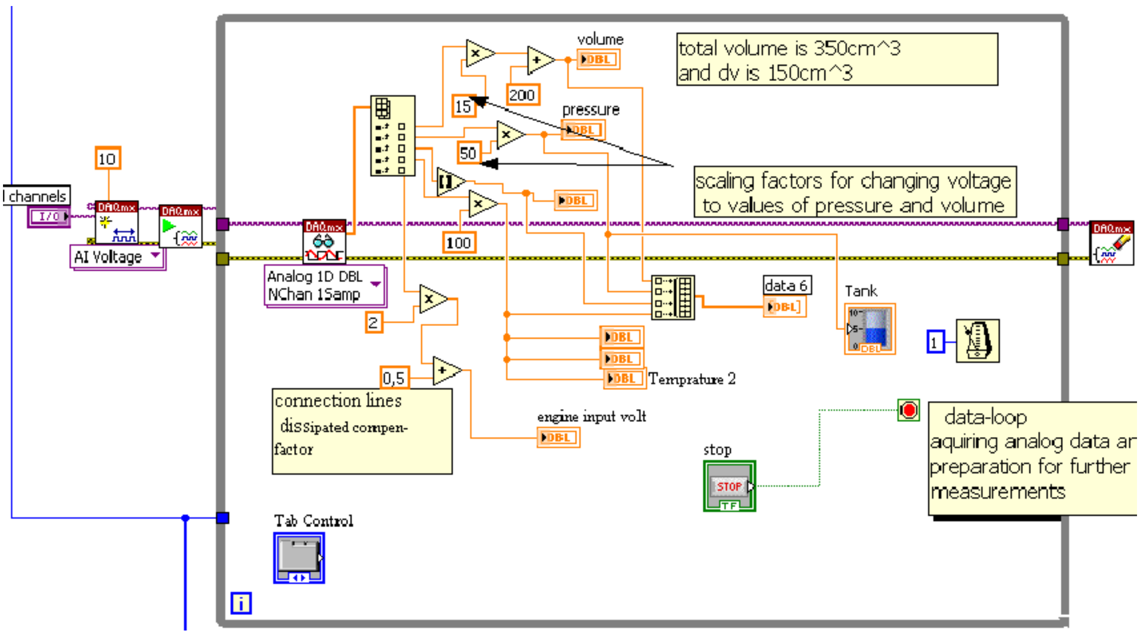


Figure 28 data loop (DAQmax configured to acquire analog inputs)

Other acquired values have got proper compensation factor to show real values. As it is seen (figure 28) temperature is multiplied by 100 gives TC (cooling side temperature) of engine in Celsius degree. The engine heating voltage is multiplied by 2 and a dissipation factor 0.5 is added to it, final value is instantaneous heating voltage (input) of engine in volt. This loop is timed for one millisecond so it is almost impossible to lose instantaneous values considering the highest rpm of this engine which is 500rpm.

5.3 PV diagram loop

The PV loop is designed to obtain PV graph of Stirling engine's cycle. The for loop inside while loop does the main role and provides arrays of measured pressure and volume 51 times during one cycle, which is used for drawing PV graph by specific nodes. As it shows (figure 29) pressure and volume are connected to input shift registers then outputs of shift registers are indexed to form two different arrays of measured pressure and volume in a cycle, the achieved results are connected through a cluster bundle to XY graph indicator which displays PV graph of engine's cycle.

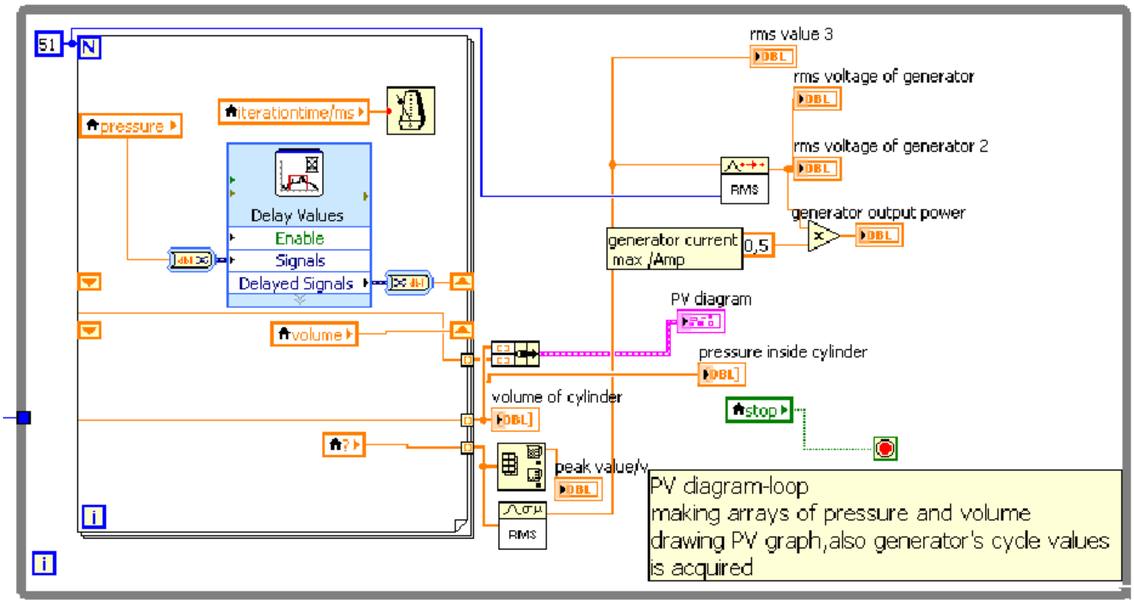


Figure 29 PV diagram loop

For loop reads values 51 times then sends data out to while loop where they are monitored on the screen. The iteration time of loop comes from rpm loop respect to instantaneous rpm and it is constant for one second at least, so iteration time is synchronized with duration time of a cycle. A delay value function is used to delay pressure value as much as two iterations, and synchronized it with volume sensor output. Because volume sensor is an old electromechanical tool and its speed response to changes are less than pressure sensor which owns new digital technology. The process is tested manually many times, results showed a delay have to be applied if accurate outcome is important in process calculation.

Generator output values also are calculated by this loop. Generator data is inserted to an indexing tunnel and output result is an array of values of generator output, then needed values of generator in obtained by using different mathematical function of LabView. But these values do not have anything to do with PV graph just this loop is used for calculation. A question may arise that why loop's iteration number is 51 when iteration time is based on 50? Because it is wanted to produce a closed area on PV graph indicator, adding one or two more iteration does not make changes in final results because the cycle is a closed continuous one, and iteration time is constant for at least one second which may cover more than 200 iterations.

5.4 Power loop

Power loop contains all elements to calculate different aspects of power and efficiency. There are many values in this loop that they are not needed in calculation or in programming, these kinds of data has been created for comparing, analyzing and research about behavior of this engine and system. Explanations of the most important ones come in the following.

5.4.1Instantaneous power

Arrays of pressure and volume are brought to this loop (figure 30) and connected to the for loop's tunnel, then indexed and divided by 1000 that gives instantaneous output energy of engine. The unit of power is in joule/t, because pressure is considered in kilo Pascal. Instantaneous power is indexed again and the result is averaged so it produced cycle average output energy, also by another function maximum and minimum work or let say energy of a cycle are achieved.

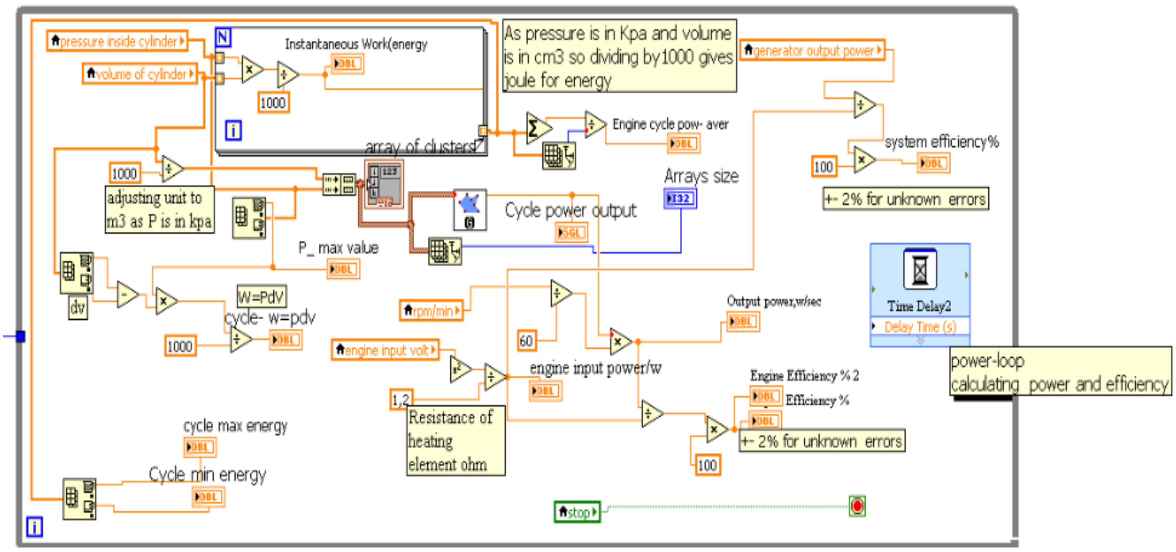


Figure 30 power loop

5.4.2 Theoretical Maximum work

Theoretical Maximum work of a cycle is calculated by formula (5.16). LabView functions are used to find out max and min volume values in a cycle then the difference between them which is dv is multiplied by max pressure and the result is theoretical max power of cycle.

$$work = W_{max} = P_{max}dv. \quad (5.16)$$

Where;

Wmax= possible maximum theoretical work

P = maximum pressure

dv= total change in volume

5.4.3 Cycle energy output

It is known that area under the curve is equal to work done by piston. When there is a closed area consists of upper and lower curves (figure 31) which presents one cycle of heat engine, then the area between two curves is equal to engine's output energy in one cycle. In fact power is rate of provided energy per unit of time, so that energy per cycle multiply by rpm (as rpm can be interpreted as cycles per unit of time) gives output power of engine in watt per unit of time, unit time can be second, minute or etc.

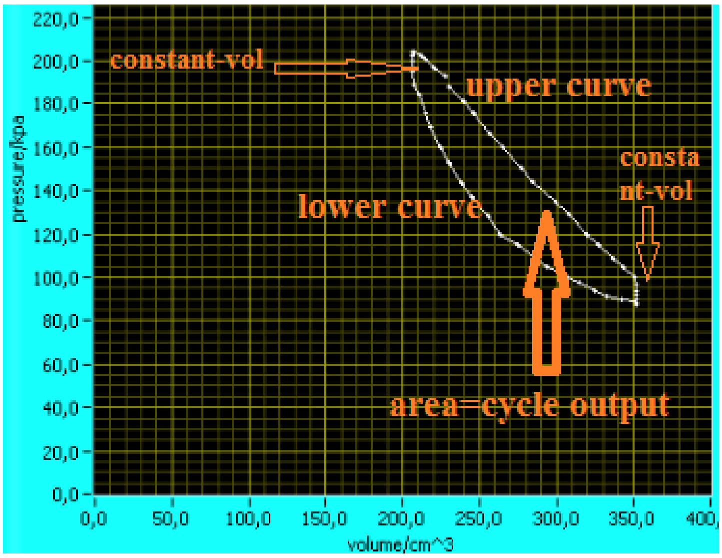


Figure 31 Stirling cycle illustration

As graph shows cycle figure can be considered as an irregular polygon with 50vertices so the area can be calculated by following formula (5.17):

$$A = \frac{1}{2}|(x_1 * y_2 + x_2 * y_3 + \cdots + x_n * y_1) - (y_1 * x_2 + y_2 * x_3 + \cdots + y_n * x_1)|. \quad (5.17)$$

Front image shows points of measured pressure and volume. Calculation can be either clockwise or anticlockwise, while formula considers the absolute value.

The more points on a cycle the more accurate result will be obtained. In this project different experiences sowed that fifty points is the best.

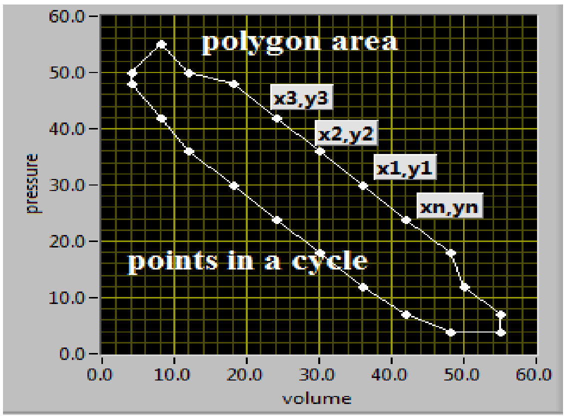


Figure 32 Stirling cycle instant P,V values image

The formula (5.17) can be written on a formula node then the input of node be connected to X,Y(P,V) arrays, or using polygon function which gets X,Y values and shows the area of polygon (energy of cycle here) as it is done in power loop (figure 30).

Another easy way is using for loop with two shift registers, putting a few math nodes inside and outside of the loop then wiring them in to shift registers in a way that formula (5.17) be applied by shift registers (figure 33), this is experienced and it worked as good as polygon vi.

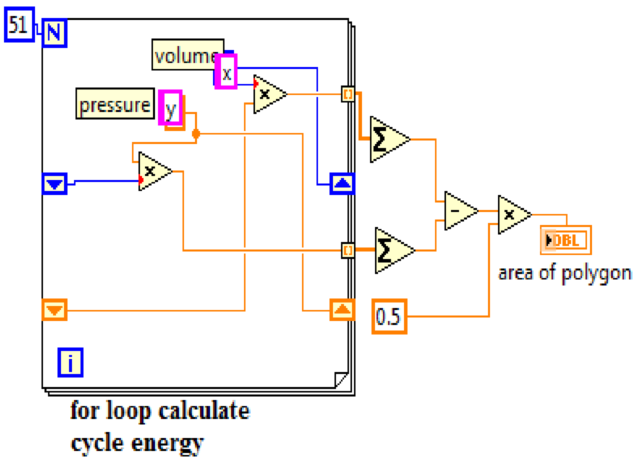


Figure 33 formula (5.17) applied to shift register

5.4.4 Engine's power output

When polygon area (cycle's energy) is obtained, it is easy to calculate engine's output power. Multiplying obtained area by rpm gives power per minute, it can be in second or hour, and this does not make differences.

Let's try formula for finding units and have example;

$$power = \frac{\text{energy(J)}}{\cancel{\text{cycle}}} * \frac{\text{n}\ \cancel{\text{cycle}}}{\text{sec}} = \frac{\text{n(J)}}{\text{sec}} = \text{W(watt)}. \quad (5.18)$$

so pure watt per second is left

For example; if cycle output energy is 4joule/round and rotational speed is 5r/sec, power is; 4joule/r*5r/sec= 20w.

5.4.5 Engine's input power

Input power is the power that consumed by heating resistor inside cylinder to provide heat to hot side of engine. While load is resistive and resistance value of heating element is known R=1.2Ω, instant terminal voltage of element also is known to the program by AI4, so that input power is calculated by formula (5.21) in power loop.
Power can be calculated directly from formulas for a resistive load;

$$P = VI. \tag{5.19}$$

or;

$$P = RI^2. \tag{5.20}$$

It is Known that R=V/I, I=V/R, by substituting these fractions in the formula instead of voltage and current of load gives;

$$P = \mathrm{RI}^2 = \mathrm{R}\frac{\mathrm{V}^2}{\mathrm{R}^2} = \frac{\mathrm{V}^2}{\mathrm{R}}. \tag{5.21}$$

Where;

P= Power consumed by resistive load (w)

V= terminal voltage of load (v)

I= current of load (A)

R= resistance of load (Ω)

The power is calculate by formula (5.21) because current unknown to the program.

5.4.6 Efficiency of Stirling cycle

Efficiency of Stirling cycle is obtained by formula (2.7) dividing cycle power by input power. Another efficiency can be calculated here which obtained from dividing generator power by input power of engine. Let's name it system efficiency as this is an individual station. The iteration time of loop is one second, it means data will be updated after a second. As it is mentioned already many unnecessary types of data is built especially in this loop and their indicators are put in hidden option, these data are for the purpose of maintenance and debugging.

5.5 Feeding loop

Main job of this loop (figure 35) is providing control voltage to feeding transformer. The output voltage of transformer (engine heating voltage) can be varied from 0to 30v, it can be controlled either manually or by software. When it is connected to a computer, manual control is disabled automatically. Control of transformer accepts variable voltage from 0 to 10v, when input changes from (0…10v) its output varies from 0% to 100% respectively. Feeding loop provides a secure and full controlled voltage to input control of transformer, so that it can control the amount of heat and of course the engine's rpm.

A DAQ assistant (figure 35) is configured to AO1 for sending control voltage to the feeding transformer (figure 34), control voltage comes from a PID advanced vi to the DAQ assistant, the function has either manual or automatic connection, so it make easy to control the engine's input power.

Figure 34 Feeding transformer

A limitation has been set up for control voltage that allows the control voltage only changes between 4 to7.5 volts. If control voltage be less than 4v or more than 7.5v the circuit will be switched to10v constant on transformer's output, and an indicator will show on the screen over limit voltage. Experiences showed that when control voltage is less than 4v engine cannot be run properly and when control voltage is more than 7.5 it may damage the engine , so that limitation is built up for protective reasons.

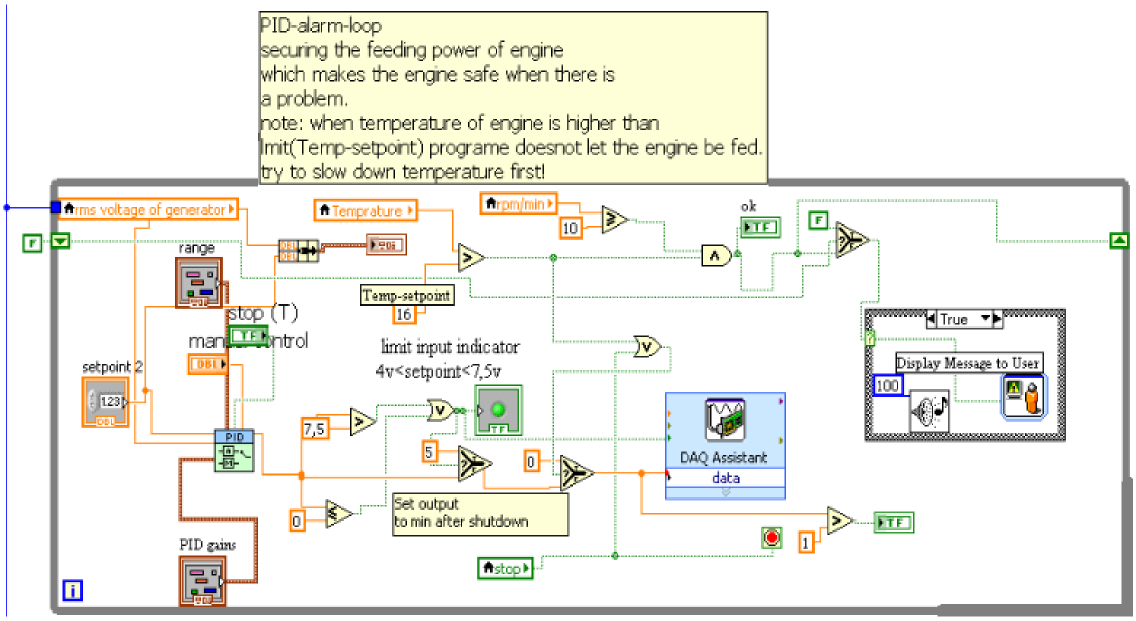


Figure 35 Feeding loop

Most of logic nodes are added to this loop for making the station more secure and removing observed possible troubles during this study.

For example if cooling temperature increased over its set point, loop stops DAQ assistant, sets output to zero, sends warning message on control panel by case structure loop (figure 35), sends a signal to writing data loop for publishing the most recent cycles data history to an excel file or other directed document and stops writing data when rpm is less than 10 rounds per minute.
Another important point in this part is that feeding transformer remembers the last input so if the stop button is pressed and program is stopped but feeding voltage will be on until the input is changed to zero. This problem damages engine components after few minutes, thus the problem is solved by adding nodes and programming it in a way that if program is going to stop for any reason it set the output to zero before stopping.

5.6 Writing data loop

Writing data loop is providing analytical information and records them in a directed document with a defined format.
This part consists of three loops, for loop, case structure loops and while loop. Essential data have been gathered inside for loop (figure 36) in an array of ten elements, for loop’s iteration number is 51 same as PV diagram, when for loop has finished reading values it records them in a 2D array and sends to case structure.
2D array of data is changed to fractional string format in case structure loop, then another 1D array of string which represents date& time of incidents is inserted into 2D array as a column, again a constant array of string which contains headers is added as a row into 2D array.
Finally this ready 2D array is connected to writing to spread sheet vi and also in parallel to a data table (table 2) which is visible on front panel under analytical tab.

Another function of this loop is that, when some error occurs or cooling temperature is over high limit, it becomes active and records the most recent cycle’s values until rotational speed falls less than ten revolutions per minute. All details and dependant circuits can be seen in the (figure 36) loop.

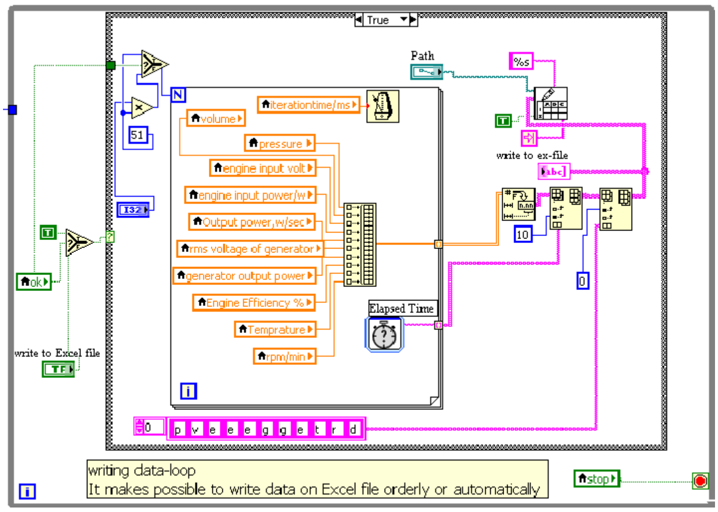


Figure 36 Writing data loop

When a user whishes to record data, he (she) first should define on the front panel, how many cycles have to be record, chose a file where information will be recorded if has not done already, then press the button write to a file.

when user open the file he(she) can see all desired information in a neat understandable format with exact date of occurrence for each iteration. This is a great help for analyzing and diagnostic purposes in a system.

Table 2 Data table includes variables’ name, values, date and time

write to ex-file

Data table

pressure/kpa	volume/cm3	eng-feeding/v	eng-input pow-w/	eng-output pow-	gen-output/v	gen-output pow/	efficiency	temperature/c	rpm	date/time
92,134168	351,555017	0,504842	0,211297	0,000000	NaN	NaN	0,000000	14,942115	0,000000	20.8.2012 16:25:
92,134168	351,555017	0,504842	0,211297	0,000000	NaN	NaN	0,000000	14,942115	0,000000	20.8.2012 16:25:
92,247745	351,555017	0,495756	0,211297	0,000000	NaN	NaN	0,000000	14,942115	0,000000	20.8.2012 16:25:
92,247745	351,555017	0,495756	0,211297	0,000000	NaN	NaN	0,000000	14,942115	0,000000	20.8.2012 16:25:
92,247745	351,555017	0,495756	0,211297	0,000000	NaN	NaN	0,000000	14,942115	0,000000	20.8.2012 16:25:
92,199069	351,550149	0,490564	0,211297	0,000000	NaN	NaN	0,000000	14,942115	0,000000	20.8.2012 16:25:
92,199069	351,550149	0,490564	0,211297	0,000000	NaN	NaN	0,000000	14,942115	0,000000	20.8.2012 16:25:
92,199069	351,550149	0,490564	0,211297	0,000000	NaN	NaN	0,000000	14,942115	0,000000	20.8.2012 16:25:
92,199069	351,550149	0,490564	0,211297	0,000000	NaN	NaN	0,000000	14,942115	0,000000	20.8.2012 16:25:
92,199069	351,550149	0,490564	0,211297	0,000000	NaN	NaN	0,000000	14,942115	0,000000	20.8.2012 16:25:
92,199069	351,550149	0,490564	0,211297	0,000000	NaN	NaN	0,000000	14,942115	0,000000	20.8.2012 16:25:
92,199069	351,550149	0,490564	0,211297	0,000000	NaN	NaN	0,000000	14,942115	0,000000	20.8.2012 16:25:
92,199069	351,550149	0,490564	0,211297	0,000000	NaN	NaN	0,000000	14,942115	0,000000	20.8.2012 16:25:
92,199069	351,550149	0,490564	0,211297	0,000000	NaN	NaN	0,000000	14,942115	0,000000	20.8.2012 16:25:
92,231520	351,550149	0,498352	0,211297	0,000000	NaN	NaN	0,000000	14,909665	0,000000	20.8.2012 16:25:
92,231520	351,550149	0,498352	0,211297	0,000000	NaN	NaN	0,000000	14,909665	0,000000	20.8.2012 16:25:
92,231520	351,550149	0,498352	0,211297	0,000000	NaN	NaN	0,000000	14,909665	0,000000	20.8.2012 16:25:
92,231520	351,550149	0,498352	0,211297	0,000000	NaN	NaN	0,000000	14,909665	0,000000	20.8.2012 16:25:
92,231520	351,550149	0,498352	0,211297	0,000000	NaN	NaN	0,000000	14,909665	0,000000	20.8.2012 16:25:

5.7 Graphic indicator loop

Graphic indicator loop is designed to show measuring variable either graphically or numerically. All six I/O values are brought in to this loop and rearranged in 1D array of data, resulted 1D array is inserted to a build array function which gives data out in 2D array of one column and six rows.

Finally obtained 2D array is connected to a wave form chart. The wave form chart must be enabled for stacked plots and numerical display.

When program is run this chart shows all six variables’ values separately with their numerical indicator in one column and six rows.

Loop is timed with 3 millisecond delay. That causes the graphical indicator be more visible, the loop is the simplest one in this program and does not have any other specifications.

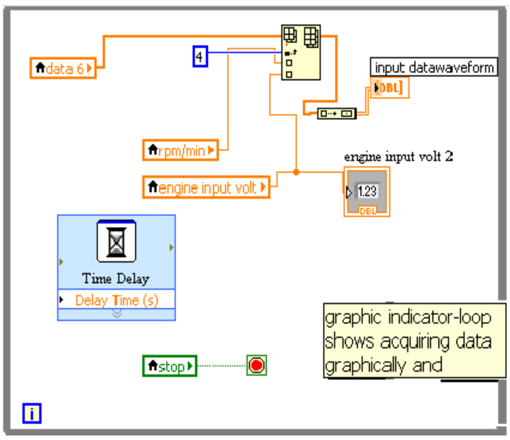


Figure 37 Graphic indicator loop

6 RUNNING PROGRAM AND FINAL TEST

When software programming is completed and all possible faults are checked and removed then program is run. The results were about what is expected from theoretical point of view. This is not obtained in the first run for sure, many pre-tests have been conducted and corrections have been carried out as much as was needed.
Basically a loop was tested independently when codes were written on it as much as possible and again it was tested when the loop was bundling to other loops, so that program's debugging has been done in advance step by step.
Doing more tests more defects revealed and improvements took place till result fulfilled the goal of project.
Final test did not raise unexpected problems. Some decoration have been done on user interface to give it more visibility and friendly appearance, also changes happened in calculation methods to make them more understandable.
Two separate tests carried out idle test and load test. Each test consists of ten times recording data at different range of power, recorded result graphed and monitored by excel. Explanation comes in following.

6.1 Idle test

The Idle test is done in eight different ranges of power. Results showed cycle efficiency of this beta type of Stirling engine in the best stable conditions is about 19% ±2%. This result has been carried out through a series of tests with different feeding power and rotational speeds (rpm). The rpm is proportional to feeding power, any increase or decrease in power affects rpm directly.
The test showed that efficiency stands almost constant between 175 to 310rpm. But when rotational speed is less than 175rpm or more than 310rpm efficiency begin to decline, results are shown in (table 3) and an excel graph (figure 38). Each row (range) of values was observing for five minutes, after being sure there are no interferences on engine's working from previous range of power, and then data has been written down.

Stirling engine has large dead time. Thus if set point is changed process variable does not follow it instantly, always it fluctuates many times before being stable, so that it takes plenty of time to complete a series of reliable tests. The engine has high reliability at constant continuous working but cannot be controlled fast enough. This is the main disadvantage of Stirling engine while controlling is the first priority in any application where an engine should be chosen.

Table3 Data table of idle tests

No	input power/w	output power/w	speed RV/min	efficiency%
1	152.6	26.8	336	17.56
2	122.77	25.05	318	20.04
3	95.225	19.03	252	19.98
4	77.8	15.8	210	20.30
5	61.77	12.7	174	20.56
6	60.77	11.2	156	18.43
7	56.7	9.3	132	16.40
8	51.17	8.1	114	15.82

Note: x axis steps do not have same length.

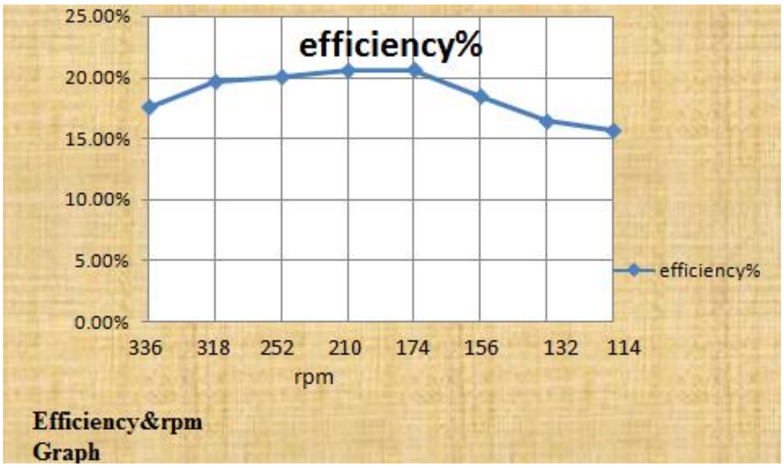


Figure 38 Excel graph of efficiency at idle test

Observing above experiences proved that this type of Stirling engine has good performances when it is running at 175 to 318 rpm. Best suggested rpm rate for idle running is 210 rpm, considering the mechanical wear and tear of this type engine.

6.2 Load test

Load test is done by plugging two small bulbs in to output of generator (table4). Two kinds of efficiency is considered, cycle efficiency and system efficiency. Cycle efficiency is obtained same as idle test, but system efficiency is calculated from active power of generator divided by engine’s heating power. Loads are two small bulbs which are specified as 12v, 2w and 6Ω and are connected in parallel to generator. Ten different ranges of power are used during test.

Provided power is calculated from formula (5.19);

P=VI.

Where;

P=max produced power

V= voltage connected to loads

I= max current of circuit or generator

It is a resistive circuit so no need extra calculations. Maximum power absorbed by load circuit is 4 watt and maximum power of generator is experienced 4.1watt in idle test so that 100% of produced power will be consumed by loads, generator cannot work load less partly. The data table and it's excel graph are shown below.

Table4 Load test data table of efficiency

No	Input power/w	Output power/w	Genrams/v	rpm	Engine efficiency%	System efficiency%
1	68.5	10.49	4.1	132	15.31%	2.96%
2	75.4	11.3	4.6	140	14.99%	2.84%
3	85.06	13.2	5	162	15.52%	2.63%
4	106.42	16.3	5.7	198	15.32%	2.24%
5	125.6	19.43	6.3	228	15.47%	2.00%
6	135.9	22.6	6.8	246	16.63%	1.92%
7	139	22.8	7	264	16.40%	1.90%
8	158	24.6	7.2	276	15.57%	1.70%
9	183	27.01	7.6	294	14.76%	1.51%
10	201.6	31	7.8	330	15.38%	1.39%

Note: x axis steps do not have same length.

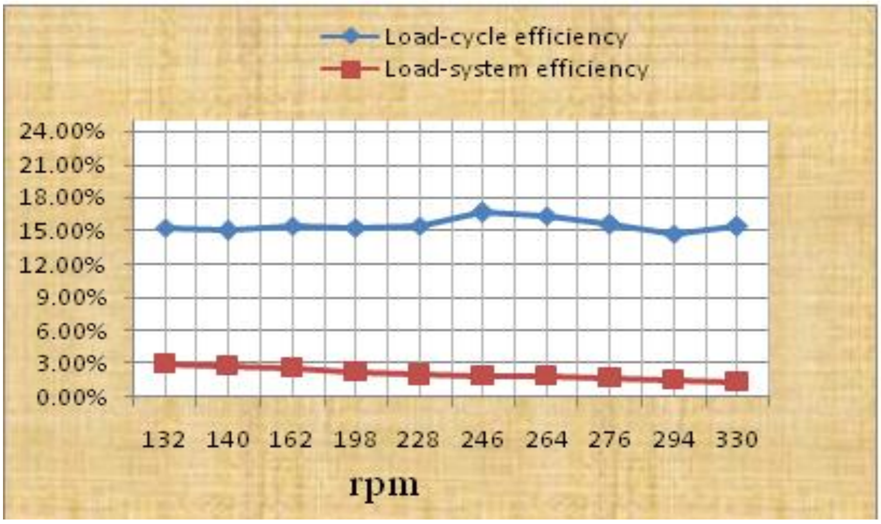


Figure 39 Excel graph of efficiency in load test

Looking at above graph one can understand that the best performance of engine at load test is obtained at rates of 230 to 270rpm.
The efficiency is smoothly 16%±2% as results are shown in (figure 39). The experiences are not far from their theoretical specifications and expectations.

From system efficiency graph it is found out that system efficiency is too low, in all experiences about 80% of cycle energy is remained useless. This happened because of using very low power generator. The behavior of Stirling engine is in a way that it takes time to get its nominal continuous power, if a more powerful generator is used it took at least twenty minutes to be started up and loaded. Optimistically the above table and graph say system efficiency is about 2% which is nothing compare to input power. The highest system efficiency is recorded at lowest rpm.

7 ANALYZING AND STUDYING THE RESULTS

Recent experiences say the most sophisticated Stirling engines have efficiency rate about 30 to 35%, depends on type of engine. This study gives the efficiency rate about 19%±2% for this beta type of Stirling engine, let's examine the results with comparing them to theoretical cycle model.

Looking at cycle graph one can recognizes that output energy or net work by a cycle is equal to supplied heat Qs minus rejected heat Qr. Supplied heat occurs during expansion from phase 3 to 4 and rejected heat is during compression phase from 1 to 2, so work is equal to Qs-Qr.

Temperature is constant during both compression and expansion phases, volume is constant during 2 to 3 and 4 to 1 as it is seen in (figure 40) in the front of text.

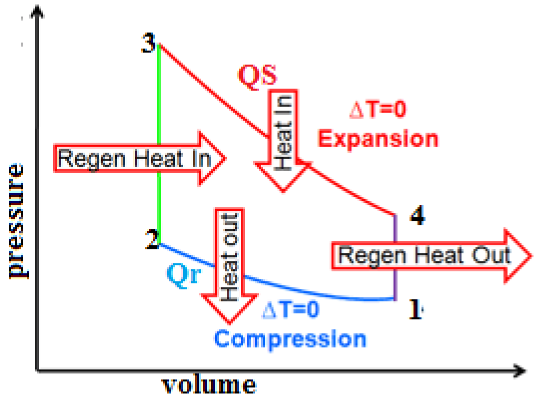


Figure 40 Stirling cycle heat transferring illustration

Process of Stirling engine takes place as comes in the following;

(a) The air is compressed isothermally from state 1 to 2 (TL to TH).
(b) The air at state-2 is passed into the regenerator from the top at a temperature T1. The air passing through the regenerator matrix gets heated from TL to TH.
(c) The air at state-3 expands isothermally in the cylinder until it reaches state-4.
(d) The air coming at temperature TH (condition 4) enters into regenerator from the bottom and gets cooled while passing through the regenerator matrix at constant volume and it comes out at a temperature TL at condition 1, and the cycle is repeated.
(e) It can be shown that the heat absorbed by the air from the regenerator matrix during the process 2-3 is equal to the heat given by the air to the regenerator matrix during the process 4-1, and then the exchange of heat with external source will be only during the isothermal processes. (Prof T Sundararajan Madras UT India.)

Now we can write, Net works done as;
W = Qs – QR. (7.22)
Where;
QS = Heat supplied during the isothermal process 3-4.
QR=Heat rejected during isothermal phase 1- 2.

For having real example and optimizing it more clearly a theoretical cycle graph is adapted to measure values of a random cycle at idle test as shown in (figure 41). Total changes in volume and pressure can be mentioned while total volume and pressure are known.

The following values are observed from a random cycle and matched to theoretical cycle as below;
V1=V4=351.53cm^3
V2=V3=200cm^3
P1=87.32kpa
P3=204.65kpa

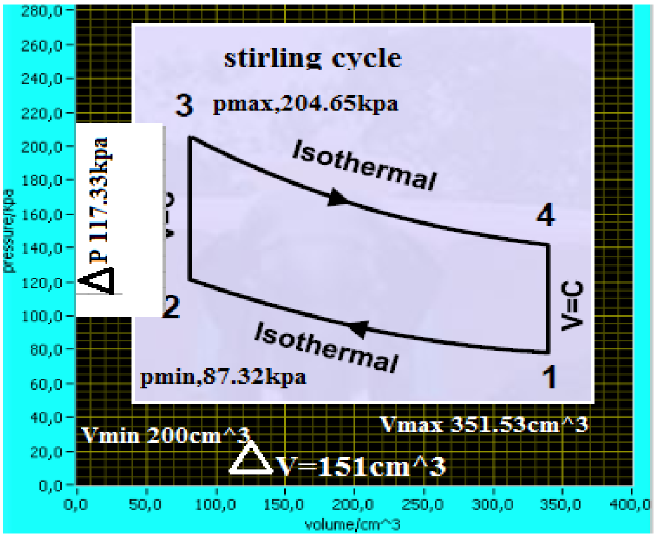


Figure 41 Cycle adapted to random measured data

So from following formulas the net work can be calculated as;

$$Qs = P_3V_3 ln\left(\frac{V_4}{V_3}\right). \quad (7.23)$$

$$QR = P_1V_1 ln\left(\frac{V_1}{V_2}\right). \quad (7.24)$$

When$V_{1=}V_{4,and}V_2 = V_3$,

W net=Qs-QR=$P_3V_3 ln\left(\frac{V_4}{V_3}\right) - P_1V_1 ln\left(\frac{V_1}{V_2}\right)$so; (7.25)

W net=$(P_3V_3 - P_1V_1)ln\left(\frac{V_4}{V_3}\right)$. (7.26)

Where;
W= net work output by a cycle
P3= pressure at state 3
P1= pressure at state 1
V1=volume at state 1
V3=volume at state 3

All elements of equation are known from a cycle recorded by program let see;

W=$Wnet = (204.65kpa * 200cm^3 - 87.32kpa * 351.53cm^3) * \ln\left(\frac{351.53}{200}\right) =$

$5771.97, when\ pressure\ in\ kpa\ and\ volume\ in\ cm^3 then, \frac{5771.97}{1000} = \frac{5.7719 Joule}{cycle}$.

For estimating the average power during idle test, obtained rpm's is averaged (211.5rpm) from table (3) and multiplied by net work from the equation. Thus it is enough to multiply cycle energy by rotational speed per second to fine the power of engine, so;

$$P_{ave} = \frac{5.7719 Joule}{cycle} * \frac{211.5 cycle}{60 sec} = \frac{20.34 Joule}{sec} = 20.34 watt$$

.

The result makes a real sense between theoretical approach and experimental idle test for this engine, let's calculate cycle energy of a monitored rpm (252) in idle test table and compare results;

$$Cycle\ energy_{(252rpm)} = \frac{P}{rpsec} = \frac{19.03 \frac{Joule}{sec}}{\frac{252 cycle}{60 sec}} = \frac{4.53 Joulr}{cycle}.$$

Again the result proves that theoretical thermodynamic principles support the experimental achievements in this study.

This type of Stirling engine uses a heat regenerator so that it is possible to use Carnot efficiency formula for calculating its efficiency.
Carnot formula;

$$\eta = 1 - \frac{TL}{TH}.$$

Where TL and TH are cool side and hot side temperature of engine, these values for this engine has been defined at nominal power by the manufacturer; TL=345K, TH=450K.

From given data and Carnot formula; $\eta\% = 1 - \left(\frac{345K}{450K}\right) * 100 = 23\%$

The following formula also can be used for calculating net work and then efficiency when Δvolume, TL and TH are known.

$$Qs = nRT_H ln\left(\frac{V_4}{V_3}\right). \tag{7.27}$$

$$QR = nRT_L ln\left(\frac{V_1}{V_2}\right). \tag{7.28}$$

So that work= $nRT_H ln\left(\frac{V_4}{V_3}\right) - nRT_L ln\left(\frac{V_1}{V_3}\right)$. (7.29)

V1=V4, V2=V3, so;

$$W = nR(T_H - T_L) \ln\left(\frac{V_4}{V_3}\right). \tag{7.30}$$

Where new parameters are;
n=Molar quantity of gas inside cylinder (mol)
R=Gas universal constant (8.314)

TH =Hot side temperature (K)
TL=Cool side temperature (K)

The only unknown of equation is molar quantity of gas (n). The (n) quantity can be calculated through the constant molar volume of ideal gas law (22.414l/mol). Because cylinder pressure at max volume is equal to atmospheric level. There is no extra pressure inside cylinder, only atmospheric pressure (air) is compressed during phases 2-3. Therefore according to Ideal gas law one mole of any gas occupies 22.14 liters at STP (standard temperature and pressure), here the gas is air and volume is 351.53cm^3 which is equal to 0.35153 liter, so n mole quantity cab be obtained by;

$$n_{air-inside-cyli} = \frac{0.35153L}{22.414L} = 0.01568mol.$$

Trying the above formula (7.30) gives theoretical maximum energy of a cycle about 7.6J which is not too far from obtained random idle test 5.7J, considering LTP (local temperature and pressure) conditions. With above tried theoretical formulas one can be assured that obtained result by the program is acceptable and enough close for proving its theoretical aspects. (G. Deacon, C. Coulding, Physics education 180-200 (1994))

8 CHALLENGES AND PROBLEMS SOLVING

Serious challenges have been met in both hardware and software parts. Firstly making a power supply seemed simple, but in practice raised too much problem when all components were powered from 30VDC output by different voltage dividers.
Despite of producing very smooth pure Dc voltage it modulated some noises in the circuit in a way that PV diagram could not be monitored by program, just showed some confusing points. Too much time is spent on debugging and recalibrating which had no effect on the results. Ultimately it was solved by powering each sensor from separate voltage output using voltage regulator IC AN7805, and adding two extra capacitors to out puts.
Another serious challenge was making a physical ring or let say pulley to transfer the piston's displacement scale which is 51mm to position meter displacement scale 32mm. Attempts were succeeded at last by making a pulley with two grooves and different diameters, so that it can transfer full displacement of piston to position meter.
Hard work was centralizing the smaller groove on top of bigger one, where pulley turns only 230° degree and backs again cyclically respectively to the piston down up movement. However it is done and worked.

Software troubles were most confusing parts since LABVIEW is a huge program with numerous functions. It becomes worse when the computer is not compatible with software and its DAQ card and components, as it was in this study. For example; moving a node or a vi function constitutionally and correctly inside a loop caused high disturbances to the program which led to reprogram it from stretch.
Studying then experiencing step by step gave the ability to come them all over and understanding how to tackle with such a time killer problems. Many programs was written and removed just for experiencing behavior of nodes and loops. There are tips and tricks that cannot be experienced theoretically, one have to do something for learning them especially in making user interface.

Lack of internet connection to station's computer was another problem that always hindered process of study. It took a lot of times to go to computer class and searching something then trying it at laboratory and back again and again if not succeeded.

9 CONCLUSIONS

Using labview software to calculate the efficiency of a beta type of the Stirling engine was quite useful for touching again the theoretical and practical lessons of engineering physics. The obtained results met planned goals fully and supported the theoretical examinations of the Stirling cycle and its PV graph illustration. The highest efficiency was about 19%±2% with the idle and 16%±2% with the load test, the best range of rpm was 210-240 taking into consideration the efficiency and mechanical wear and tear for this type of the engine

Comparisons with different tests and data monitored the efficiency of a beta type of the Stirling engine very closely. The temperature difference ($\Delta T = T_H - T_C$) between hot side T_H and coolside T_C has a significant effect on the output power and efficiency, in a few observations it seemed that efficiency was proportional to ΔT, the highest temperature difference ΔT causing the highest efficiency.

Experience showed that if the cooling water tab to the engine is closed when the engine is running, after a short time the efficiency decreased by 50% and the pressure also dropped which was normal. But when cooling tab was opened fully again the engine reacted instantly and backed to its nominal speed. This means that the engine's response to ΔT is faster than to the input power and a heating element.
When input power was increased or decreased the engine speed remained constant for a moment, then followed the set point and crossed it, then fluctuated till it stabilized around the set point. There was no fluctuating when ΔT was changed. The engine has high dead time compared to an internal combustion engine, because the heat element cannot lose or gain heat instantly.
It came to my mind if it were possible to change the TC fast enough technically, the speed could be controlled desirably by a combination of changes in the input power and the TC, since control problem is the highest disadvantage of a Stirling engine.

The Stirling engine is mostly suitable for laboratory work and research, the engine has a high performance in constant continuous operation, thus it has been applied to produce a large scale of solar electricity in a few locations in the United State up to 1.5GW.

Using software to monitor data on the user interface panel is of great help. It enables the operator to have a full control on the process plant. But a designer has to know the behavior of each signal or variable, and consider them when he /she is going to acquire analog or digital form of data. Noise or incompatibility between software and hardware can cause numerous problems and errors in the results.
One should check firstly the compatibility and synchronization between the system's components, secondly split the program in to smaller parts and carry out possible manual tests and calibrations, thirdly to improve and finalize the program.

REFERENCES

Measurements and automation tools. Accessed 01.05-12.06.2012
https://moodle2.hamk.fi/course/view.php?id=5396

Robert Stirling Engine. Accessed 01-30.06.2012
http://www.robertstirlingengine.com/principles.php

Hyperphysics& Thermodynamics. Accessed 15.07.2012
http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

Stiling online library. Accessed 18.07.2012
http://library.thinkquest.org/C006011/english/sites/stirling.php3?v=2

Stirling engine workshop. Accessed 21.07.2010

//arpa/Portals/0/Documents/ConferencesAndEvents/PastWorkshops/Stirling%20Engine_readout.pdf
http://newenergydirection.com/blog/2009/06/stirling-engine-efficiency/

Stirling engine cycle efficiency calculation. Accessed 01 -30.07.2012
http://outreach.phas.ubc.ca/phys420/p420_08/Hiroko%20Nakahara/pdfs/StirlingEngineProposal.pdf

Buffalo education faculty of physics engineering. Accessed 25.07.2012
http://www.ee.buffalo.edu/faculty/paololiu/edtech/roaldi/tutorials/labview.htm
Stirling engine

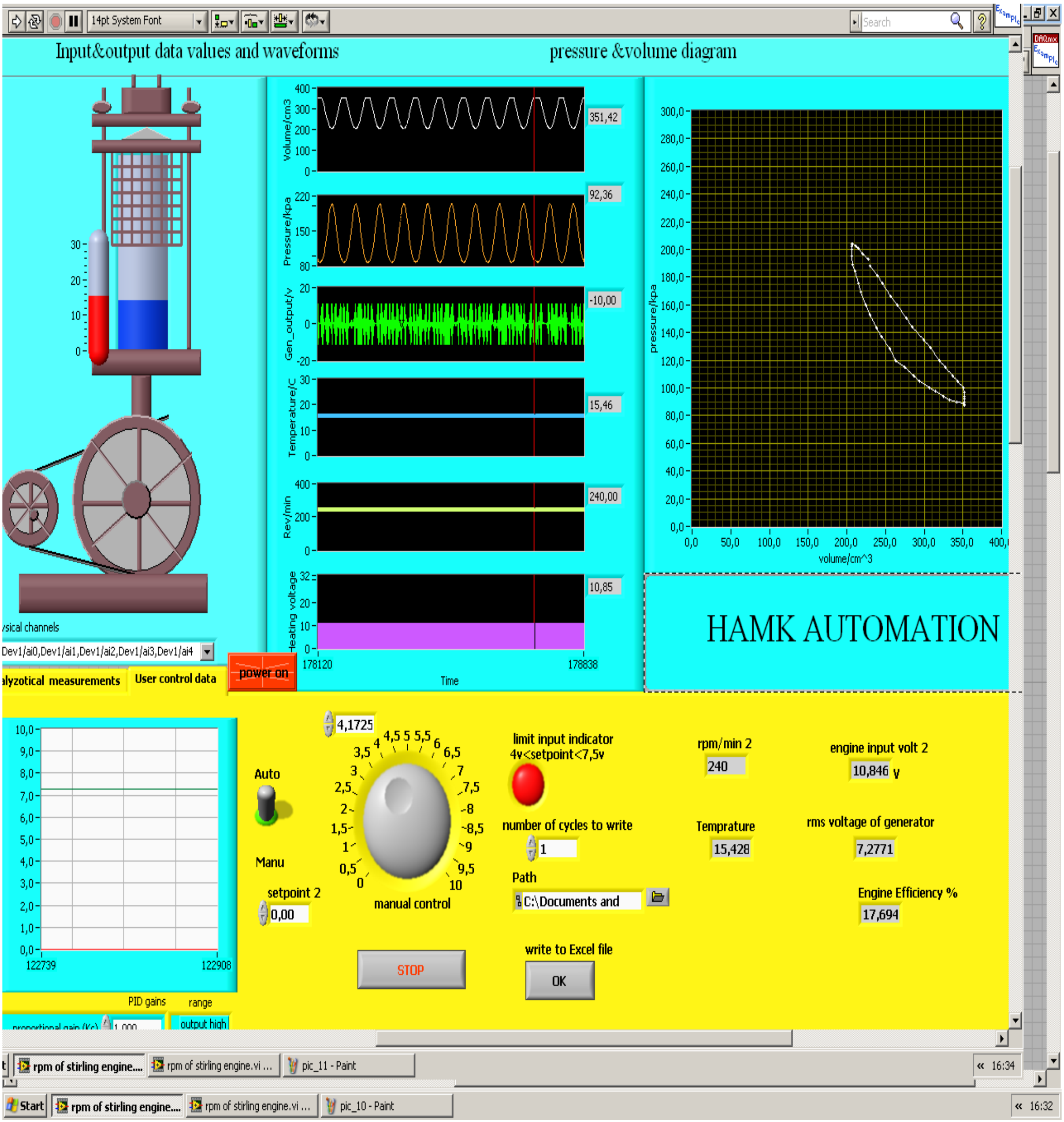
Practical types of Stirling engine. Accessed 30.07.2012
http://www.youtube.com/watch?v=BDfe1QYJC04

Stirling engine principles and calculations. Accessed 05.07.2012
http://www.sesusa.org/StirlingPrimer.htm

Lab view online tutorial. Accessed 01.5-30.08.2012
http://www.ni.com/

Appendix 1

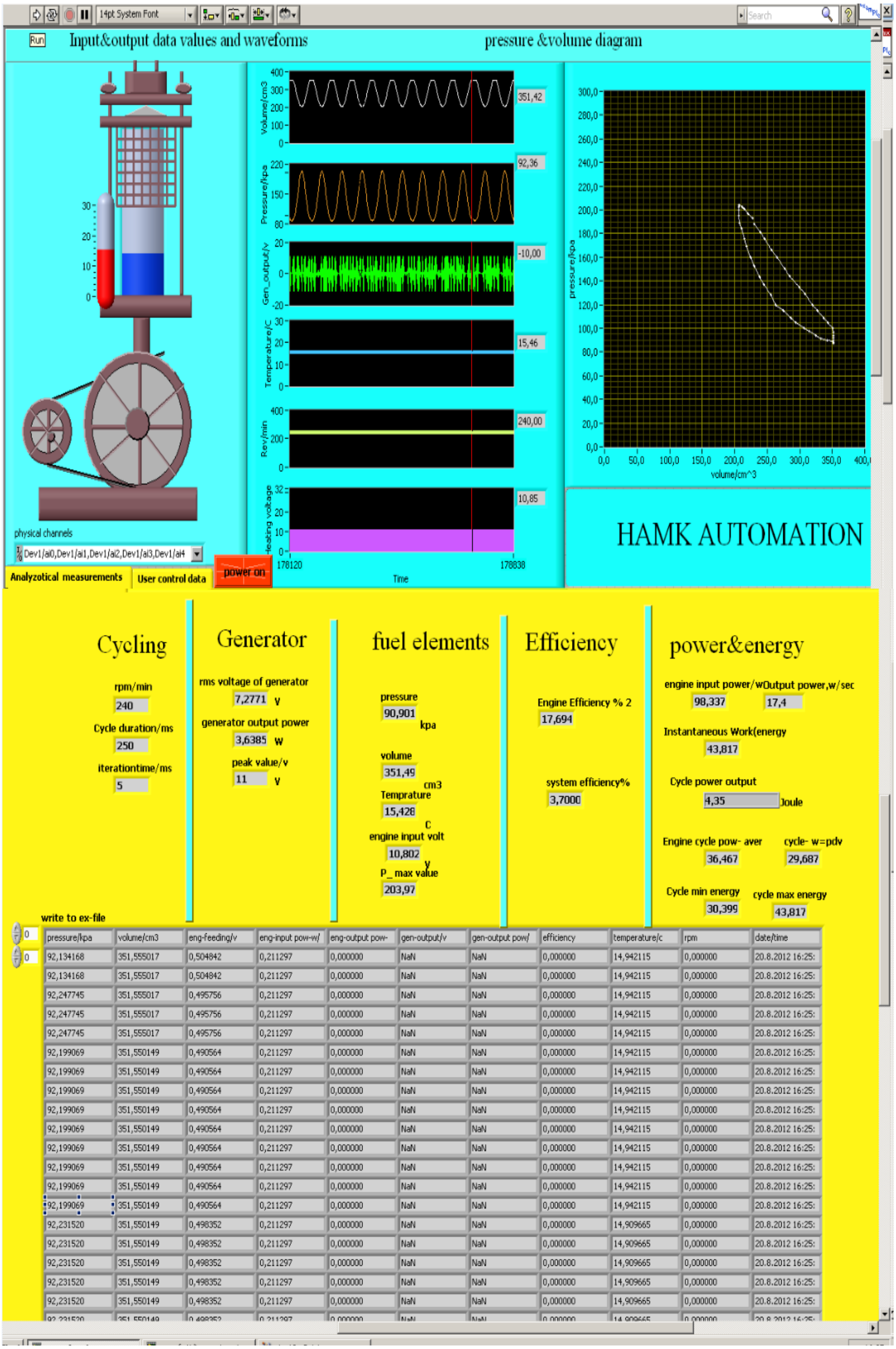
USER INTERFACE (USER TAB)



Note: Images can be zoomed to be more visible

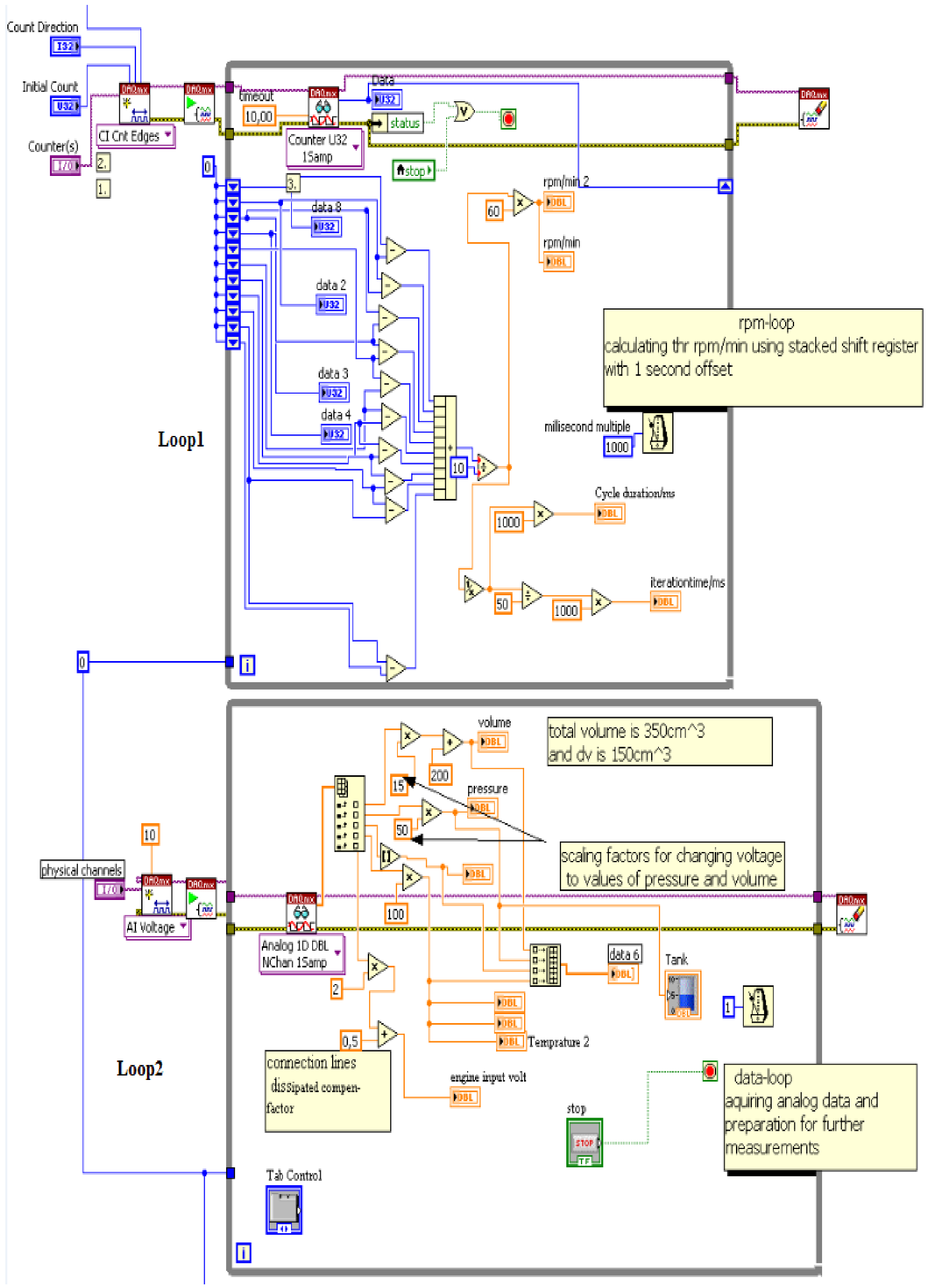
Appendix2

USER INTERFACE (ANALYTICAL TAB)



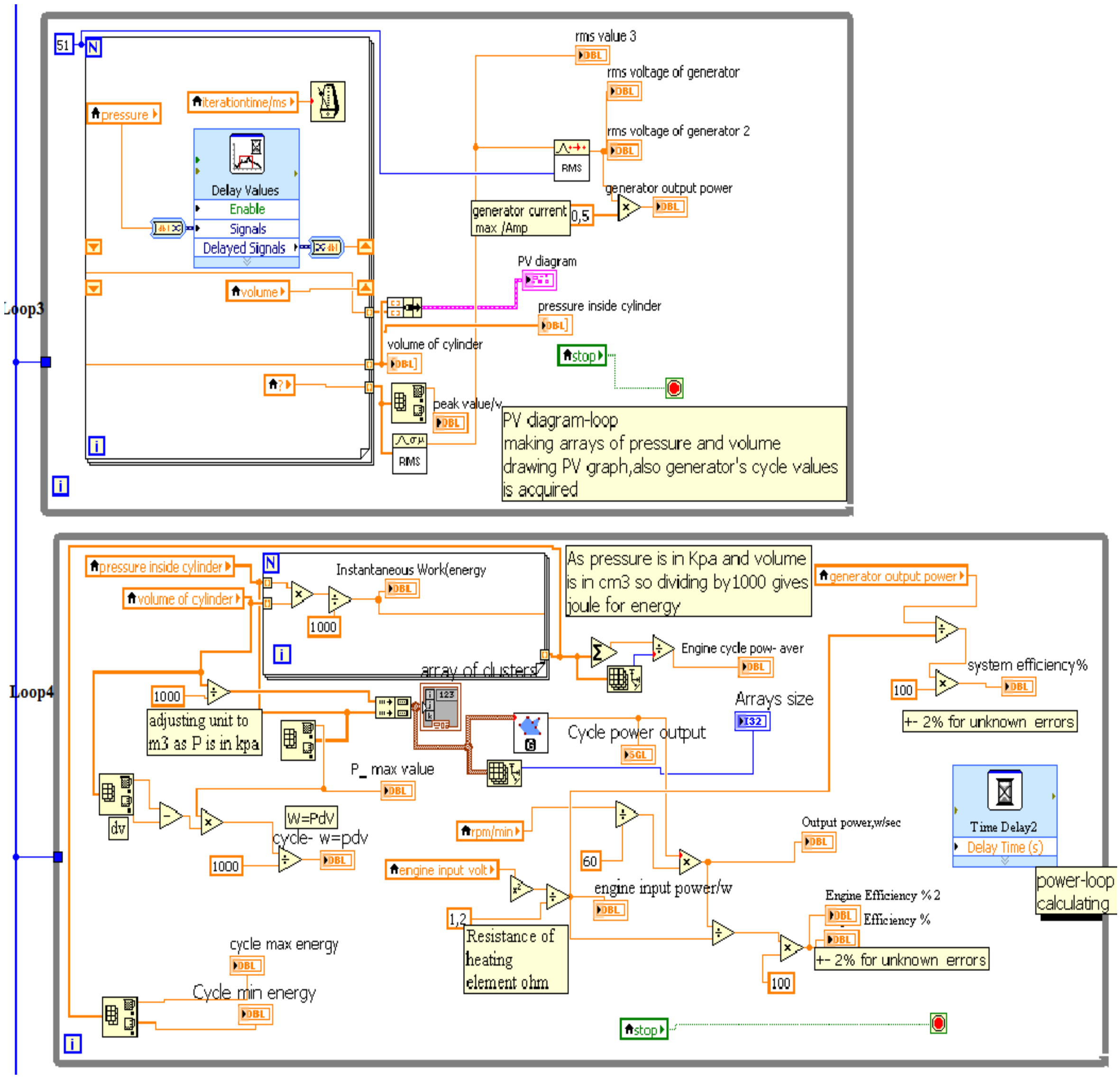
Appendix3

BLOCK DIAGRAM: RPM LOOP, DATA LOOP.



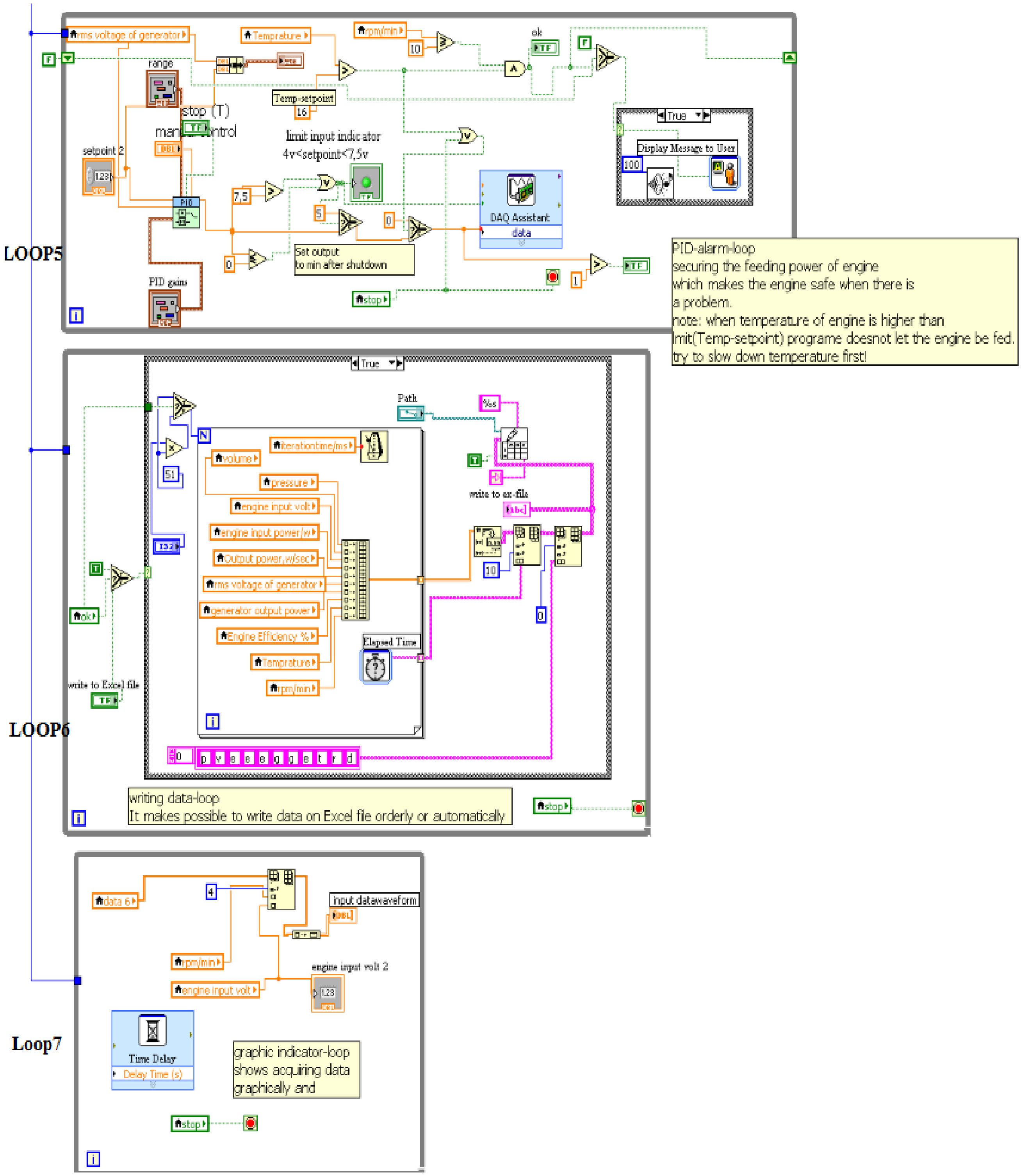
Appendix4

BLOCK DIAGRAM: PV DIAGRAM AND POWER LOOPS.



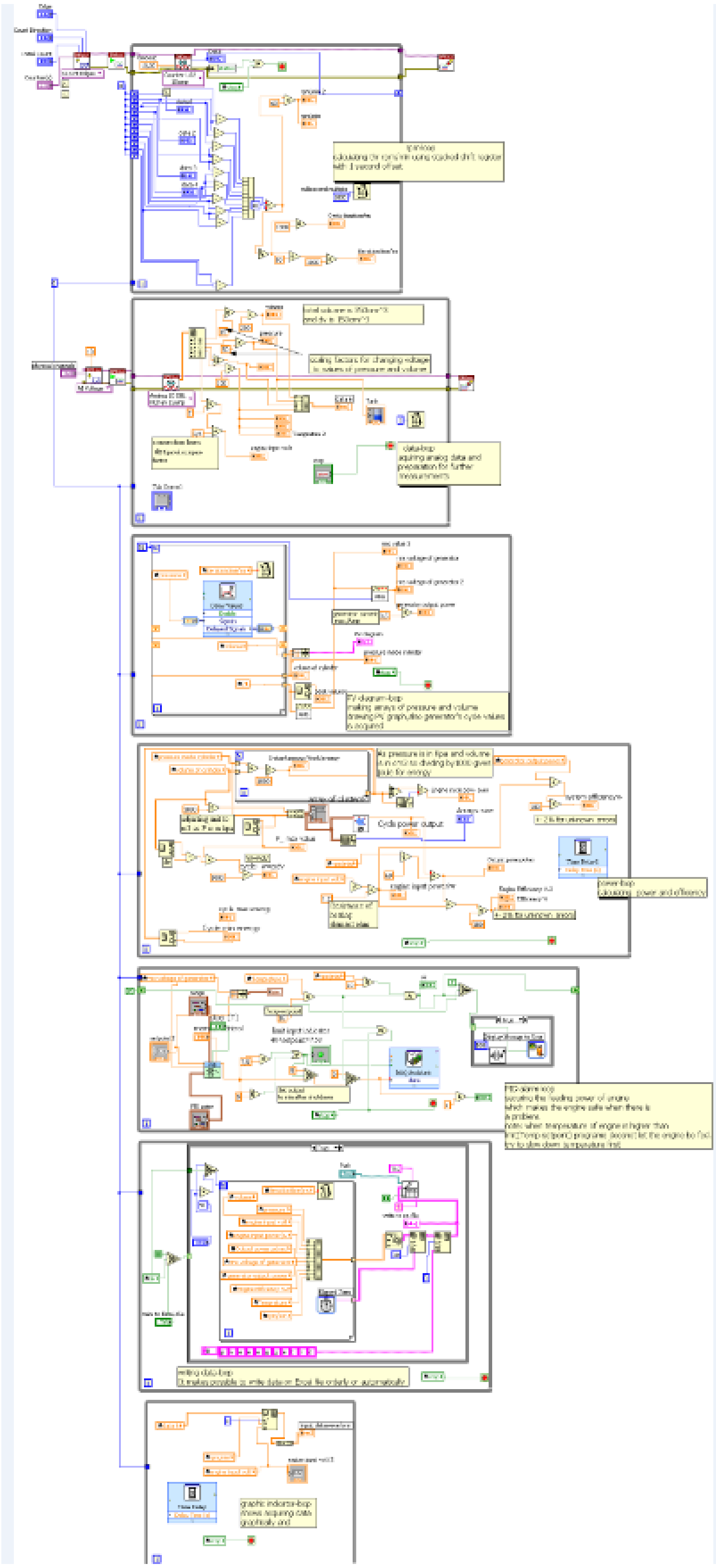
Appendix5

BLOCK DIAGRAM: FEEDING LOO, WRITING DATA TO A FILE, AND GRAPHIC LOOPS.



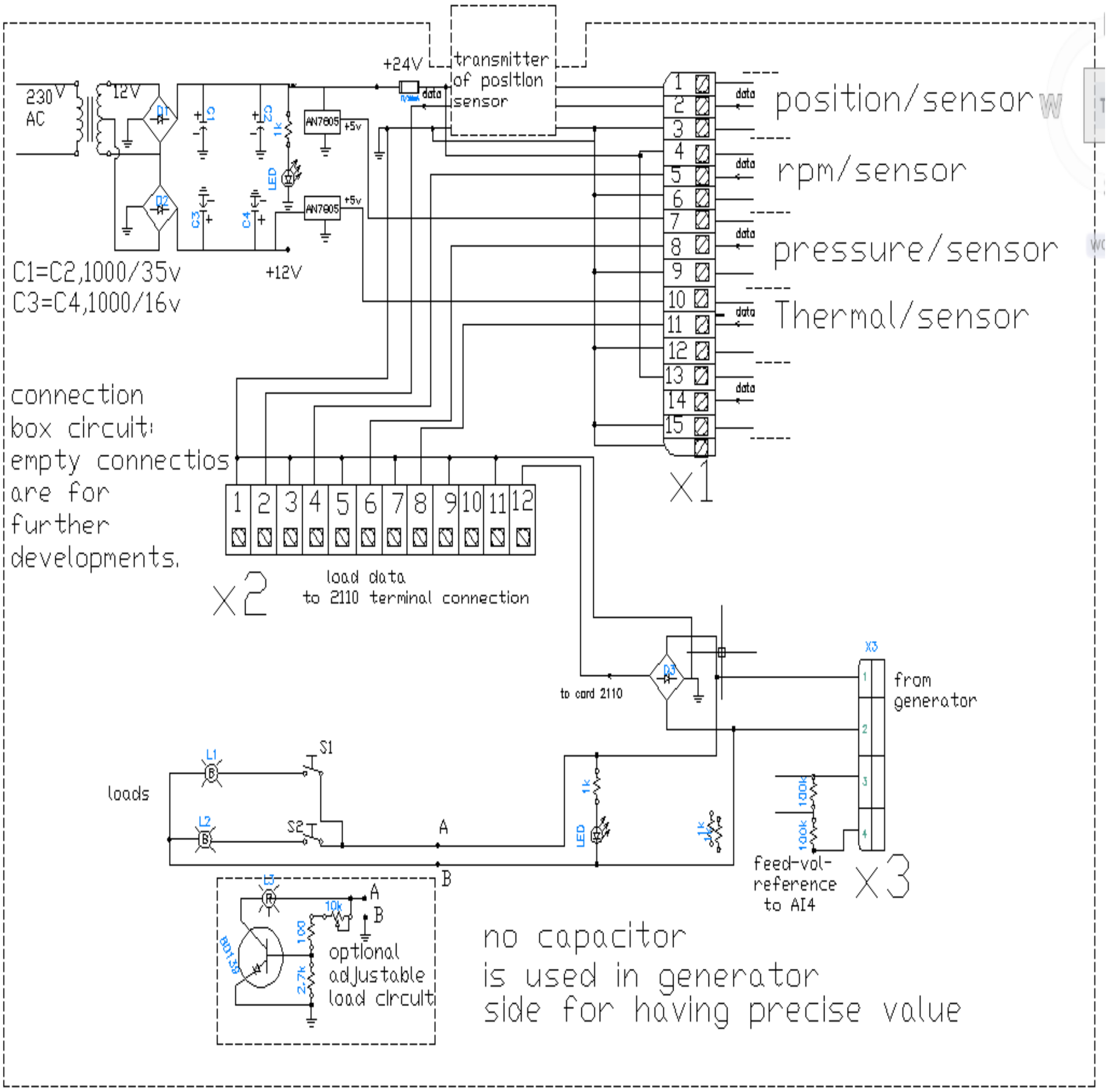
Appendix6

THE WHOLE BLOCK DIAGRAM



Appendix7

POWER SUPPLY, ELECTRICAL WIRING AND CONNECTION CIRCUIT



Appendix8

EXAMPLE OF WRITTEN DATA ON AN EXCEL FILE

	A	B	C	D	E	F	G	H	I	J	K
1	pressure/kpa	volume/cm3	eng-feeding/v	eng-input pow-w/s	eng-output pow-w/s	gen-output/v	gen-output pow/w	efficiency%	temperature/c	rpm	date/time
2	113.616357	310.837098	11.000624	99.776687	17.552446	7.268667	3.634334	17.591731	15.526222	240	20/08/2012 16:41
3	109.349124	318.416	10.974015	99.776687	17.552446	7.268667	3.634334	17.591731	15.526222	240	20/08/2012 16:41
4	105.536197	325.980314	11.031128	99.776687	17.552446	7.268667	3.634334	17.591731	15.493772	240	20/08/2012 16:41
5	100.603731	336.290001	10.909113	99.776687	17.552446	7.268667	3.634334	17.591731	15.493772	240	20/08/2012 16:41
6	96.661003	345.450949	11.023989	101.273603	17.552446	7.268667	3.634334	17.591731	15.526222	240	20/08/2012 16:41
7	94.50305	350.484127	10.91755	101.273603	17.38344	7.268667	3.634334	17.164828	15.493772	240	20/08/2012 16:41
8	91.647412	351.501472	10.946756	101.273603	17.38344	7.268667	3.634334	17.164828	15.493772	240	20/08/2012 16:41
9	90.446746	351.516075	10.98375	101.273603	17.38344	7.268667	3.634334	17.164828	15.461321	240	20/08/2012 16:41
10	88.937801	351.520943	11.040863	101.273603	17.38344	7.268667	3.634334	17.164828	15.526222	240	20/08/2012 16:41
11	88.321243	351.525811	10.877312	101.273603	17.38344	7.268667	3.634334	17.164828	15.493772	240	20/08/2012 16:41
12	87.883162	351.530678	10.984399	101.273603	17.38344	7.268667	3.634334	17.164828	15.526222	240	20/08/2012 16:41
13	87.866937	351.530678	10.900027	101.273603	17.38344	7.268667	3.634334	17.164828	15.493772	240	20/08/2012 16:41
14	88.337468	351.530678	10.935723	101.273603	17.38344	7.268667	3.634334	17.164828	15.493772	240	20/08/2012 16:41
15	89.473233	351.535546	10.863033	101.273603	17.38344	7.268667	3.634334	17.164828	15.526222	240	20/08/2012 16:41
16	90.219593	351.540414	10.948703	101.273603	17.38344	7.268667	3.634334	17.164828	15.493772	240	20/08/2012 16:41
17	92.685826	348.439702	10.910411	101.273603	17.38344	7.268667	3.634334	17.164828	15.493772	240	20/08/2012 16:41
18	94.438149	342.997643	10.927286	101.273603	17.38344	7.268667	3.634334	17.164828	15.493772	240	20/08/2012 16:41
19	97.585841	333.07248	10.989591	101.273603	17.38344	7.268667	3.634334	17.164828	15.461321	240	20/08/2012 16:41
20	100.425254	326.014387	10.921445	101.273603	17.38344	7.268667	3.634334	17.164828	15.493772	240	20/08/2012 16:41
21	105.227918	314.935642	10.948054	101.273603	17.38344	7.268667	3.634334	17.164828	15.493772	240	20/08/2012 16:41
22	111.101448	303.39937	10.976611	101.273603	17.38344	7.268667	3.634334	17.164828	15.493772	240	20/08/2012 16:41
23	115.401132	295.061148	10.902623	101.273603	17.38344	7.268667	3.634334	17.164828	15.493772	240	20/08/2012 16:41
24	122.880961	282.999225	10.913656	101.273603	17.38344	7.268667	3.634334	17.164828	15.526222	240	20/08/2012 16:41
25	128.251511	275.138059	10.935074	101.273603	17.38344	7.268667	3.634334	17.164828	15.461321	240	20/08/2012 16:41
26	137.288964	263.426644	10.914305	99.268386	17.38344	7.268667	3.634334	17.164828	15.493772	240	20/08/2012 16:41
27	143.487004	255.974378	10.918849	99.268386	17.38344	7.268667	3.634334	17.511557	15.461321	240	20/08/2012 16:41
28	153.10857	245.518827	11.002571	99.268386	17.38344	7.268667	3.634334	17.511557	15.526222	240	20/08/2012 16:41
29	159.744695	239.069297	10.998677	99.268386	17.38344	7.268667	3.634334	17.511557	15.493772	240	20/08/2012 16:41
30	169.544744	230.390425	11.011008	99.268386	17.38344	7.268667	3.634334	17.511557	15.493772	240	20/08/2012 16:41
31	178.695786	223.089079	10.927286	99.268386	17.38344	7.268667	3.634334	17.511557	15.493772	240	20/08/2012 16:41
32	184.212374	218.961386	10.855894	99.268386	17.38344	7.268667	3.634334	17.511557	15.526222	240	20/08/2012 16:41
33	191.659768	213.762831	10.899378	99.268386	17.38344	7.268667	3.634334	17.511557	15.526222	240	20/08/2012 16:41
34	195.797211	210.949381	10.993485	99.268386	17.38344	7.268667	3.634334	17.511557	15.493772	240	20/08/2012 16:41
35	200.697242	208.111593	10.95714	99.268386	17.38344	7.268667	3.634334	17.511557	15.526222	240	20/08/2012 16:41
36	202.790301	207.016393	10.928584	99.268386	17.38344	7.268667	3.634334	17.511557	15.493772	240	20/08/2012 16:41
37	204.558856	206.033146	10.930531	99.268386	17.38344	7.268667	3.634334	17.511557	15.493772	240	20/08/2012 16:41
37	204.558856	206.033146	10.930531	99.268386	17.38344	7.268667	3.634334	17.511557	15.493772	240	20/08/2012 16:41
38	204.656208	205.930927	11.000624	99.268386	17.38344	7.268667	3.634334	17.511557	15.493772	240	20/08/2012 16:41
39	203.439312	206.135364	10.933127	99.268386	17.38344	7.268667	3.634334	17.511557	15.493772	240	20/08/2012 16:41
40	200.421412	208.306296	10.980505	99.268386	17.38344	7.268667	3.634334	17.511557	15.526222	240	20/08/2012 16:41
41	197.533314	211.294978	10.913656	99.268386	17.38344	7.268667	3.634334	17.511557	15.526222	240	20/08/2012 16:41
42	191.838246	215.924028	10.905868	99.268386	17.38344	7.268667	3.634334	17.511557	15.493772	240	20/08/2012 16:41
43	187.262722	219.594169	10.997379	99.268386	17.38344	7.268667	3.634334	17.511557	15.493772	240	20/08/2012 16:41
44	179.490824	227.04154	10.925988	99.268386	17.38344	7.268667	3.634334	17.511557	15.526222	240	20/08/2012 16:41
45	173.811985	232.65871	10.872769	99.268386	17.38344	7.268667	3.634334	17.511557	15.493772	240	20/08/2012 16:41
46	164.385115	241.863282	10.961034	100.120228	17.38344	7.268667	3.634334	17.511557	15.493772	240	20/08/2012 16:41
47	154.860896	252.138728	10.907166	100.120228	17.38344	7.268667	3.634334	17.362565	15.493772	240	20/08/2012 16:41
48	148.435701	259.883045	10.896133	100.120228	17.38344	7.268667	3.634334	17.362565	15.461321	240	20/08/2012 16:41
49	139.106191	271.643129	10.922743	100.120228	17.38344	7.268667	3.634334	17.362565	15.526222	240	20/08/2012 16:41
50	132.989278	279.757405	10.892239	100.120228	17.38344	7.268667	3.634334	17.362565	15.526222	240	20/08/2012 16:41
51	124.811763	291.955613	10.92469	100.120228	17.38344	7.271127	3.635563	17.362565	15.493772	240	20/08/2012 16:41
52	119.58724	300.303566	10.863682	100.120228	17.38344	7.271127	3.635563	17.362565	15.526222	240	20/08/2012 16:41
53	pressure/kpa	volume/cm3	eng-feeding/v	eng-input pow-w/s	eng-output pow-w/s	gen-output/v	gen-output pow/w	efficiency%	temperature/c	rpm	date/time
54	87.509983	351.535546	10.826689	98.761382	16.944977	7.250317	3.625158	17.157492	15.493772	234	20/08/2012 16:42
55	87.509983	351.535546	10.826689	98.761382	16.944977	7.250317	3.625158	17.157492	15.493772	234	20/08/2012 16:42
56	88.418594	351.535546	10.954544	98.761382	16.944977	7.250317	3.625158	17.157492	15.526222	234	20/08/2012 16:42
57	89.148729	351.535546	10.972068	98.761382	16.944977	7.250317	3.625158	17.157492	15.526222	234	20/08/2012 16:42
58	90.868602	351.404118	10.872769	98.761382	16.944977	7.250317	3.625158	17.157492	15.526222	234	20/08/2012 16:42
59	93.205033	345.0518	10.881206	98.761382	16.944977	7.250317	3.625158	17.157492	15.526222	234	20/08/2012 16:42
60	95.184509	338.835788	10.967524	98.761382	16.944977	7.250317	3.625158	17.157492	15.493772	234	20/08/2012 16:42
61	98.883858	328.389799	10.856543	99.753016	16.944977	7.250317	3.625158	16.986932	15.493772	234	20/08/2012 16:42
62	101.966649	321.244097	10.981154	99.753016	16.944977	7.250317	3.625158	16.986932	15.526222	234	20/08/2012 16:42
63	107.077593	310.092351	10.920147	99.753016	16.944977	7.250317	3.625158	16.986932	15.493772	234	20/08/2012 16:42
64	111.150124	301.997497	10.994134	99.753016	16.944977	7.250317	3.625158	16.986932	15.526222	234	20/08/2012 16:42
65	117.964717	289.692177	10.974664	99.753016	16.944977	7.250979	3.62549	16.986932	15.558673	234	20/08/2012 16:42
66	125.996204	277.829838	11.010359	99.753016	16.944977	7.250979	3.62549	16.986932	15.526222	234	20/08/2012 16:42
67	129.095223	273.468475	10.952597	99.753016	16.944977	7.250979	3.62549	16.986932	15.493772	234	20/08/2012 16:42
68	142.51349	256.485474	10.998677	99.753016	16.944977	7.250979	3.62549	16.986932	15.526222	234	20/08/2012 16:42
69	147.153908	251.209021	10.925339	99.753016	16.944977	7.250979	3.62549	16.986932	15.493772	234	20/08/2012 16:42
70	157.018854	241.157484	10.907166	99.753016	16.944977	7.250979	3.62549	16.986932	15.526222	234	20/08/2012 16:42
71	163.703655	234.965937	10.883802	99.753016	16.944977	7.250979	3.62549	16.986932	15.526222	234	20/08/2012 16:42
72	173.276552	226.866308	10.868875	99.753016	16.944977	7.250979	3.62549	16.986932	15.558673	234	20/08/2012 16:42

Appendix9

STIRLING ENGINE BETA TYPE (READY STATE AT HAMK) IMAGE