Hydrogen Engine: Building an Air Flowmeter and Improving the Engine Control System

Bogdan Pavlov

Abstract in Czech

Hlavním cílem projektu bylo vyvinout systém na měření průtoku vzduchu vstupujícího do motoru, který byl poháněn vodíkem. Bylo zvoleno aplikovat princip clonového měřidla. Vedlejším cílem projektu bylo vylepení systému zapalování motoru, aby bylo možné měnit dobu kdy zapalování nastává. Práce na projektu se konala v laboratoři spalovacích motorů školy Union College ve státě New York, USA.

Abstract in English

The primary goal of the project was to develop and build an air flowmeter for an internal combustion engine that runs on hydrogen. The secondary goal was to improve the spark ignition control system to access variable spark timing. The project was conducted at Union College in Schenectady, NY, USA during the author's study abroad at this school.

1. Hydrogen Engine: Project Background

Alternative fuels are a hot topic in engineering research nowadays. There are many types of alternative fuels that have been developed or adopted for use in power generation: natural gas, ethanol, propane, biogas, methanol, several types of alternative diesel and some others. But none of them can fully replace traditional oil. Reasons may be different – some are limited in their availability or expensive to make, others produce too much pollution. Among new fuels hydrogen is one of the most promising. Product of hydrogen combustion is simply water vapor, so pollution is not a question for hydrogen (combustion in air might still produce some harmful nitrogen oxides but their amount is negligible). The biggest disadvantage of hydrogen is its producing which is expensive and might still cause some pollution.

Hydrogen Engine project at Union College is aimed to study hydrogen as a fuel for internal combustion engines. The project is oriented on the hydrogen combustion, specifically on its visualization inside the engine's cylinder. The reason is that there are still many questions on fuel combustion, while improving combustion can really make a difference in engine's performance. Moreover, combustion visualization itself allows making advanced and very exciting engineering research and studies, which is great for college engineering.

Laboratory and main research equipment, including the engine was established in Potter Lab at Union College, and several Mechanical Engineering students have been working on the project in the past years. This summer we were continuing the research by working on two subprojects. One was aimed on fixing a problem with spark ignition system and the other was building an air flow meter for the engine.

Figure 1. Internal Combustion Engines Lab Overview

2. Spark Ignition System: Overview

In spark ignition engines, air-fuel mixture is ignited by an electric spark. The spark is created by the spark ignition system of the engine and must be generated at a very exact crankshaft angular position (e.g. 350 degrees). The engine is very sensitive to the spark timing and might not work properly in case the spark does not occur at the right time. An overview of the whole engine's control and measurement system is depicted in fig.2.

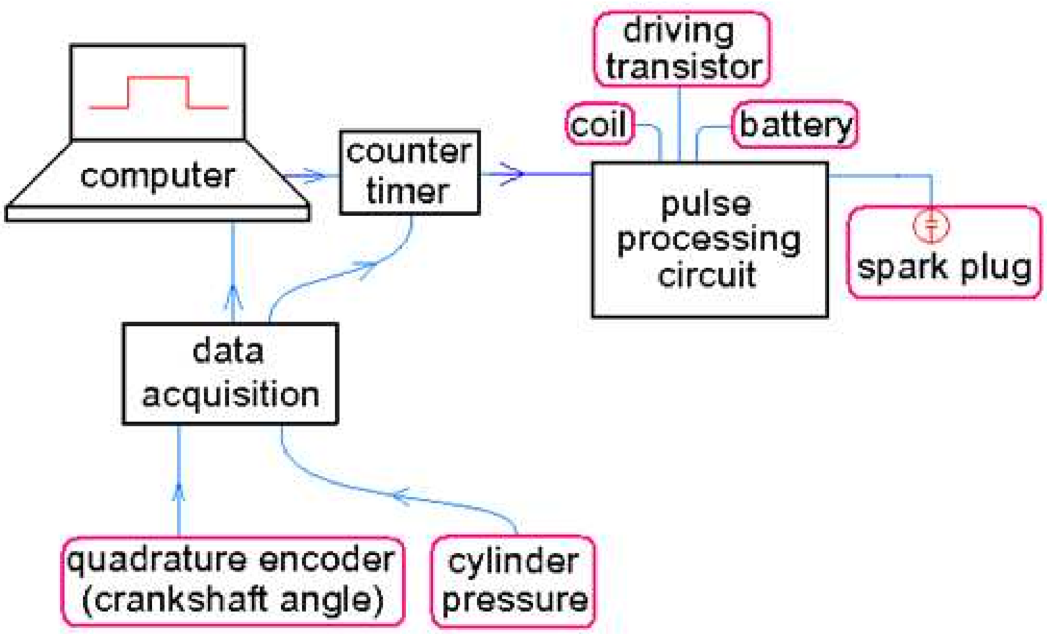

Figure 2. Spark Ignition System Overview

The general two components of the system were computer and electric circuitry. Computer included data acquisition hardware which consisted of two National Instruments PCI boards. One was Data Acquisition Board and the other was Counter Timer Board. Together with LabView program and these two boards, the computer was used to control the engine and perform measurements. The main components of the pulse processing circuit are coil, driving transistor battery and spark plug. Through the data acquisition, computer reads the crankshaft position (measured by quadrature encoder) and pressure in the cylinder (measured by a pressure transducer). When it is time to spark, the counter timer board sends a pulse to the pulse processing circuit, which then creates the spark. The pulse that computer created is a digital logics TTL signal, shown in fig.3.

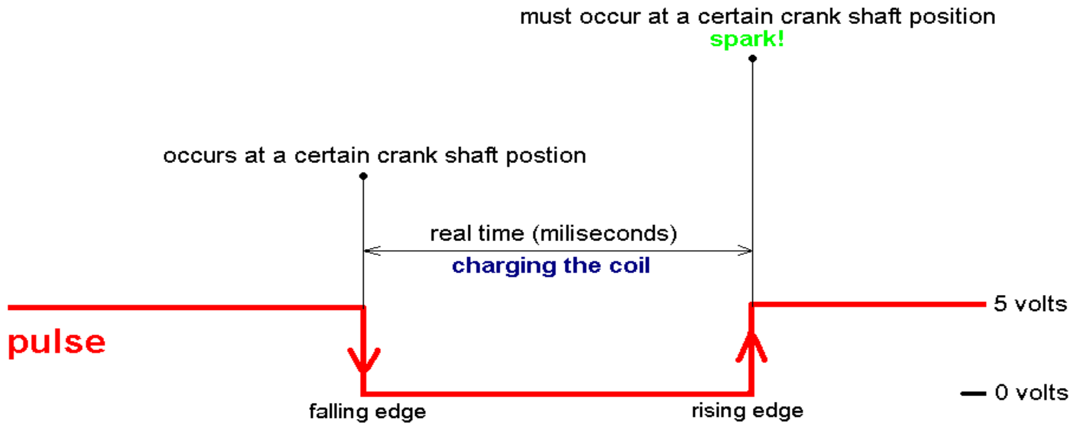

Figure 3. Initial TTL signal for the spark control

According to the fig.3, the pulse starts with the falling edge (falling from 5 to 0 Volts). Then it continues as “low”, which is 0 Volts, for a certain period in real time (e.g. 8 milliseconds). This period when signal is low is also called dwell time. After the dwell, the signal goes back to “high” at rising edge.

2.1 Spark Ignition System: Problem Description

It is important to understand, that in LabView program, controlling the ignition system, we could specify two pulse characteristic: angle, at which pulse starts (which is falling edge) and the dwell time. The pulse processing circuit is design the way that it charges the coil when the signal is low and then stops charging and sparks when the signal is high again (rising edge).
Such circumstances raise a problem. Since the dwell is independent of the crankshaft, the rising edge is not tied to the shaft position and hence, so isn’t the spark. The reason for this is that crankshaft will turn a different number of degrees during the dwell time dependently on its speed. *The conclusion is that since the circuit sparks at the rising edge, the spark event is not tied to the crankshaft position.*

2.2 Spark Ignition System: Goal

The engine used for research had a problem with the ignition system. Certain circuitry components have been changed while software equipment was not updated to follow these hardware changes. Our task was to redesign the system (both hardware and software) so that the spark happens at a certain crankshaft angular position. It should occur independently from the engine speed and we should be able to set whatever spark angle we want.

2.3 Spark Ignition System: Further Analysis and Solution

We had to design a system that would charge the coil shortly before it would generate the spark – precisely at a certain crankshaft angle. Normal charging time for coil should be about 4 - 5 milliseconds, although it may vary (from 4 to about 10 ms) without having a significant influence. However, if the time is too long, the coil heats up and may burn down.
The ideal ignition system would do the following: start charging the coil at a certain time, so that after e.g. 4 milliseconds the crankshaft reaches desired spark angle and the spark occurs.

The problem is that we do not know where the crankshaft will be in 4 ms (crankshaft speed may be quite unstable), so we do not know at which angle the dwell should be started.

In order to solve such a problem, we decided to sacrifice exact dwelling time for having exact sparking time. The idea is that we would create a signal, where both dwell start and spark event are tied to the crankshaft position. This way, the dwell length would depend on the engine speed. In order to ensure that the dwell time is right, we would calculate the angle, at which the dwell should start. Therefore, as the engine speed varies, the spark would still occur at the right time but the dwell time is what will change. As mentioned, the dwell time variation within certain limits is not critical.

In order to get the right type of signal, we had to combine two signals like the one in fig.3. The second signal was reversed, and by combining these two signals in a NAND gate we would get the right type of pulse (fig.5). Table 1 shows, how the NAND operation (which is inversed to AND) works.

Table 1. - Digital Logics NAND for signal combination

Signal 1	Signal 2	AND	NAND
low	high	low	high
high	high	high	low
high	low	low	high
low	low	low	high

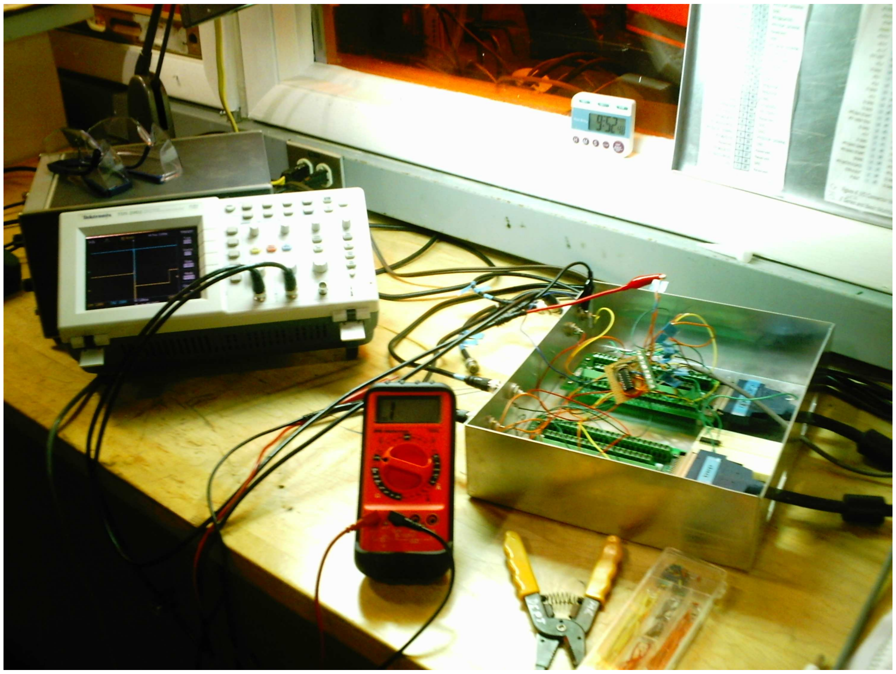

Figure 4. Output slots of the National Instruments computer boards

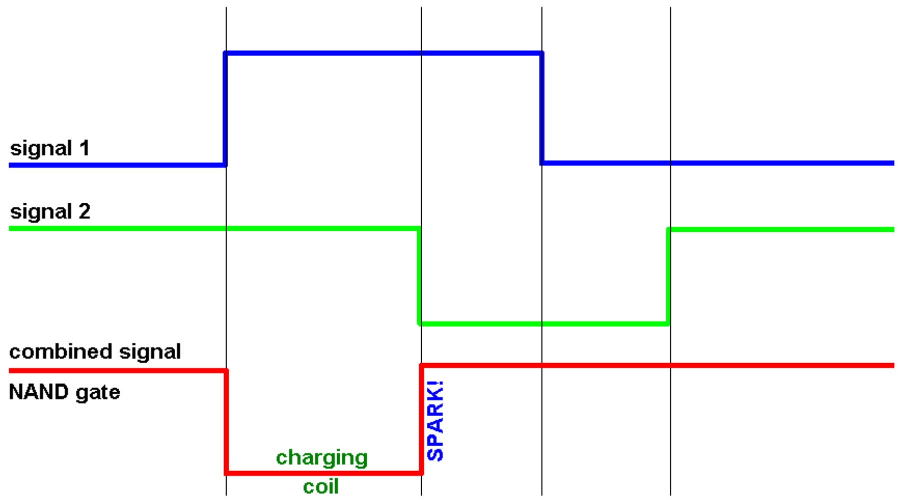

Figure 5. Improved TTL Signal for the Spark Control (combined two signals)

The computer, together with LabView program and counter timer board stands for a pulse generator that produces these two signals. As signal 1, we used our old spark signal. But in order to create one additional pulse (signal 2), we had to introduce certain changes in both the program and physical wiring on the counter timer board.

Also, we had to add one additional step – calculation of the desired dwell start. Earlier, input to the program was the spark angle (in degrees) only, while now the inputs are the spark angle, desired dwell length (in milliseconds) and expected engine speed (in rpm). From this input the new program will calculate the desired dwell start:

$$desired\ dwell\ start = spark\ angle - (expected\ engine\ speed) \times (dwell\ time)\ [Eq. 1]$$

Now, because the first edges of both signals 1 and 2 are tied to the crank angle, both falling and rising edges of the resulting signal are also tied to the crank angle (fig.5), which is what we sought to achieve. In order to combine the signals physically, we used a 7400 NAND gate chip. However, it brought some complications because the chip was dissipating some part of electric power of the signals, which caused a voltage to drop – instead of 5 Volts for "high" signal we had only about 2.4 Volts. This voltage was recognized by the pulse processing circuit as "low", and the circuit could not process the signal correctly. We made such a conclusion because the circuit did not create the spark if the "high" part of the signal was only 2.4 Volts. We tried different techniques to boost the voltage back to 5 Volts. Among them was a buffer chip and pull-up resistor. However, operational amplifier worked the best for some reason. We used a 741 operational amplifier and applied sp called amplifier follower scheme (fig.6).

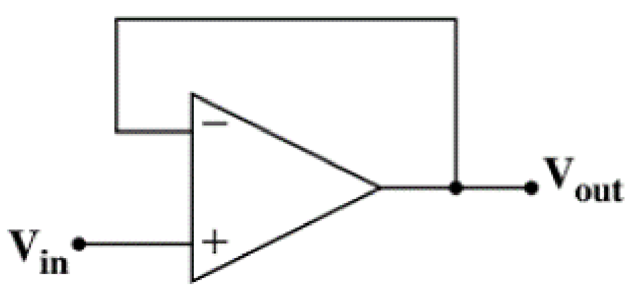

Figure 6. Amplifier follower scheme

This method really worked and it boosted the signal up to almost 5 Volts. Now everything seemed to be ready to work properly, but we still could not get the spark. After analyzing what might be going wrong we concluded that the reason lies in the driving transistor (ST Microelectronics model number VB921ZVFI) of the pulse processing circuit. The transistor used to get very hot during operation even though there was a locking system that would shut the transistor off if there is too much current going through. The way to check it would be getting a new transistor and seeing if the circuit works with a new one. At this point we had to close the project because we ran out of time. Results and Future work sections follow.

2.4 Spark Ignition System: Results and Future Work

We redesigned the system so that it creates the right signal, as shown in fig.5. The signal meets requirements that were put off and is capable of creating the spark at a certain crankshaft position. However, because of hardware problems we were not able to get to the sparking. The system does everything right besides the final step of actual sparking. The ultimate goal of this part of the research project was not accomplished, but the corner stone was laid down and the most demanding and time-consuming part of the work was done.
Future work should include trying out a new driving transistor and checking other components of the circuit (coil, resistors, optical insulator and wiring). The circuit logics might be reviewed as well (especially question on reversed logics). Also, it might be needed to measure current of the signal and check if it meets the driving transistor requirements. Finally, the spark ignition system should be able to create the spark at the right moment.

3. Air Flowmeter: Overview

In study of internal combustion engines it is useful to know how much air the engine consumes. This parameter characterizes the engine's intake system and is also important in studying combustion processes. For hydrogen engine project, which is aimed on studying hydrogen combustion it is very desirable to have an air flowmeter.

3.1 Air Flowmeter: Goal

The goal was to build a flowmeter that would measure airflow to the engine. The flowmeter should be able to do measurement for a desired engine speed: from 600 to 3000 rpm and both closed and open throttle.

3.2 Air Flowmeter: Further Analysis

In general, gas flowmeters are expensive to buy. It was the reason why we decided to build our own. When choosing a principle of the flowmeter, there are several concepts available. Among them we have chosen orifice flowmeter because it is relatively simple to build and also it is the most common in the engines application (is commonly used in research and industry). A concept of such a flowmeter is presented on fig.7.

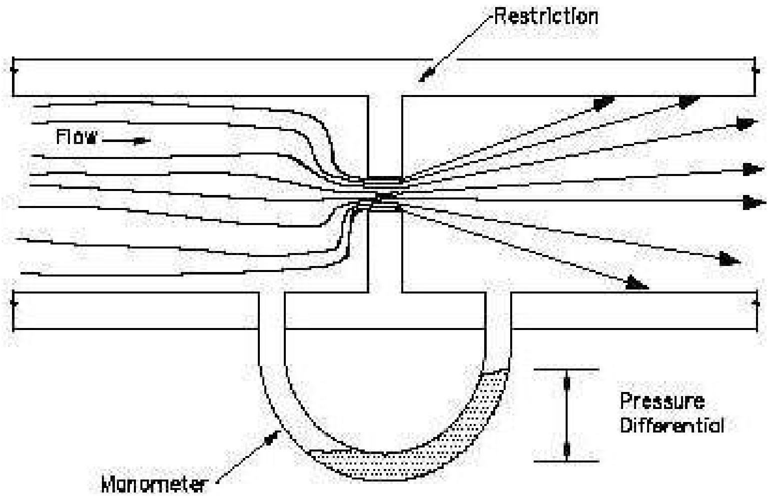

Figure 7. Orifice Flowmeter Principle

The idea is that a restriction in the flow causes pressure to drop – pressure of the flow before restriction is higher than after it. This pressure drop is proportional to flow rate – the higher is the flow rate, the higher will be the pressure drop. Thus, by measuring the pressure difference we can estimate the flow rate. In the orifice type of a flowmeter, the orifice plate, which is simply a plate with a round hole in it (there are certain requirements for geometry details of the plate), functions as a restriction in the flow. The diameter of the hole is the most important parameter and will be called orifice diameter in this paper. Orifice plate is only one of the components of the flowmeter system. The overview of the whole measuring system is shown in fig.8:

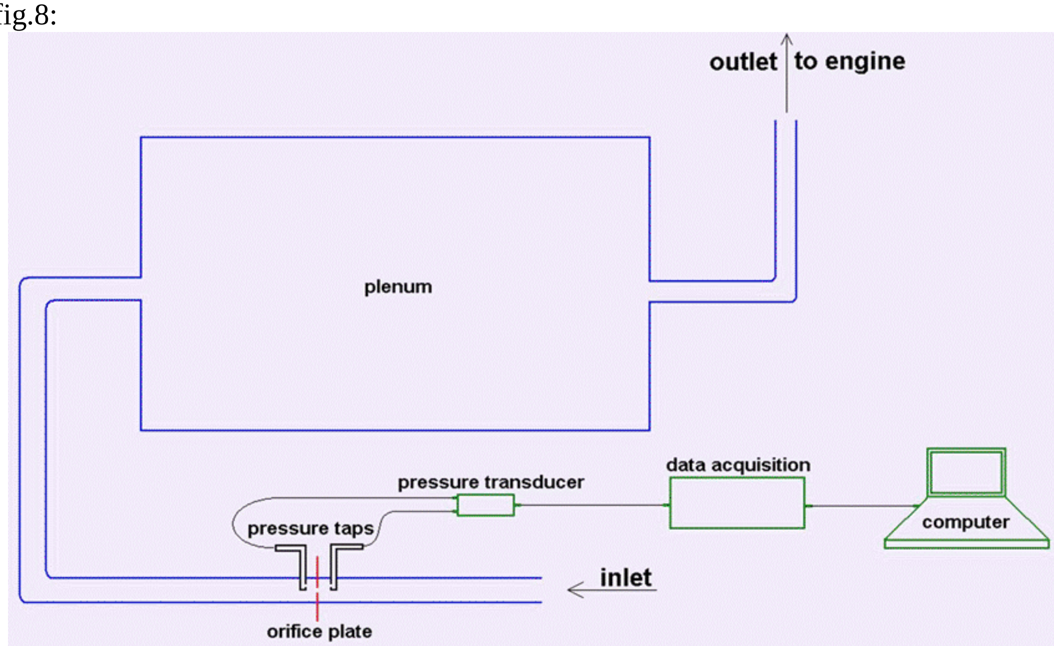

Figure 8. Flowmeter system

Inlet to the system is on the center bottom part of the picture. Air will enter this way and will flow through the orifice plate, where the pressure measurement will be performed with a differential pressure transducer. Then air will enter a big plenum, and only after that it will pass the engine's throttle and go to intake manifold.

The plenum is needed to damp out fluctuations in the flow because the orifice flowmeter requires steady flow to work properly. The fluctuations are present mostly because the engine draws air periodically, only during intake stroke, which is one out of four. If the plenum is big enough, the flow at the plenum's inlet (and hence at the orifice metering section) is steady even if the flow at the plenum's outlet is unsteady and pulsating due to the operating engine. Finally, the signal from the pressure transducer will be processed in a data acquisition system so that it can be further read and processed by a computer.

3.3 Air Flowmeter: Solution

As a guide for building the flowmeter, we used an ASME (American Society of Mechanical Engineers) standard ASME-14M-2003 "Measurement of Fluid Flow Using Small Bore Precision Orifice Meters". The standard gives directions on calculating geometry of the orifice plates and provides equations and directions for finding the flow rate. The design process was based on three variables:

Flow rate = f (orifice diameter, pressure drop) [Eq. 2]

In other word, if we want to design an orifice plate, we should know expected values of the flow rate and determine the pressure drop we want to be able to measure. The expected flow rate for a four-stroke engine can be calculated from equation below:

$$\dot{V} = \eta \frac{V_{cyl} \times n}{K \times 60} \quad \text{[Eq. 3]}$$

In Eq. 3, $\dot{V}$ is volumetric flow rate in m^3/sec, η is volumetric efficiency of the engine (for pre-calculations it was estimated to be 0.9), V_{cyl} is volume of the cylinder (449 cm^3), n is the engine speed in rpm and coefficient K is equal to 2 for a four-stroke engine. The constant 60 is present due to conversion from minutes into seconds.

So, this is volumetric flow rate through the intake manifold. The volumetric flow rate through the orifice might be different depending on the throttle's position. If the throttle is closed, pressure in the manifold will about 5 times lower than atmospheric (throttle behaves like a restriction in the flow – just as the orifice does). In this case, principle of mass conservation yields that the flow rate in the manifold will be 5 times faster than through the orifice. If the throttle is fully open, the manifold pressure and flow rate will be the same as at the orifice metering section.

As a pressure transducer, we chose to use the one that was already available at our department. It is Omega PX277-01D5V, whose range is (0 – 250) Pascals. Therefore, in order to obtain more accurate results, we have had to use most of the scale, so we decided to measure in the range of 150 Pa and more.

When we had to make calculations of the orifice diameter, we used a computer program ISO-5467-2003 version 6.5 by Vertical Market. The program sizes orifice plates for given conditions according to standard ISO 5467. The program can calculate one of the three parameters: orifice diameter, flow rate and pressure drop – if the two other are known. The calculation steps we performed were as follows:

1) For a certain orifice diameter and pressure drop (either 150, 200 or 250 Pa) we found the flow rate through the orifice plate (using the program).
2) For a given throttle position (either open or closed), we determined the value of the flow rate in the intake manifold

3) Knowing intake manifold flow rate, we calculated corresponding engine speed using eq. 3
4) If the engine speed was out of the range of interest (600 – 3000) rpm, we would continue changing the input conditions, which was a combination of the orifice diameter and pressure drop, until we achieved the desired speed range.

This way we were able to calculate the orifice diameters for the desired rpm range. The second part was doing actual mechanical design of the orifices and the whole measuring device. A model of an orifice plate and two flanges for its attachment is shown in fig.9. The principle of this concept is that the orifice is fixed between two flanges, and then the flanges are bolted together. The orifice has three holes for the mounting pins that ensure its co-axial fixation, and 6 holes for bolting the flanges. The flanges were machined out of PVC and glued to a PVC pipe, through which the air is running.

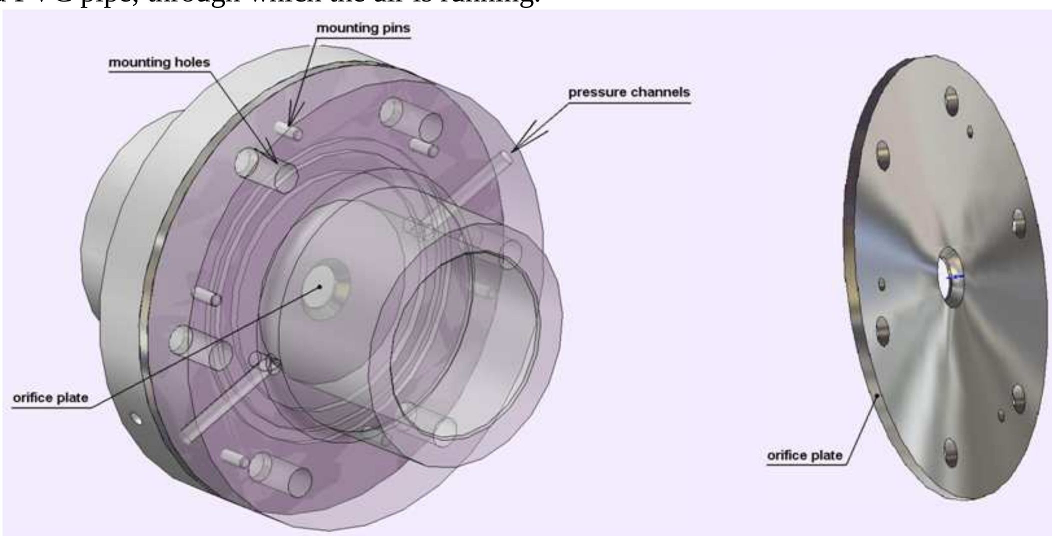

Figure 9. SolidWorks model of the flanges and orifice plate

Each flange had two channels for the pressure measurement that were connected to a pressure transducer by using pressure taps. On inner side of each plate there was an o-ring for sealing. Unlike the flanges, orifice plate was made from Aluminum to satisfy high accuracy and tolerances requirements of the ASME standard that we used. Detailed drawings of the plate and flanges are available at the Union College Machine Shop.
Then we had to design the rest of the system which includes the plenum, piping and connections. In case of the plenum, we had to calculate its desired volume. Eq. 4 is commonly used in this application:

$$V = \frac{417\times10^6\times K^2\times d^4}{V_{dis}\times n^2} \quad \text{[Eq. 4]}$$

In this equation, V is desired volume of the plenum, K is equal to 2 for four-stroke engine, d is the orifice diameter in meters, V_{dis} is displaced volume of the cylinder and n is the engine speed in rpm. From this equation it is evident, that a larger plenum is needed for a lower engine speed and simultaneously a bigger orifice diameter. For our application, the minimum volume of the plenum turned out to be about 0.6 m^3. We decided to compose the plenum from three 54-gallon plastic barrels.

3.4 Air Flowmeter: Results

We designed and built whole metering section, which includes assembly of two flanges with pipes and one orifice plate (like the one in fig.7, plus each flange was also epoxied to a 3-foot PVC pipe). We manufactured only one orifice plate to test the system. If it works successfully the rest of the plates will be machined as well. We dimensioned 19 orifice plates to cover the desired engine speed for both closed and open throttle (refer to figures and tables in the attachment).

Figure 10. Manufactured orifice plate with a flange, PVC tube and a pressure tap attached to it

Figure 11. Manufactured barrel with inlet and outlet flanges

3.5 Air Flowmeter: Future Work

Future work will include designing and establishing all needed piping in the lab (plenum was adopted to be attached to lab's ceiling). Pressure transducer tubes will have to be connected to the flanges and then a signal line between transducer, data acquisition and computer will have to be established.

4. Conclusion

The primary goal of the project was achieved. The flowmeter system was built, although certain additional tasks (piping and setting up pressure transducer readings) had to be performed in order in order to start measurement. Designing a flowmeter was an invaluable research experience in general, and in Fluid Mechanics discipline particularly. The theory was combined with a practical need to actually build the device, and this combination was well presented in the ASME standard that was used to guide the design process. Work with the standard was also a valuable practical experience (since standards are widely used in industry and research).

The secondary goal of the project, which concerned the spark ignition system, was worked out to almost the end. Certain procedures were needed to be performed to finalize the work done. Working on this goal has especially contributed to our knowledge of digital logics. Important experience was obtained in the field of programming data acquisition and device controlling with LabView.

Generally, as for a junior undergraduate student, such research work was extremely important and valuable for his future engineering studies.

List of used symbols

$\dot{V}$	volumetric flow rate	[m^3/sec]
η	volumetric efficiency of the engine	[1]
V_{cyl}	volume of the cylinder (the same as displaced volume)	[m^3]
n	engine speed	[rpm]
K	coefficient, equal to 2 for a four-stroke engine (equals to 1 for two-stroke)	[1]
V	volume of the plenum	[m^3]
V_{dis}	displaced volume of the cylinder	[m^3]
d	orifice diameter	[m]

References

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[2] Dubbel, H., Kuttner, K., H., Beitz, W., “Handbook of Mechanical Engineering”, Springer-Verlag Telos, 1994

[3] Cengel, Y., A., Cimbala, J., M., “Fluid Mechanics: Fundamentals and Applications”, McGraw Hill, 2006

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ATTACHMENT

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1. Comments to the tables and figures in this attachment

Each plate in tables 2 and 3 has its number (1 through 19). Since the pressure transducer that we have is capable of measuring up to 250 Pa, we designed the plates for a range of 150-250 Pa. We calculated expected flow rate through the orifice for pressure drops 150, 200 and 250 Pa. Knowing whether the throttle is open or close, we calculated corresponding flow rate in the manifold (for open throttle it is the same as through the orifice and for closed it is 5 times lower). And finally, knowing the manifold flow rate we can calculate engine speed from eq. 1 in the paper. Figure 1 shows graphically the plate diameters and corresponding engine speeds (each vertical line represents one orifice plate and the length of the line is the speed range).

Table 1. - Parts that were bought for building the flowmeter

Part	Manufacturer/Seller	Part number	Price ($)
O-ring	McMaster	4464T218	11.40
Plastic welding rod	McMaster	7889A36	7.74
Ultra-Elastic Clear Gel Rubber	McMaster	1782T36	10.39
2 Cable Connectors for Encoder	US Digital	CA-FC5-SH-NC	39.59
5” PVC rod	McMaster	8745K67	59.21
12x24 6061 Aluminum sheet	McMaster	1655T32	97.88
		TOTAL	**226.21**

Table 2. - Orifice Plates Specifications for Closed Throttle

Flow rate through orifice (Sm^3/hr)	Flow rate in manifold (m^3/hr)	RPM	Press Drop (Pa)	Orifice diameter (inches)	Orifice number
1,4	7,0	577	150	9/32	1
1,6	8,0	660	200	9/32	
1,8	9,0	742	250	9/32	
1,6	8,0	660	150	19/64	2
1,8	9,0	742	200	19/64	
2,0	10,0	825	250	19/64	
1,9	9,5	784	150	21/64	3
2,2	11,0	907	200	21/64	
2,4	12,0	990	250	21/64	
2,1	10,5	866	150	11/32	4
2,4	12,0	990	200	11/32	
2,7	13,5	1114	250	11/32	
2,5	12,5	1031	150	3/8	5
2,8	14,0	1155	200	3/8	
3,2	16,0	1320	250	3/8	
2,9	14,5	1196	150	13/32	6
3,3	16,5	1361	200	13/32	
3,7	18,5	1526	250	13/32	
3,4	17,0	1402	150	7/16	7
3,9	19,5	1609	200	7/16	
4,3	21,5	1774	250	7/16	
4,1	20,5	1691	150	31/64	8
4,8	24,0	1980	200	31/64	
5,3	26,5	2186	250	31/64	
5,0	25,0	2062	150	17/32	9
5,7	28,5	2351	200	17/32	
6,4	32,0	2640	250	17/32	
5,9	29,5	2433	150	37/64	10
6,8	34,0	2805	200	37/64	
7,6	38,0	3135	250	37/64	

Table 3. - Orifice Plates Specifications for Wide Open Throttle

Flow rate through orifice (Sm^3/hr)	Flow rate in manifold (m^3/hr)	RPM	Press Drop (Pa)	Orifice diameter (inches)	Orifice number
7,3	7,3	602	150	41/64	11
8,4	8,4	693	200	41/64	
9,4	9,4	775	250	41/64	
8,5	8,5	701	150	11/16	12
9,8	9,8	808	200	11/16	
10,9	10,9	899	250	11/16	
10,2	9,8	808	150	3/4	13
11,8	11,8	973	200	3/4	
13,1	13,1	1081	250	3/4	
12,2	12,2	1006	150	13/16	14
14,0	14,0	1155	200	13/16	
15,6	15,6	1287	250	13/16	
14,4	14,4	1188	150	7/8	15
16,6	16,6	1369	200	7/8	
18,5	18,5	1526	250	7/8	
17,6	17,6	1452	150	61/64	16
20,2	20,2	1666	200	61/64	
22,6	22,6	1864	250	61/64	
21,4	21,4	1765	150	1--1/32	17
24,6	24,6	2029	200	1--1/32	
27,4	27,4	2260	250	1--1/32	
25,9	25,9	2136	150	1--7/64	18
29,8	29,8	2458	200	1--7/64	
33,2	33,2	2739	250	1--7/64	
31,5	31,5	2598	150	1--3/16	19
36,2	36,2	2986	200	1--3/16	
40,3	40,3	3324	250	1--3/16	

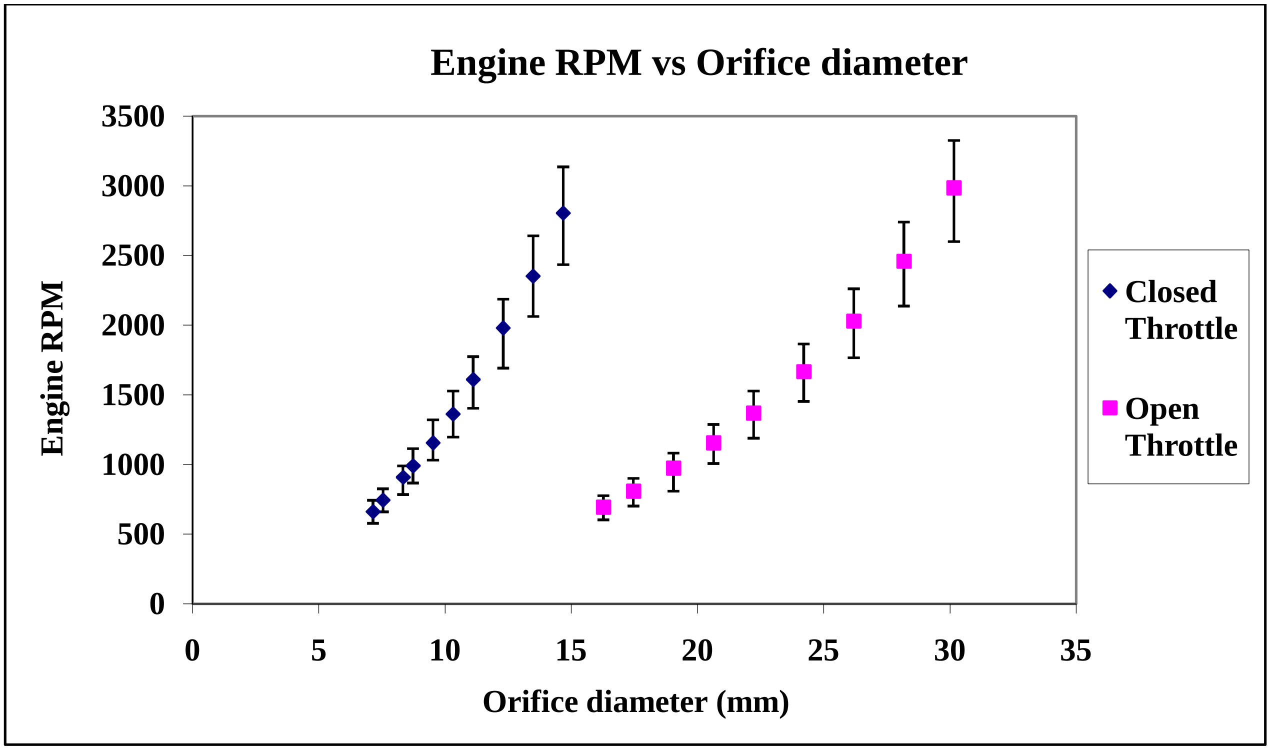

Fig. 1. Engine Speed vs. Orifice Diameter