

Development of Acoustic Sensor for

Flow rate monitoring

by

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## ABSTRACT

The project is mainly aimed at detecting the gas flow rate in Biosensors and medical health applications by means of an acoustic method using whistle based device. Considering the challenges involved in maintaining particular flow rate and back pressure for detecting certain analytes in breath analysis the proposed system along with a cell phone provides a suitable way to maintain the flow rate without any additional battery driven device.

To achieve this, a system-level approach is implemented which involves development of a closed end whistle which is placed inside a tightly fitted constant back pressure tube. By means of experimentation pressure vs. flowrate curve is initially obtained and used for the development of the particular whistle. Finally, by means of an FFT code in a cell phone the flow rate vs. frequency characteristic curve is obtained. When a person respire through the device a whistle sound is generated which is captured by the cellphone microphone and a FFT analysis is performed to determine the frequency and hence the flow rate from the characteristic curve. This approach can be used to detect flow rate as low as low as 1L/min. The concept has been applied for the first time in this work to the development and optimization of a breath analyzer.

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## Chapter-1

### INTRODUCTION

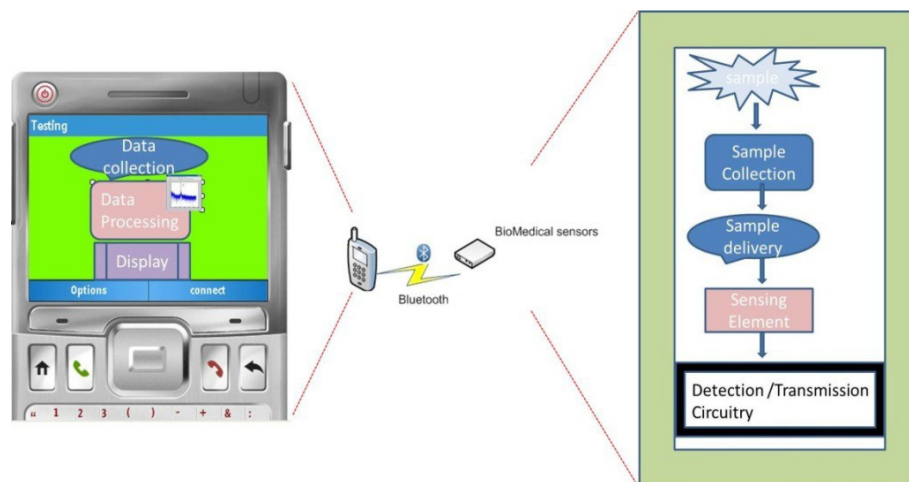
#### A. Mobile Health and Breath Analysis

Breath analysis acts as a non-invasive method of detecting analytical biomarkers. It has been identified that a normal human breath contains a lot of volatile organic compounds as well as compounds produced as a result of normal human activity [1]. Human breath contains more than 1000 compounds at different concentration levels and some of them include volatile organic compounds [1-5]. Among these different compounds, some of them have been identified as biomarkers for certain diseases and physiological disorders. For example nitric oxide has been determined as a biomarker for asthma, acetone has been identified as a biomarker for diabetes, and ethane has a biomarker for vitamin E Deficiency in children's and so on [1,10]. Periodic detection of these biomarkers can be very useful in diagnosing as well as preventing many diseases.

Also in many cases, a single analyte can be the biomarker of many diseases for example NO can act as a biomarker for asthma, bronchiectasis, and rhinitis. [6-9] Since the device has to specifically identify the required analyte from a large number of molecules selectivity and sensitivity play an important role in most of the breath analyzers [1]. Some of the conventional method which were initially employed to breath analysis include Gas Chromatography- Mass Spectrometry which had a great selectivity [11-12]. But the major drawbacks with those devices are their bulkier size and the complexity in sample collection unit [13-15]. Also since most of these devices are expensive that a general public cannot afford, they

were mostly limited to laboratory testing purposes only. Hence the need for portable miniaturized health monitoring sensors which can detect specific biomarkers is evident. Also with the advancements in mobile phone technology as well as its usage enabled these miniaturized sensors to be integrated along with them to form mobile health device [17-19].

M-Health devices play an important part in our lives for monitoring health related problems as discussed earlier, thereby easily helping doctors in diagnosing them. Also most of the m-Health application comes along with some automated feedback for management of the person's health condition. Nowadays the conventional health monitoring devices are more or less replaced by Mobile health devices mainly due to its portability. The usage of cellphone has become common among general public [18]. The solutions that are provided m- Health devices can be availed anywhere and the data can be sent to the hospitals for regular checkups. This in turn reduces the need of the person to visit hospitals frequently. Regular backups of data can also be recorded [21-24].



*Figure1 Process Flow in m-Health Device*

## *B. Motivation*

Biosensors are sensors that are used to measure and track human activities such as blood pressure, Lung Capacity, brain waves etc. [25]. Among all these flow rate is an important parameter in health related applications. As discussed earlier, controlled sample collection is an essential parameter for effectively detecting certain analytes in breath analysis [26, 27]. This need motivated this thesis work in order to find a cost effective mechanism to control the flowrate at which the person blows into a breath analyzer, a whistle based acoustic flowmeter has been developed. The closed end whistle in a constant back pressure tube along with the cell phone can provide a regulated sample to the sensing unit.

In addition to flowrate, lung capacity is an important parameter that is normally measured while a respiratory activity of a person is monitored for sleep related studies. The airflow rate measurement is one of the most common and accurate methods of measuring the lung capacity [28-30]. By this method the flowrate is initially obtained and integrated in order to obtain the lung volume. Health checkups done for any sports person requires determination of lung capacity for detection of any respiratory and lung related issues. Although spirometers are more effective in determining the lung capacity [30]. The proposed system provides a cost effective way of determining the lung capacity with the help of mobile phone which is in constant usage under general public. For instance Most sportsperson check their lung capacity regularly to determine their level of stamina and this device can be used in any place including rural

areas having a very minimal amount of hospital facilities. This also helps the sportsmen to record the data at regular interval enabling him to increase his stamina and avoid any health problems [31].

### C. Organization of the Report

The next chapter begins with a brief background description of the importance of flow rate detection in medical application and the various methods that are practiced now. This is followed by a discussion of the methodology used in the development of a whistle sensor system which is the focus of this work. Once a basic theoretical foundation has been established, experimental results are presented along with a critique of sensor performance and analytical characterization. The final chapters present the author's conclusions and the possibility of future work.

## Chapter-2

### BACKGROUND

#### *A. Importance of Flow rate in Medical Application*

Flow rate has been an important parameter that has been detected in day to day life across various fields such as automotive, chemical, biomedical and almost all forms of engineering. Considering the healthcare field, in which we are very much interested in, flowmeter often provide a helping hand as a diagnosing tool for early detection of many diseases as well as a tool used for monitoring the amount of medication given to people [35]. For example Blood flowrate is an indicator of blood pressure and one of the most important parameter that is measured while treating chronic diseases [34]. Different types of blood flowmeters are available based on different principles some of which will be discussed in the upcoming pages.

In the case of Oxycom, a device mainly employed for measuring resting energy expenditure based on the oxygen expenditure, optical based turbine flow meter is employed in order to determine the rate of volume of oxygen consumed and carbondioxide produced per minute [36].

$$\text{REE (Kcal/day)} = f(V_E) \dots \dots \dots (1)$$

Where;  $V_E$  is the exhaled volume in ml/min

$f$  is a function that relates to consumed oxygen and produced carbondioxide

REE is resting energy expenditure in KCal/day [37, 38]

Similarly peak flowmeter is a device which is mainly employed for detecting the severity of asthma at early stages itself [32]. Peak flowmeter is basically a handheld device used to determine the rate at which air is expelled from the lungs. Peak flowrate is a measure of severity of asthma and it can be used to provide medications in order to treat asthma [32]. Also spirometer is a device which enables us to measure the rate at which the air is expelled from the lung as well as lung capacity. These devices are of great help in order to keep track of the severity of asthma as well as other respiratory ailments [33, 40].

From the breath analysis field point of view, flowsensor have been employed in order to get controlled sample collection which is an important aspect for the sensitivity of the device [26, 27].

### *B. Current Methods*

The different methods by which the flowrate of any fluid is normally determined are differential pressure types which include orifice plate, venturi tube, flow nozzle and variable area flowmeter [39]. These devices work on the principle of Bernoulli's Equation, where the flow is calculated by means of measuring the pressure drop by introducing obstruction in the flow, and here the pressure drop is a function of the fluid flow velocity. Some of the spirometers

employ these differential pressure flowmeter to determine the flowrate and hence the lung capacity [40].



*Figure 2 Differential Pressure Type Spirometer [40]*

There are other types of flowmeter which calculate the speed at one or more points by using an ultrasonic probe and calculate the speed of flow by integrating it over the flow area. These types of flowmeters are called velocity flowmeter [39]. There are also cases where the flowrate is determined by measuring the rate at which turbine blades rotate due to fluid flow. The rate of rotation of the blade can be determined either by optical or magnetic methods [41]. These kinds of flowrate detection sensors are called Turbine flow meter and they are mainly employed in obtaining the flowrate in devices which are used for measuring the resting energy expenditure from the amount of oxygen consumed and carbon dioxide exhaled. [37, 38]



*Figure 3: Turbine flow meter employed in Oxycom (Center for Biosensors and Bioelectronics ASU)*

#### Flowmeter based on Ultrasonic Doppler Effect

Ultrasonic blood Doppler blood flow sensors are commonly employed for the detection of blood flowrate in human beings, Since we know that the heart pumps the blood into aeries and veins in accordance with the heart rate The blood flowmeter consists of an ultrasonic transmitter and receiver attached to a single probe [42]. A known frequency ultrasonic wave is generated by the ultrasonic transmitter which gets reflected by the blood tissue cells. The reflected



signal is received by an ultrasonic receiver which is manipulated in order to obtain the change in frequency as a measurement of the blood flowrate. The frequency of the transmitted beam is affected by the movement of blood in the vessel and by comparing the frequency of the upstream beam versus downstream the flow of blood through the vessel can be measured. The difference between the two frequencies is a measure of true volume flow [42, 34].

#### MEMS based Piezoelectric Respiratory Flow Sensor

With advancement in science MEMS and technology researchers have developed based piezoelectric sensor for respiratory air flow measurement. With advancement in CMOS technologies, a flow sensor, ie a miniaturized cantilever beam, is integrated in a chip along with its post processing circuit in a chip [30]. When the sensor is placed in the passage of the air flow based on the fluid flow velocity the cantilever beam gets deformed and hence by means of piezoelectric effect the flow rate is determined.

The flowsensor that is being proposed here is an acoustic sensor. The sensor consists of a closed end whistle which is placed inside a constant back pressure tube. During the fluid flow a change in flowrate causes a change in the frequency of the sound produced by the whistle thereby the flowrate is measured by means of the frequency of the sound produced [30].

#### *C. Whistle as Sensors*

Until now we would have heard about whistle as a device which produces sound when air is forced through it [43]. Though whistle had many

applications , the first thing which comes to our mind is the whistle which is commonly used by policemen. Apart from that they are used in toys, siren, boats, trains, and other military applications. Often the whistle has been thought of as a sign of emergency or for entertainment purposes. Usage of it as a sensor has been done only by very few.

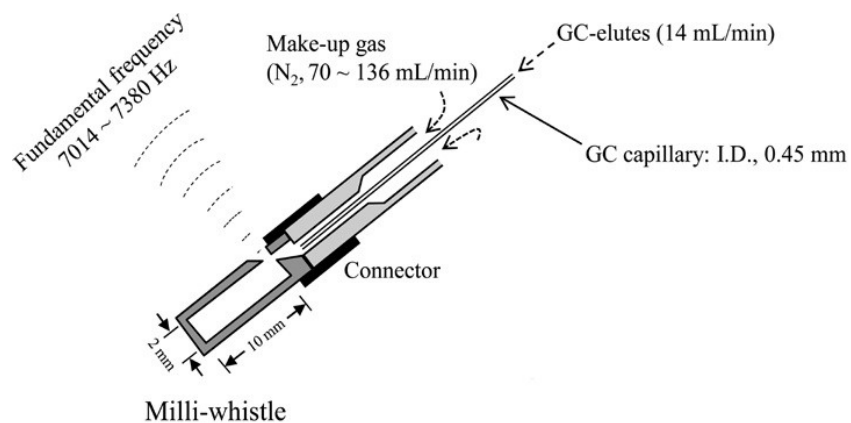
One such application where a whistle is used as a sensor is acoustic flute web edge sensor [44]. The main application of this sensor is detection of product edges (edge sensing) in a manufacturing environment. The sensor consists of an acoustic flute or resonator in the form of a pipe which is attached to the main body of the material handling equipment. In order to determine the edge of the web which moves along the surface of the body, the acoustic pipe is provided with an opening which is partially covered by edge of the object as a function of the position of the edge of the object. When an air column is caused to resonate the resulting acoustic signal has a frequency spectrum corresponding to the location of the edge of the web. A change in the location of the web hence causes a change in the acoustic signal [44].

Other applications are the usage of whistle as an acoustic transducer for nuclear reactor monitoring. Here the whistle is mainly used to monitor the temperature of the coolant, ie based on the temperature of the coolant, a temperature sensitive material changes the length of the resonating material hence providing a change in the narrow band of the whistle sound produced. The acoustic signal is picked up and transmitted to a remote location thereby enabling remote monitoring of nuclear power plants [45].

## Application in Medical Field

Considering the medical field whistle has been employed in a peak flowmeter called the whistle watch [45] which is an instrument used for the early detection of asthma among young children. Peak Flow meters normally determine the peak flow rate i.e. the maximum rate at which air can expelled from the lungs. The peak flow rate is a measure of severity of asthma and also in some case it helps us to determine the status of the lungs. This whistle based peak flowmeter once set by the physicians to the set limit according to each patient will produce a sound once that volume is reached [31, 32, and 46].

In the case of gas detection, a milli whistle developed using brass material is used as a detection mechanism in Gas Chromatography [46]. In this device the pressurized fluid and the makeup gases are passed by means of capillary tube produces a sound and the sound is recorded by means of a microphone and a FFT algorithm is applied on it [46].



*Figure 4 Milli Whistle used in Gas Chromatography Detection [46]*

Based on the frequency shift the amount of analytes ie. GC elutes can be easily determined. The device was placed inside a sound insulation chamber along with the temperature sensor. The Frequency of the sound produced changes when the amount of the gas mixture or the temperature or the amounts of analytes change [46].

## Chapter-3

### METHODOLOGY

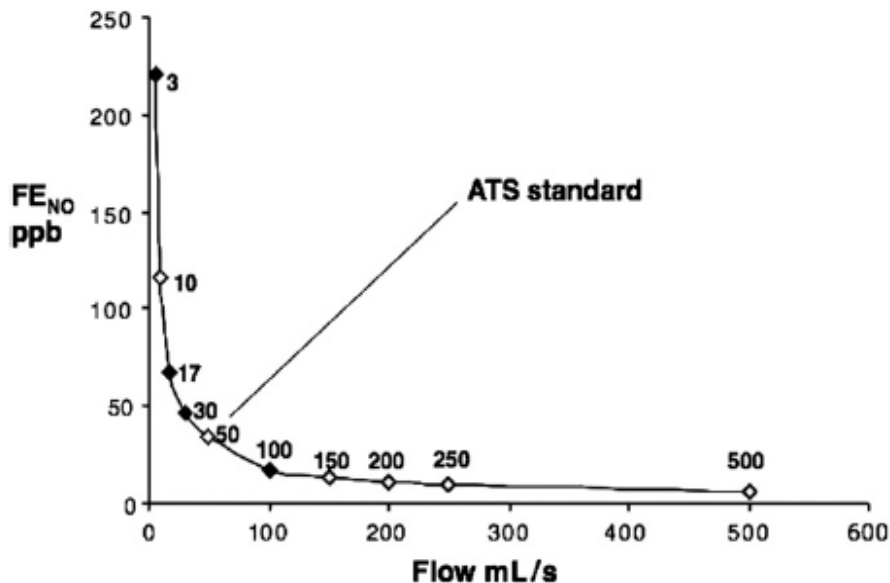
The accuracy and reproducibility of majority of the device used for breath analysis and m-health devices are influenced by a lot of different parameters some of which are flow rate and relative humidity. Hence a controlled sample collection is essential for accurate detection [48, 49].

#### *A. Flow Controlled Sample Collection*

A controlled flowrate is essential for measuring certain components during breath analysis in order to measure the components originating from the lower respiratory tract in opposition to the gases from the upper respiratory tract. For example in the case of measurement of NO<sub>x</sub> from the lower respiratory tract a desired flow rate has to be maintained in order to avoid the air from the nasal cavity, having a higher concentration of NO<sub>x</sub>, to get mixed with the intended sample . Also flow rate has a great impact on the duration of time the sampled gas stays in the respiratory tract hence affecting the concentrations of the analytes to be measured [48]. Since different people breathe at different flow rates maintaining a controlled flow rate provides us a unique consistent method for the detection of the desired analyte in the human breath.

The relationship between exhaled flow rate and the detection of nitric oxide on the other hand has been studied extensively and is well known [49]. As mentioned earlier a standard has been set for the exhaled flow rate when detecting nitric oxide in a human breath sample by the American Thoracic and European

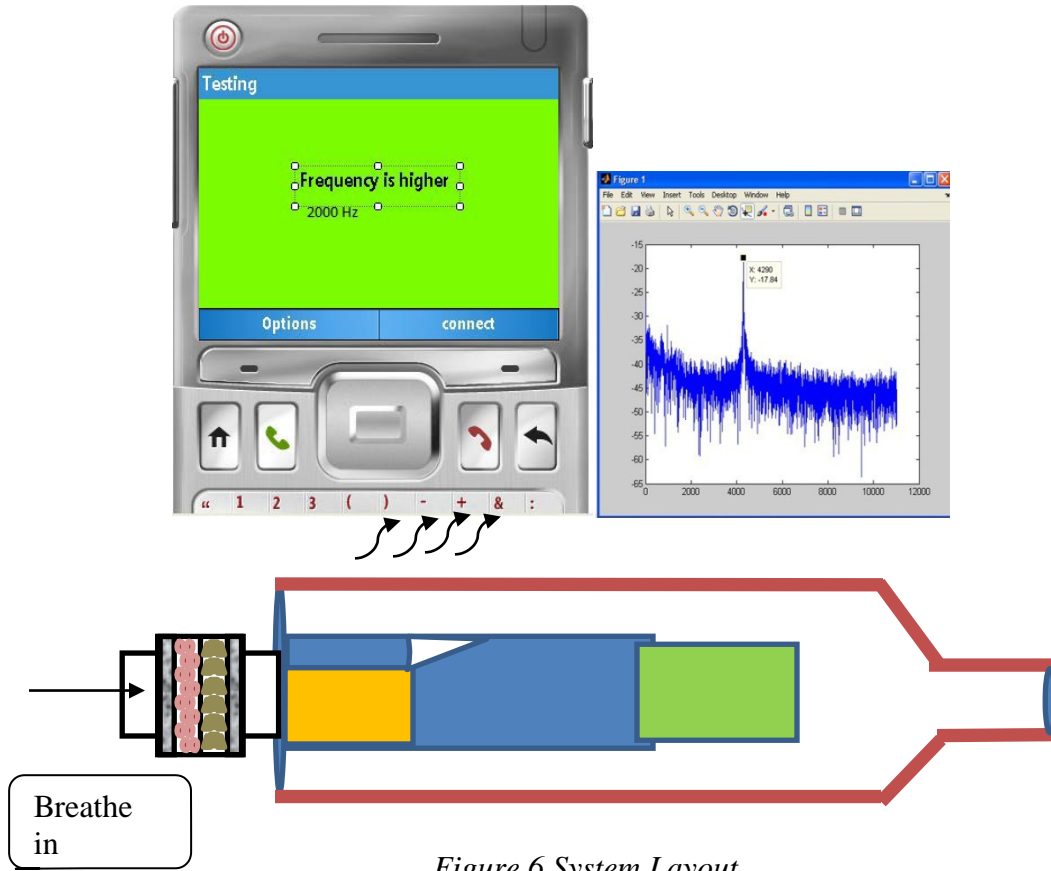
respiratory Societies (ATS/ERS) of 50ml/s [49]. As far as nitric oxide detection in the human lungs is concerned, backpressure is also a critical parameter to control. The ATS/ERS requirements for backpressure when measuring nitric oxide are set as an upper and lower limit. The upper pressure limit is 20 cm H<sub>2</sub>O and is set in order for patients to comfortably provide a sample. The lower pressure limit is 5 cm H<sub>2</sub>O which is necessary for velum closure to avoid contamination of the sample with nasal NO which has been shown to measure in concentration an order of magnitude higher than that of alveolar NO [49]. *Figure 5* below displays the relationship between exhaled NO levels and flow rate in ml/s. From this plot, we can see that a low flow rate and resulting low back pressure does not allow the velum to close properly and hence the values of FE<sub>NO</sub>ppb are very high due to the contamination of NO from the nasal cavity [48, 49].



*Figure 5. Plot displaying multiple subjects measured breath NO (ppb) vs. flow (ml/s)*

### *B. System Layout & Detection*

The project is mainly aimed at detecting the flow rate in biosensors and medical health applications by means of an acoustic method using whistle based device. Considering the challenges involved in maintaining particular flow rate and backpressure for detecting certain analytes the proposed system along with a cell phone provides a suitable way to maintain the flow rate without any additional battery driven device. To achieve this, a system-level approach is implemented which involves development of a closed end whistle which is placed inside a tightly fitted constant backpressure tube. By means of experimentation, pressure vs. flow rate curve is initially obtained and used for the development of the particular whistle. Finally, by means of an FFT code in a cell phone, the flow rate vs. frequency characteristic curve is obtained. When a person respire through the device, a whistle sound is generated which is captured by the cellphone microphone and a FFT analysis is performed to determine the frequency and hence the flow rate from the characteristic curve. This approach can be used to detect flow rate as low as 1L/min. A similar concept has been applied and successfully proven to work in commercial sensors and in design of sensors for breath analysis [47].



*Figure 6 System Layout*

Fig. 6 shows setup for detection of flow rate. The major component in the entire setup is the closed ended whistle which is placed inside a constant back pressure tube. The whistle which is employed here is a closed end type which consists of an acrylic plastic tube with an outlet plug and an inlet plug made of the same material. The whistle is provided with a small aperture at its opening mainly to increase the velocity of the air that is passed through it. When a person blows through the acoustic sensor the smooth flow of air is split by means of a free flowing flap which causes the air to vibrate thereby causing the remaining portion of the acrylic tube to oscillate. The microphone in the cellphone records the sound



produced which is then manipulated by the FFT algorithm to obtain the frequency. With the help of the flow rate vs. frequency calibration curve the flow rate corresponding to the frequency is thus obtained.

Some of the various parameters that affect the resonant frequency, loudness of the sound produced and the sensitive frequency range of the whistle are the length of the resonating medium, size and position of the inlet blocker and the size of the flap which splits the air that enters through the whistle.

### *C. Flow rate vs. Frequency Calibration Methodology*

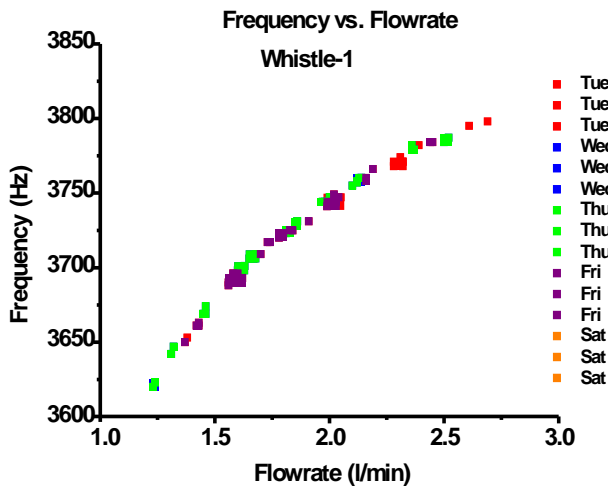
#### *Experimental Setup for Flow rate vs. Frequency Calibration Curve*

Controlling flow rate can be accomplished using a variety of methods. Different parameters can be measured to attain the same effect, which is measuring and controlling flow rate. One method for measuring the flow rate is to measure the frequency of the sound produced by the whistle as a function of the rate at which person blows through the whistle. In order to estimate the flow rate from the frequency of the sound, a flow rate vs. frequency curve was obtained for the developed whistle. This method consisted of a pressure controlled ultra-zero air cylinders, which was then connected to a water bath maintained at 37deg C, in order to simulate the human breath condition. The simulated breath was then passed through the whistle. The outlet of the whistle was connected to a flow meter. The frequency corresponding to the particular flow rate was obtained by recording the whistle sound using a cell phone and applying FFT algorithm on it. By adjusting the gas cylinder pressure the flow rate is varied, thus measuring the

frequency corresponding to each flow rate. *Figure 7* below helps to depict the method of flow rate measurement discussed.



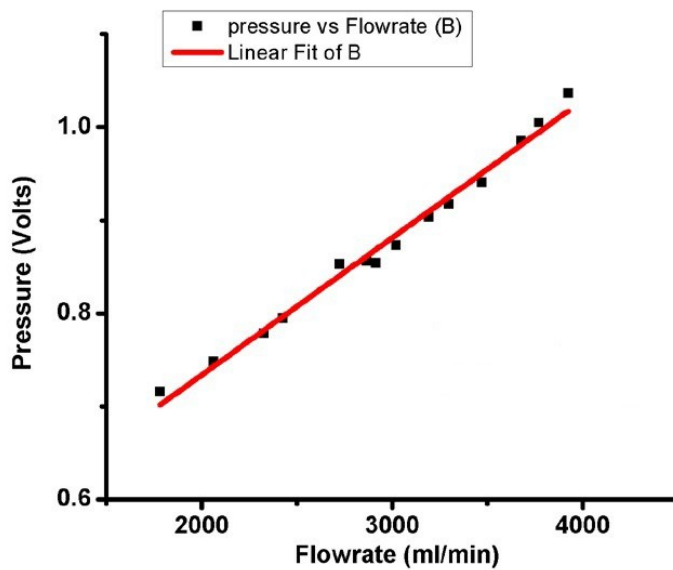
*Figure 7. Flow rate vs. Frequency Calibration Curve measurement.*



*Figure 8 Calibration curve Flow rate (l/min) vs. Frequency (Hz)*

Figure 8 shows the calibration curve obtained for the whistle

Another method utilized to measure flow rate is by measuring pressure and from pressure calculating the flow rate value. Utilizing Bernoulli's equation, a relationship between pressure and flow rate can be constructed. From this relationship pressure values can be paired with their corresponding flow rate values, therefore when pressure is measured the flow rate can be determined.



*Figure 9. Flow rate (ml/min) vs. Pressure curve &*

A pressure and flow rate relationship can still be built experimentally. Via measuring a number of pressure and flow rate values through the desired sections

of a device, a calibration plot for pressure vs. flow rate can be constructed. From this calibration plot a calibration curve can be determined. Using the calibration curve with a measured pressure value as an input, the flow rate can be calculated. This experimental method to finding a pressure vs. flow rate relationship is often used in place of the simulation method due to simplicity.

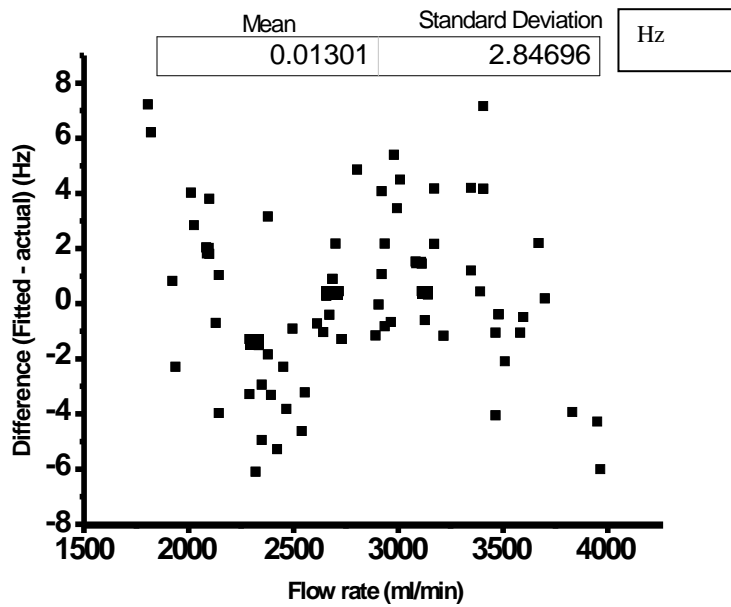


Figure 10. Flow rate (ml/min) vs. Frequency (Hz) Error Plot

Figure 10 shows the error plot obtained while obtaining the calibration curve from a set of data obtained on several days.

#### *D. External Temperature Compensation*

##### *Experimental Setup to Study the effect of temperature on the Frequency of the whistle*

External temperature affects the resonant frequency of the whistle in a couple of ways. One condition is that the sound of air increases as the temperature increases and the second possibility is that the length of the resonating material increases due to an increase in temperature. In order to study the effect of external temperature on the resonant frequency of the whistle so as to compensate for its effect when the whistle is installed on the device and used in different places having different temperature setting, an experiment is being setup as shown in the figure 11. The setup consists of a water bath setup in order to simulate the breath condition along with an external heater used to control the external temperature. A thermocouple along with its measurement circuitry is attached to the whistle in order to measure the external temperature. The output of the whistle is either connected to a flow meter or a pressure sensor is attached across the whistle to measure differential pressure in order to find the flow rate.

There are two factors which mainly cause an increase in frequency with increase in temperature namely the velocity of the air and the length of the resonator. The change in length of the resonating pipe by means of temperature depends on the expansion coefficient of the material ( $\alpha$ ) which is given by the following equation [51].

$$\mathbf{L_T = L_0 (1 + \alpha T)} \quad \mathbf{(2)}$$

Where

$L_T$  = Length of the pipe at the required temperature

$L_0$  = Length of the pipe at 0deg C

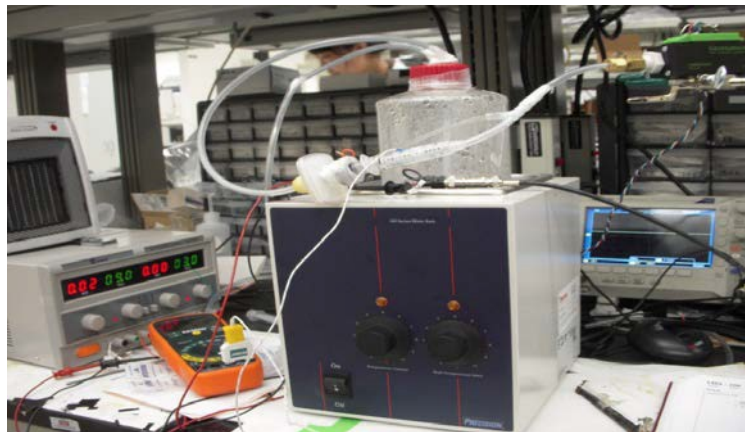
The velocity of the sound in air is given by

$$V = 331.7(1 + 0.00184T) \quad (3)$$

Also since we know that the frequency of the sound waves produced by the whistle is relational to  $V/L$  which can be written from the above equations as [50].

$$V/L = (331.7/L_0) * (1 + 0.00184 T) / (1 + \alpha T) \quad (4)$$

Hence from the above equation it is clear that an increase in external temperature of the flute causes an increase in the length of the tube and an increase in the velocity of the air, but the amount by which the length of the tube increases is negligible when compared to the speed of the air thereby ultimately causing an increase in frequency of sound produced.



*Figure 11 Experimental Setup to study the effect of Temperature on Resonant Frequency*

Initially with the help of an external heater the entire assembly is heated up to a particular temperature higher than the room temperature. After some amount of time during which the temperature gets stabilized, the flow rate is varied by means of varying the pressure of the gas cylinders, for example considering the flow rate increase from 2000ml/min to 4000ml/min and then back from 4000 to 2000ml/min as a single cycle. The experiment is carried out two cycles for each temperature and hence simultaneously measuring the resonant frequency by means of a cellphone. Finally a flow rate vs. Frequency plot as shown in the figure 12 is thus obtained for various temperature settings above room temperature.

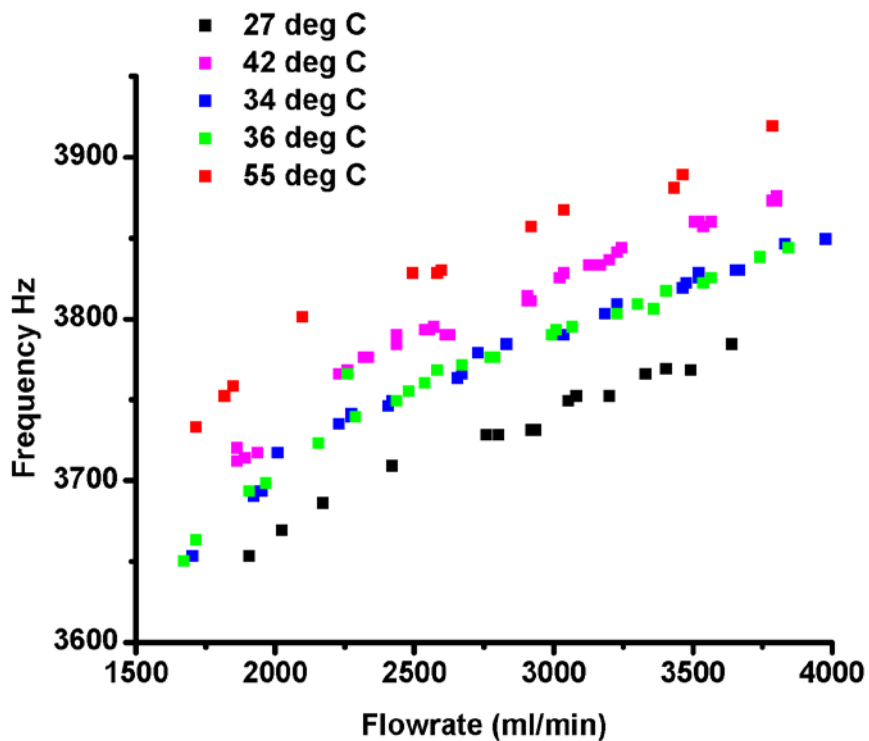


Fig 12 Flowrate (ml/min) vs. Frequency (Hz) at Different Temperatures

From the above plot we can clearly see that for a whistle having a constant flow rate an increase in temperature causes an increase in the resonant frequency of the whistle. After carefully analyzing the data obtained we can clearly see from the figure 13 that the resonant frequency change ( $\Delta f$ ) shows a steady pattern and it increase in temperature ( $\Delta T$ ).

The ( $\Delta f$ ) vs. pressure (flow rate) plot is obtained by finding out difference in frequencies for different temperature settings by keeping the data obtained at 27deg C as reference. From the figure 14 it is clear that with ( $\Delta f$ ) seems to be constant over different flow rate and it's not linearly related to different flow rates.

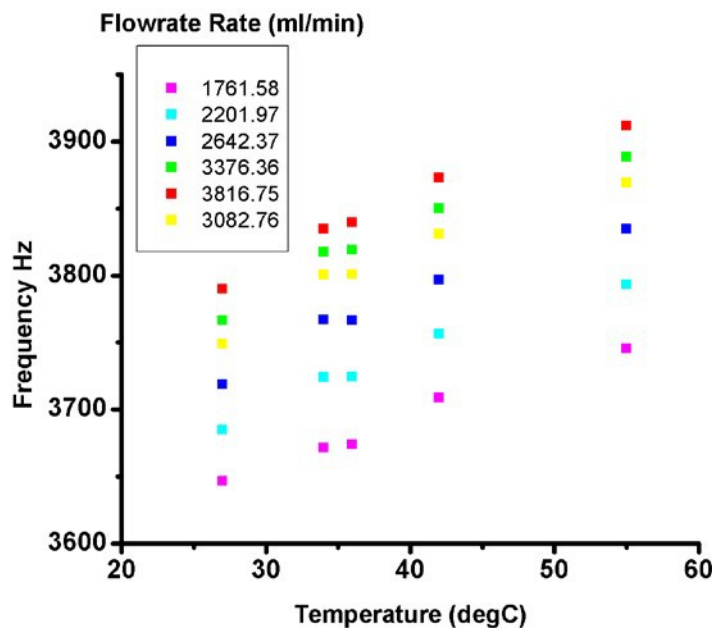
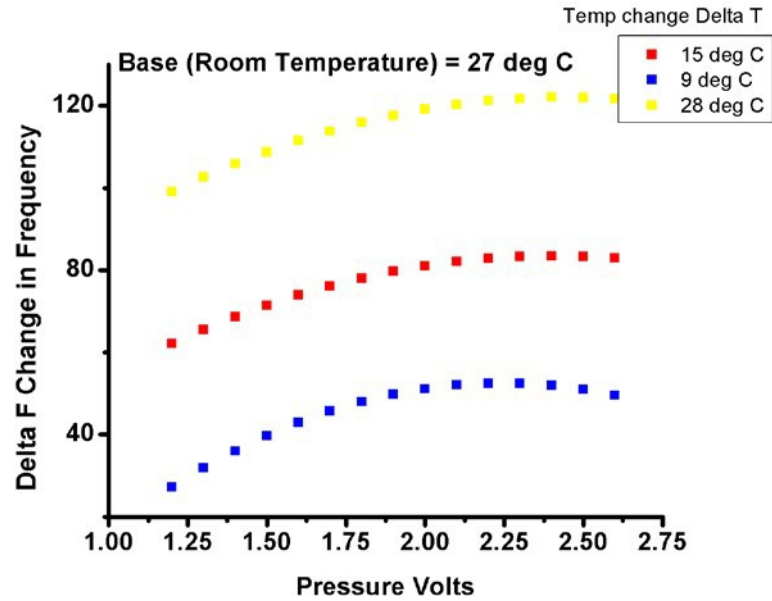


Figure 13. Actual Temperature (deg C) vs. Frequency (Hz)





$$\Delta T = \text{Elevated (test) temperature} - \text{base (room) temperature}$$

Figure 14. Pressure V (Corresponding to flow rate) vs.  $\Delta F$  (change in frequency)

Hz

#### Calculation of Calibration Factor

In order to compensate for the external temperature effects based on the data, we could see that the change in frequency is more or less the same over different temperature, a calibration factor was obtained. Initially ( $\Delta f$ ) and its corresponding ( $\Delta T$ ) values were obtained for various temperature curves by keeping the curve that we obtained at 27 deg C as reference.

The ( $\Delta f$ )/ ( $\Delta T$ ) ratio over different flow rate and temperature are averaged in order to get the calibration factor (C). In order to verify the data the calibration factor obtained from one set of data were applied to different set of data taken on a different day to verify whether the compensation factor holds the same for the data set taken on any day.

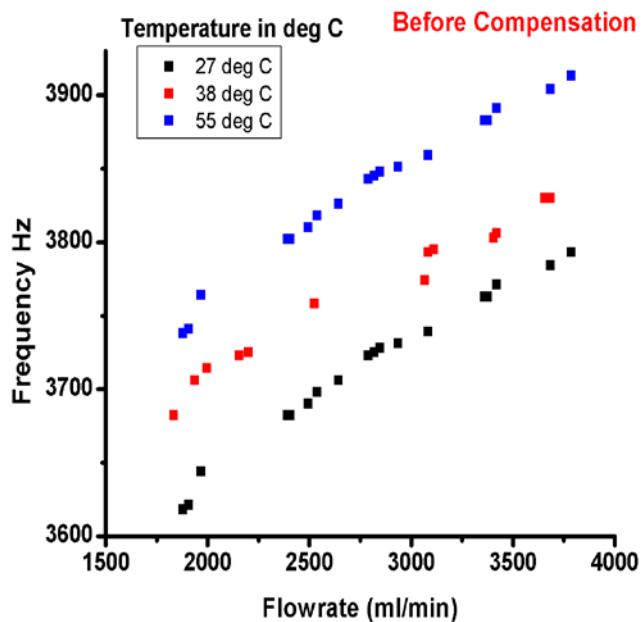


Figure 15. Flowrate (ml/min) vs. Frequency(Hz) at Different Temperatures

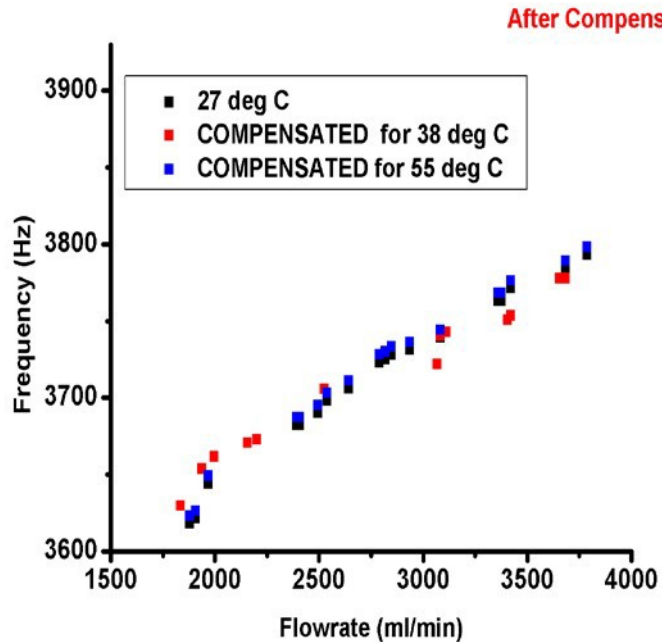


Figure 16. Flow rate (ml/min) vs. Frequency (Hz) at Different Temperatures

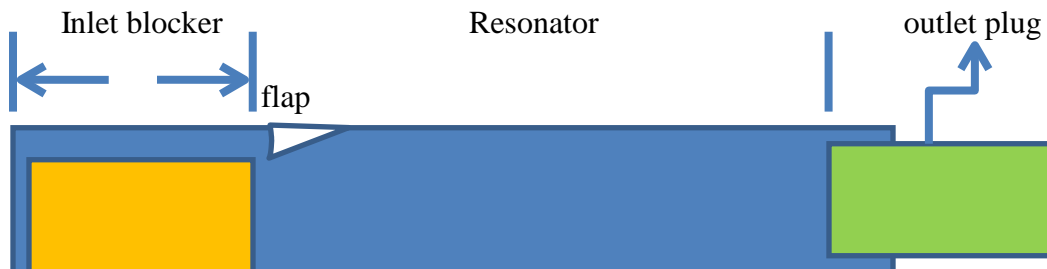
### *E. Development of Whistle*

As discussed before, there are a number of different parameters that affect the resonant frequency of the whistle. Since the whistle has to be integrated and implemented in a medical device, the material used for the fabrication of the whistle has to be approved by FDA. Based on this a list of materials were initially shortlisted which is shown in the table below [51].

Number	Material Type	FDA Approval	Melting Point
1	Polycarbonate (Polymethyl Methacrylate)	Approved	160 deg C
2	Acetal	Approved	180 deg F
3	PVC	Approved	212 deg C
4	Acrylic Tubing	Approved	266 deg F
5	Nickel Alloy, Brass Alloy	Approved	1453 deg C

*Table 1: List of Materials*

Since acrylic tubing is cost effective, easily available and has been commonly employed for the fabrication of the whistle, an acrylic tube resonator was built. A whistle as such is not a single piece. It has different parts such as



*Figure 17. Components of the whistle*

Inlet blocker (head), outlet blocker (tail), resonator and the flap. The position and length of each of these components has a direct influence on the resonant frequency of the whistle.

When a person blows through the acoustic sensor, the smooth flow of air is split by means of a flap which causes turbulence thereby making the air to vibrate causing the remaining portion of the acrylic tube to resonate. [50]

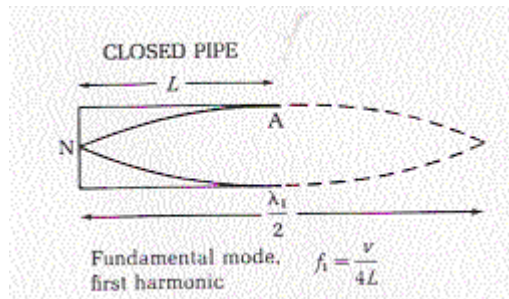


Figure 18. Mode of Oscillation for closed end Pipe [50]

If the wavelength of the sound wave of a particular frequency fits exactly inside the resonating air column then the sound wave reinforce each other thereby producing a pure tone called pitch. We can see that by changing the length of the resonating column, the frequency gets affected. The following table illustrates the data obtained experimentally by changing the length of the resonating column.

Length=3.8cm

flowrate ml/min	frequency Hz
4100	4254
3800	4249
3250	4230
3000	4225
2750	4200
2500	4175
2200	4153

Length=3.3cm

flowrate in ml/min	frequency in Hz
4200	6343
3250	4540
3000	4442
2850	4415
2750	4411
2200	4373

*Table2: Effect of length on resonant frequency of the whistle*

Also in the case of a closed end whistle of cylindrical cross section resonant frequency, without considering the effect of temperature and humidity is given by

$$f = v/4(L + 0.4d) \quad (5)$$

here

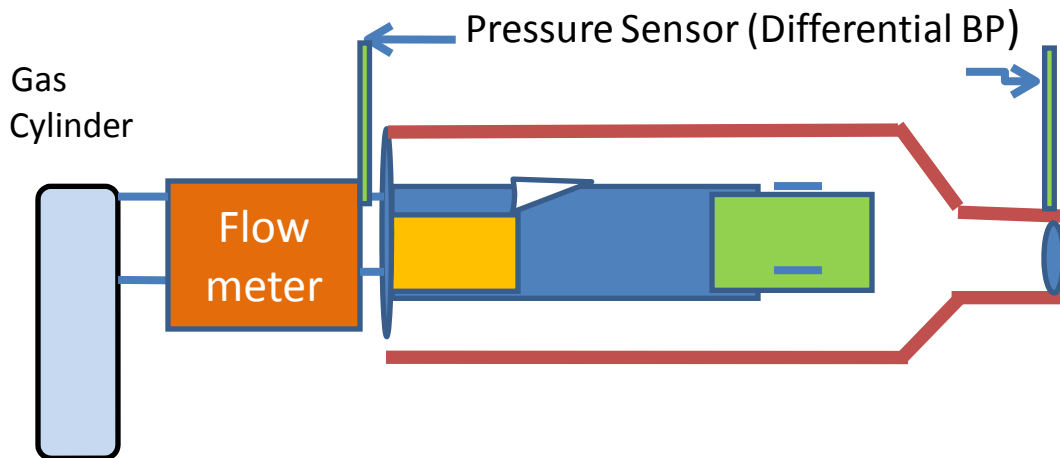
f= Resonant Frequency of the whistle

v=Velocity of Sound in air

L=Length of the resonator

d=Diameter of the resonating material

Hence from the above equation we can clearly see that resonant frequency is inversely proportional to the diameter of the whistle. As explained above, we know that frequency is directly proportional to the back pressure across the whistle.



*Fig 19. Experimental Setup for measuring Differential Back Pressure*

By means of using the above experimental setup a pressure vs. flow rate calibration curve was obtained which in turn was used to obtain the frequency in

terms of pressure reading. It is found that the Pressure vs. Flow rate was found to be quite linear.

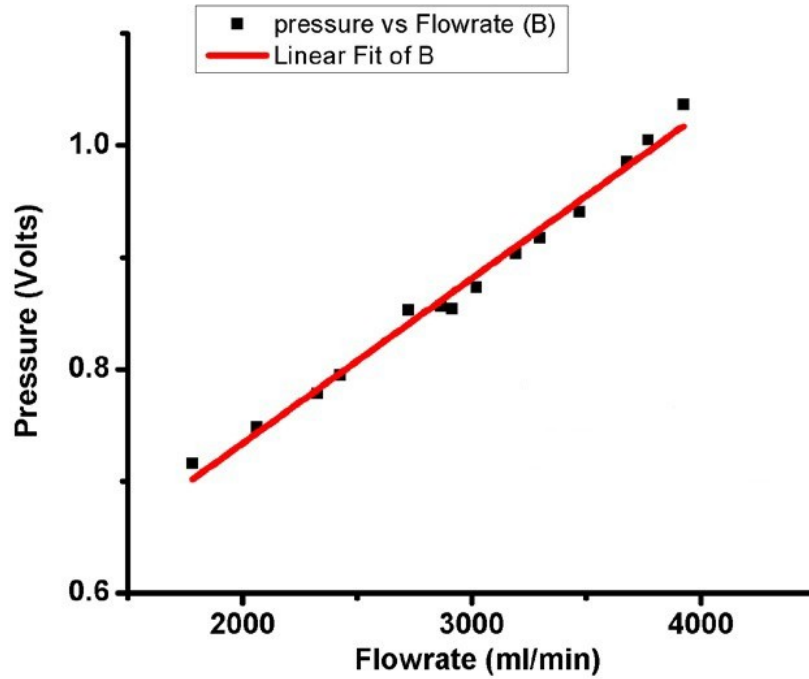


Figure 20. Flowrate(ml/min) vs. Pressure (V) Calibration

Hence the frequency can be written as a function of the differential pressure measured across the whistle.

#### *Back Pressure*

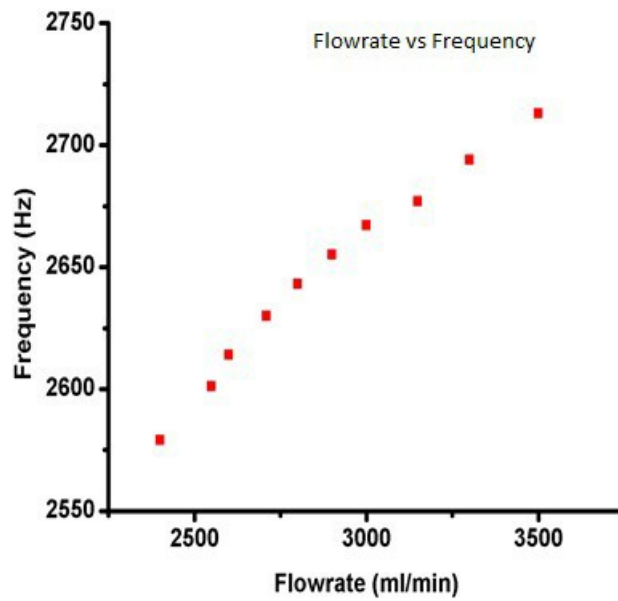
As mentioned in the previous chapters according to ATS requirement as far as nitric oxide detection in the human lungs is concerned, backpressure is also a critical parameter to control. The backpressures when measuring nitric oxide are set as an upper and lower limit. The upper pressure limit is 20 cm H<sub>2</sub>O and is set in order for patients to comfortably provide a sample. The lower pressure

limit is 5 cm H<sub>2</sub>O which is necessary for velum closure to avoid contamination of the sample with nasal NO which has been shown to measure in concentration an order of magnitude larger than that of alveolar NO.

Hence for this requirement a lot of whistles were examined and finally a whistle having a lower backpressure value is thus obtained

Flow rate (ml/min)	Frequency (Hz)	Back Pressure (cm of water)
2400	2579	3.98
2550	2601	4.28
2600	2614	4.45
2710	2630	4.79
2800	2643	5
3000	2667	5.6
3150	2677	5.89
3300	2694	6.2
3500	2713	6.9

*Table3: Flow rate(ml/min) vs. Frequency (Hz) for Low Back Pressure Whistle*



*Figure 21 Flow rate (ml/min) vs. Frequency (Hz) Calibration (Low back Pressure whistle)*

The above figure shows the flow rate vs. frequency characteristic curve of the lower back pressure whistle



F. Effect of humidity

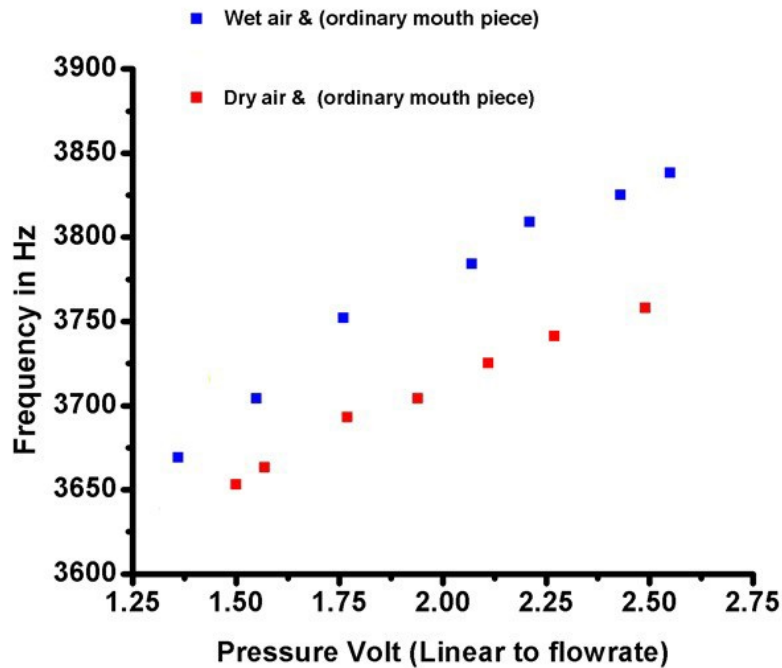


Figure 22. Differential Pressure (linearly related to flow rate) in V vs.

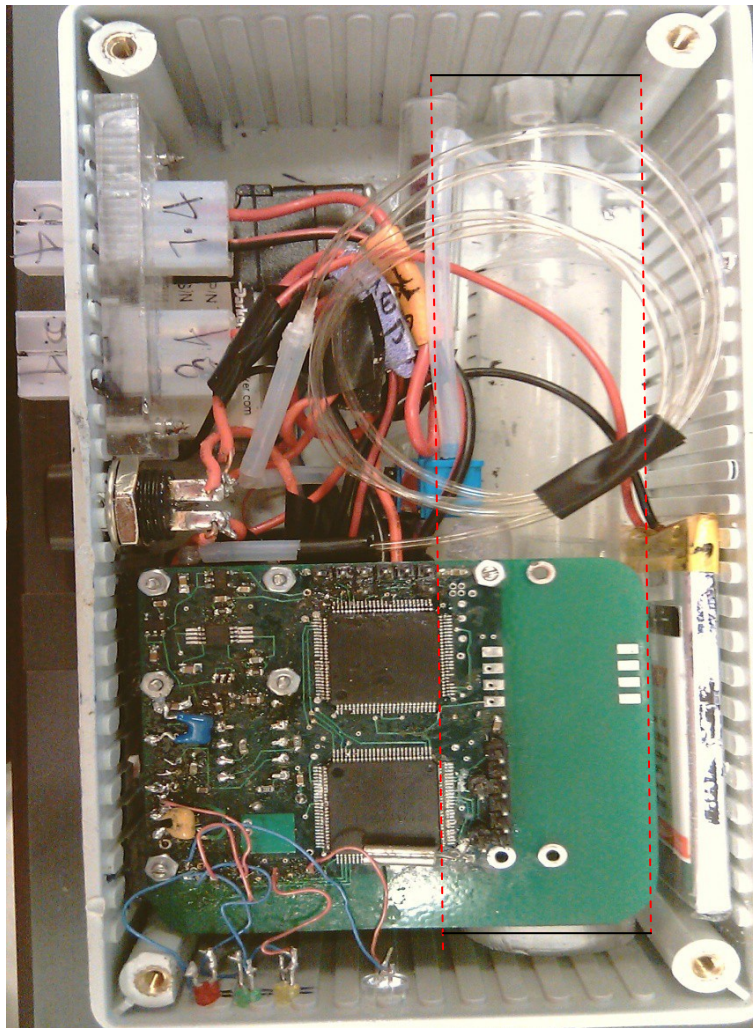
Frequency (Hz) under different Moisture conditions

From the above graph we can clearly see that an increase in moisture content will cause an increase in the frequency of the whistle. But in the case of breath analysis, since the amount of humidity has to be maintained at a constant level, a mouthpiece has been employed which maintains a constant level of humidity in the breath. Also since the humidity level is constant in most of the human breath samples, a calibration curve is obtained using real human breath samples.

## Chapter-4

### RESULTS AND DISCUSSION

As mentioned before, the whistle had been successfully integrated with the nitric oxide detection breath analysis. Also, as per the American thoracic society, a flow rate of 50ml/sec as well as a back pressure ranging between 5cm of water and 20 cm of water was achieved.



*Figure 23. Integration of the whistle with Asthma m-Health device*

*(Developed in Center for biosensors and bioelectronics ASU)*

The whistle along with the cellphone forms an automatic feedback control system which can be used to control the flow rate at which a person is blowing into the device while maintaining the backpressure requirements. For instance, when a person starts blowing into the device, the cell phone records the frequency of the sound produced and interpolates its corresponding flowrate value from the pressure vs. flow rate calibration curve. Also, with the help of the same calibration curve, the frequency corresponding to the upper and the lower flow rates are obtained and fed into the cell phone code. Based on the condition checking done in the cellphone, when the flow rate is below range, the cellphone sends a signal to the microcontroller in the device, which in turn turns on a yellow LED. The green LED is turned ON when the flowrate is in range and the red LED is turned ON when the flowrate gets above the prescribed value.



*Figure 24. Whistle implemented Asthma Device with cellphone measuring the flow rate*

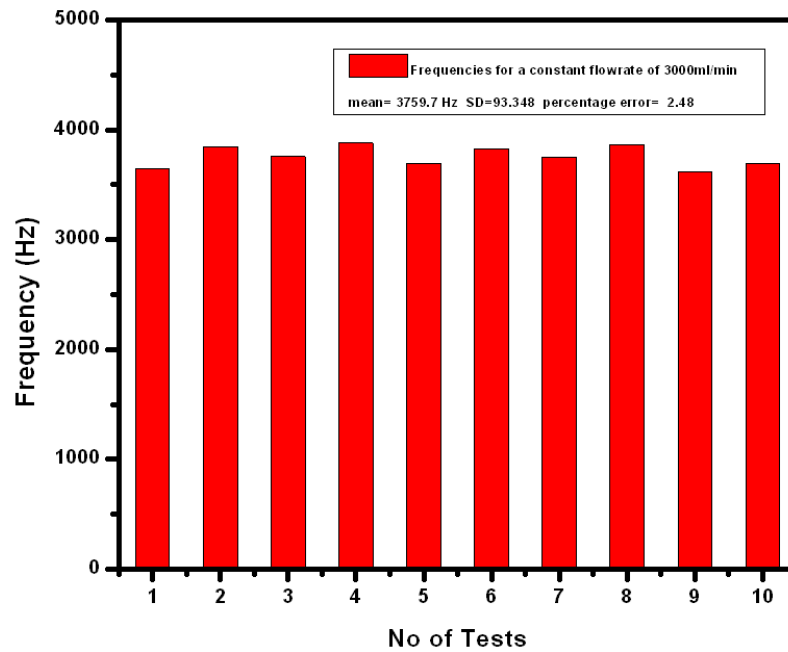


*Figure 25. Whistle implemented Asthma Device with cellphone measuring the flow rate & frequency in Range*



*Figure 26. Whistle implemented Asthma Device with cellphone measuring the flow rate & frequency out of Range*

## REPRODUCIBILITY OF RESULTS



*Figure 27: Graph showing the reproducibility of results*

The reproducibility of the whistle is tested by measuring the frequency of the whistle for a constant flow rate of 3000ml/min for 10 days using real breath of different people for testing.

## Chapter-5

### CONCLUSION

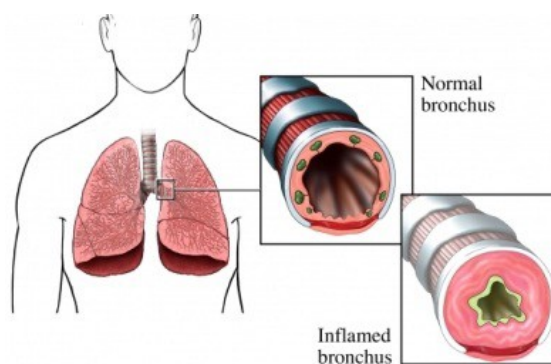
This work has demonstrated a system-level approach for designing a sensor system that demonstrates the construction and working of a whistle based acoustic sensor for the detection of flowrate in breath analysis devices and other medical applications. Change in frequency corresponding to flow rate change when a person blows through the whistle placed in a constant backpressure tube is used to find the rate at which the person blows in. As it does not require any power requirement, it can be successfully integrated in any breath analysis device where flowrate is an important parameter.

Nitric oxide measurement and tracking is one of the examples shown in this work. Mobile health systems developed with innovative engineering are always welcomed by people. The results obtained reveal that the whistle along with the cellphone provided a regulatory flow to the detection circuit. The back pressure and the resonant frequency can be changed by changing the length of the whistle and the size of the resonator thereby making the device suitable for many different applications. This results in a device that can be constructed with low cost and miniaturized components, which is ideal for many health and other applications.

## Chapter-6

### FUTURE WORK

The aim of this research has been to demonstrate the working and performance of an acoustic whistle based sensor in detecting flow rates for health based application and breath analysis devices. From the breath analysis point of view, a controlled sample collection unit is almost required in any breath analyte detection. Also since this technology does not require any power it can be easily integrated with any m-health breath analysis device. Given that backpressure and the resonant frequency can be changed by changing the parameters of the whistle, it can be modified to suit many different applications. One such application is spirometry. As explained above spirometer is a device mainly used to detect lung capacity which is mainly used to track the function of lungs and other chronic diseases. The whistle along with an application in a cellphone can easily detect the lung capacity by integrating the flowrate obtained from the flowrate vs. frequency calibration curve.



*Figure 28 Cross section of bronchus of people suffering from Asthma*

From the above figure we can clearly see that a layer of mucus is formed on the inner layers of trachea and bronchi for people suffering from cold and asthma. This in turn produces a whistle sound while breathing which in turn can be recorded using a cellphone and can be used for early detection and treatment of Asthma.



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