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Research on Low-Cost Mechanical Ventilator Specially Designed For Covid-19 Patients

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ABSTRACT: The COVID-19 pandemic has produced critical shortages of ventilators worldwide. There is an unmet need for rapidly deployable, emergency-use ventilators with sufficient functionality to manage COVID-19 patients with severe acute respiratory distress syndrome. Here, we show the development and validation of some newly designed simple, portable and low-cost mechanical ventilator that may be rapidly manufactured with minimal susceptibility to supply chain disruptions. Current pricing of commercial mechanical ventilators in low/middle-income countries (LMICs) markedly restricts their availability, and consequently a considerable number of patients with acute/chronic respiratory failure cannot be adequately treated. Our aim was to design and test an affordable and easy-tobuildnoninvasivebilevel pressure ventilator to allow a reduction in the serious shortage of ventilators in LMICs.

KEYWORDS: Low Cost Mechanical Ventilator, Low-Power, Portable Noninvasive Ventilator, Noninvasive mechanical ventilation (NIV), Acute Respiratory Distress Syndrome equipment (ARDS).

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I. INTRODUCTION

A key challenge in the battle against the disease caused by thenovel coronavirus SARS-CoV-2, COVID-19, is a potential worldwide shortage of mechanical ventilators. The required number of ventilatorsis projected to significantly exceed capacity, based on thenumber of patients expected to contract the disease in the world and the percentage of these likely to require assisted ventilation. Adding to this burdenis the fact that COVID-19 patients who develop acute respiratory distress syndrome (ARDS) often require prolonged mechanical ventilation Physiciansaround the world have been forced to make difficult triage decisionson which patients to treat and which to let go of due to inadequatenumber of ventilators. Addingto the challenges of increasing number of devices is the complexityand expense of traditional ICU ventilators further aggravated by thebreakdown of regular supply chains as a consequence of the pandemic.A pandemic caused by a potentially lethal and easily transmissibleviral pathogen like SARS-CoV-2 requires rapid,focused effort in either obtaining or manufacturing sufficient medicalequipment to save lives despite the disruption of normal supplychains, difficult working conditions and regulatory restrictionsreasonably imposed in normal times that nonetheless jeopardizeprogress during a state of emergency.

The ventilator design focuses on safe operation and reliable productionwhile addressing the specific needs of COVID-19 patientswith ARDS: minimizing part count, cost and complexity; reducing oreliminating reliance on scarce parts and resources; ensuring viableimplementation in different healthcare systems across the world;and seeking simple assembly, testing and use procedures by healthcarepersonnel with limited experience in ventilation; and no experiencewith this type of ventilator system.

Modern ICU ventilators provide complex control and intricatefeedback loops of a wide variety of respiratory parameters and ventilationmodalities. Their operation requires highly specialized staff. Regulatory requirements are understandably high,and pandemic crisis-driven emergency orders of ventilators to medicaldevice manufacturers are difficult to fulfil due to the failure ofsupply lines and the difficulty in rapidly ramping up production ofthese technically advanced ventilators. In the meantime, lives areat risk. While several emergency ventilators are commercially available,most do not meet the medical requirements of the complexARDS-like pneumonia associated with COVID-19 which requirespulmonary protective ventilation with careful control of pressureand volume as compliance of the infected lung tissue can rapidldeteriorate, placing the patient at elevated risk of barotrauma andfurther lung injury. We are left with an unmet need for COVID-19pneumonia-appropriate, rapidly deployable, comparatively simpleemergency-use ventilators.

Evolution Of Mechanical Ventiation

The use of mechanical tools to assist ventilationdates back to the late 19th century, when devicesable to apply an alternating subatmospheric pressurearound the body were used to restore ventilation byexpanding the chest wall of patients.However, itwas only after the introduction of positive-pressureventilation during the reappearance of poliomyelitisin the 1950s, when Bjorn Ibsen demonstrated adramatic reduction of mortality in patients manuallyventilated by tracheostomy, that mechanicalventilation started to be widespread .

The first positive-pressure mechanical ventilatorsbecame available in 1940. Though characterized by a significant degree of sophistication, theywere able to deliver only a pre-set tidal volume ata given respiratory rate (volume-control ventilationmode) with no or very limited capability to monitorventilation variables.At that time, respiratory physiology had alreadyestablished its foundations and was rapidly growing.The application of mathematical modelling todescribe the relationships between flow andpressure (a wonderful example of what today wouldbe considered a biomedical engineering approach),which marked the dawn of the mechanics ofbreathing, was introduced by Dixon and Brodie.

Essential Components In Mechanical Ventilation From Paitents To Machine

- Patient
- Artificial Airway
- Ventilator Circuit
- Mechanical Ventilator
- A/c or D/c Power Source
- O2 Cylinder or Central Oxygen Supply

RECENT TRENDS

Many companies, research institute, engineers and innovators have pitched in for the development of ventilators using the Bag-Valve-Mask (BVM). Many innovative ideas are being used for the compression of the BVM to supply a fixed volume of air at a defined rate. However, the function of the ventilator is not just to supply air to the lungs, there are many criticalitiesinvolved while doing so. If a fixed volume of air is forced into the patient's lungs without understanding the patient's lung compliance, it may lead to a condition known as "PulmonaryBarotrauma" (Tobin 2013). This condition is nothing but damage to the lung from rapid or excessive airway pressure. The ventilator must have pressure-releasing mechanism to dischargeexcess pressure when limit on peak inspiratory pressure (PIP) is reached, thus protecting the lungs from severe damage.

Some New Designs For Low-Cost Mechanical Ventilator

INDIAN MADE

1. CSIR-CMERI—Low cost mechanical ventilator -(CNN News).
2. Amrita School of Engineering,kollam- AMBU BAG Based.
3. IIT Bombay,NIT Srinagar &Islamic University of science – Ruhdaar.
4. AdiShankara Institute of Engineering,kalady - JeevaVayu.
5. Banglore Based Reva University - JeevaSethu.
6. GEC, Goa - low cost venti.
7. ATME, Mysore (Final year students).

NON- INDIAN MADE

1. Imperial college, Landon –JAMVENT.
2. School of Medicine, Boston University -Low cost portable Mechanical ventilator.
3. San Diego, California University - MADVENT.
4. MIT-Technology-New York - low cost ventilator.
5. Georgia Institute of technology (school of mechanical engineering) - Open-AirVentGTEmergency ventilator.
6. Massachusetts Institute of Technology-emergency ventilator.
7. Bakken Medical Devices Center - The Bakken Ventilator.
8. Michigan Technology University(Innovative Global Solutions)
9. Easy-To-Build Portable Ventilator-Engineering, Systems and Applications Laboratory,ENSA, Morocco
10. Low Cost Ambu Bag Pivoting Motor Drive Mechanical Ventilator-Bangladesh

TWO DIFFERENT TYPES OF LOW COST MECHANICAL VENTILATOR

1.Easy-To-Build Portable Ventilator

2.Low Cost Ambu Bag Pivoting Motor Drive Mechanical Ventilator

1.Easy-To-Build Portable Ventilator

Design concept

The unique concept of the proposed ventilator is depictedin Figs. 1 and 2. It comprises a plastic air tank, two woodenor plastic circles (fixed and mobile discs), a bendable wire,two check valves, a DC motor, and a support box (guide cylinder).

As shown in Fig. 1, the motor is fixed to the center ofthe upper circle. In the ON state (Fig. 3a), the motor is activated,causing the upper circle to rotate in one direction. The

movement of the motor causes the wire to bend. This pullsthe bottom circle upwards, which pressurizes the air insidethe tank. This pressurized air is consequently directed intopipes through the check valve. This state corresponds to the inspiration phase .

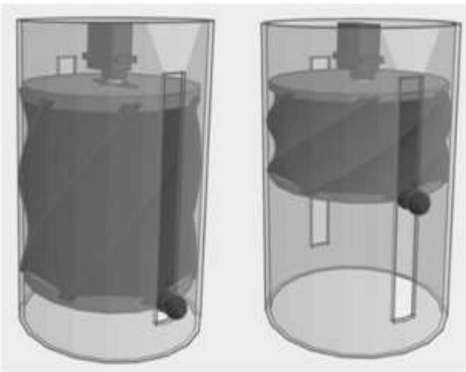

Fig. 1 3D view of the assembled ventilator

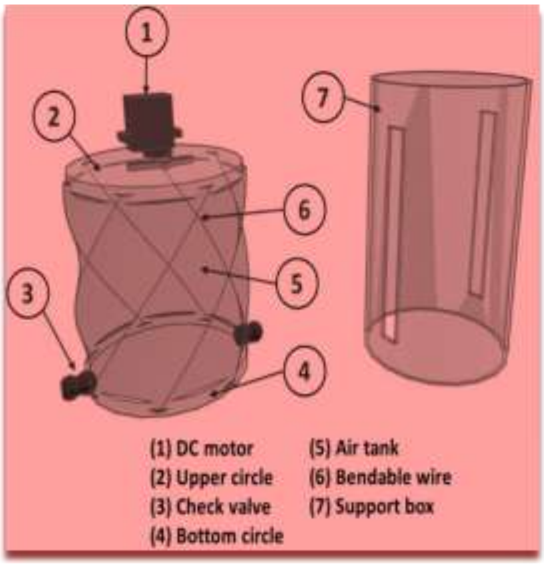

Fig. 2 3D view of the contents of the proposed ventilator device

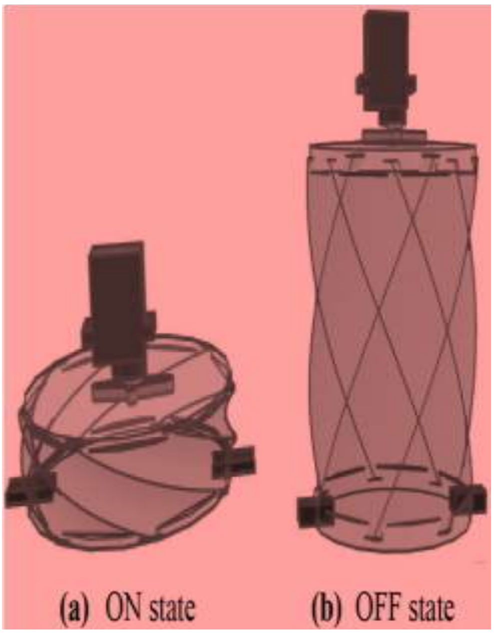

Fig. 3 Views of the ventilator in the ON (a) and OFF (b) states

In the OFF state (Fig. 3b), the motor is released. The bottom circle then moves downwards under the influence of its own weight and the release of the tension in the wire, which is restored to its initial position. Since the pressure in the lungs is higher than the pressure in the air tank, the device will draw air from the patient's lungs. Thus, the OFF state corresponds to the expiration phase. The cycling of ON and OFF states induces respiration. On the other hand, the movement of the bendable wire towards its initial position causes the motor to rotate in the opposite direction, so the motor can be used as a dynamo to generate electricity, thus recharging the battery. This would make our solution less reliant on external power. Additional components that are not presented in Fig. 2 could also be included to improve our concept. Examples of these components include:

• A temperature sensor (such as the low-cost DS18B20 sensor) on the bottom circle to measure the air temperature.

• A heating resistor on the upper circle to control the air temperature.

• A pressure sensor (such as the low-cost MPXV5050GP sensor) to measure the pressure in the air tank.

• A small rechargeable battery to supply power.

• A buzzer to generate audio alarms when, for example, the engine does not work correctly or the battery is low.

• Two LEDs (red and green) that indicate the battery status (low or high level of charge).

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• A LCD (20 × 4 characters) to display operational data for the system (temperature in the air tank, battery status, etc.).
• A system stop/start button.
All of the components would be controlled by a low-cost embedded board such as an Arduino or ESP32 (a control and data acquisition board).

Challenges

Based on the promising findings of initial developmental work on the unprecedented ventilator concept presented in this technical note, work is underway to optimize various aspects of the ventilator and to ensure the safety of the patient when the ventilator is operated. More specifically, this work includes:
• Determining the optimal dimensions of the assembly, in particular the diameter of the disc and the height of the air tank according to the maximum air volume required.
• Determining the optimal diameter and material for the bendable wire, as well as the optimal number of wires.
• Choosing an adequate DC motor (torque, speed).
• When torque from the motor is applied to each wire, the distance between the fixed disc and the mobile disc depends on the bending stiffness of the wire. Changing the distance between the discs changes the air volume in the tank. Therefore, it is necessary to perform analytical calculations relating the torque to the wire parameters (e.g., number, diameter, Young modulus, and length).
• The friction between the upper disc and the support must be studied and optimized, as the fit between the upper disc and the support must be tight enough to stop any significant air leakage, but it must not be so tight that it slows down the motor and the ascent of the lower disc during the ON state.
• Adding precise and cost-effective sensors (to measure, e.g., the pressure, volume, and flow) that can provide information employed by the user to control and monitor the tidal volume, inspiratory pressure, bpm, and the inspiratory/expiratory ratio, thus maintaining patient safety and administering air deliberately and accurately. This novel ventilator system will be developed according to medical standards such as ISO 80601, ISO 5367, and IEC 62304.

2.Low Cost Ambu Bag Pivoting Motor Drive Mechanical Ventilator

Proposed low-cost ventilator delivers breaths by compressing a conventional Bag Valve Mask (BVM) or Ambu bag with a pivoting motor drive mechanism, eliminating the need for a human operator.

Among other features, the machine should have invasive and non-invasive feature, and supports 500-600 mL tidal volume, with a continuous working capability for several days. Based on calculation, 12 Respiratory rate (RR)/min can provide required amount of tidal volume to the pneumonia patient.

Strategy of automatic arm actuated BVM compression is proven to be a viable option to achieve lowcost, low-power and portable ventilator technology that provides essential ventilator features at a fraction of the cost of existing models.

Cost Factor:

Cost-performance distribution is depicted in **Fig. 1**with manually operated BVMs on the low end ofcost and performance, and full-featured hospitalventilators on the other extreme.

Middle section of the chart includes the existingportable ventilators which can be broadlycategorized as pneumatic and electric. Pneumaticventilators are actuated using the energy ofcompressed gas, often a standard 50 psi (345kPa) pressure source normally available inhospitals.

But, to generate constant ventilation for pneumoniacases such as COVID-19 patients an automatedand low-cost ambu bag air flow system is effectiveto save life.

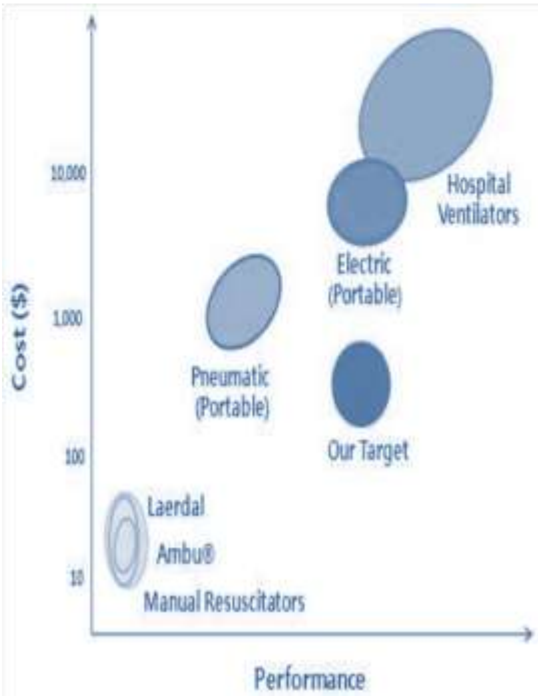

Figure 1: Cost-performance distribution of ventilators

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Methodology:
An IoT based motor drive of clockwise and counter clockwise will provide the required motion for the arm movement to maintain an automatic air flow with a controlled pressure rate. **Fig. 2** shows the working process of this proposed automatic ventilation machine.

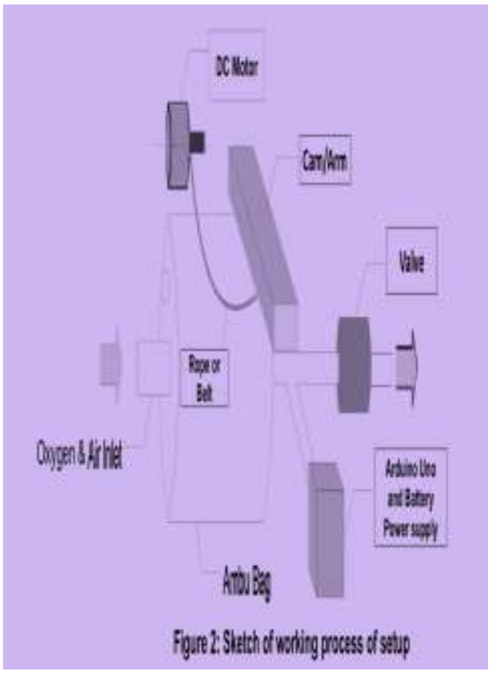

Figure 2: Sketch of working process of setup

Circuit Diagram:

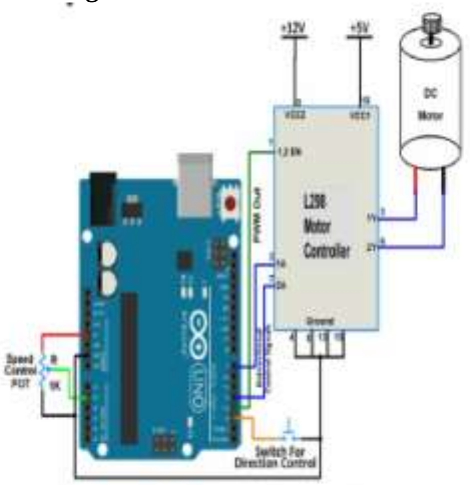

Figure 3: Circuit diagram of Arduino Uno, L293 motor drive and DC motor

Components:
Bag Valve Mask (BVM) or Ambu Bag:
• Used for resuscitation in emergencysituations, available at local chemists.
• Compressible self refilling ventilation bag withnon-re breathing patient valve with pressurelimitation valve to minimize the risk of overinflating.
• 100% latex free.

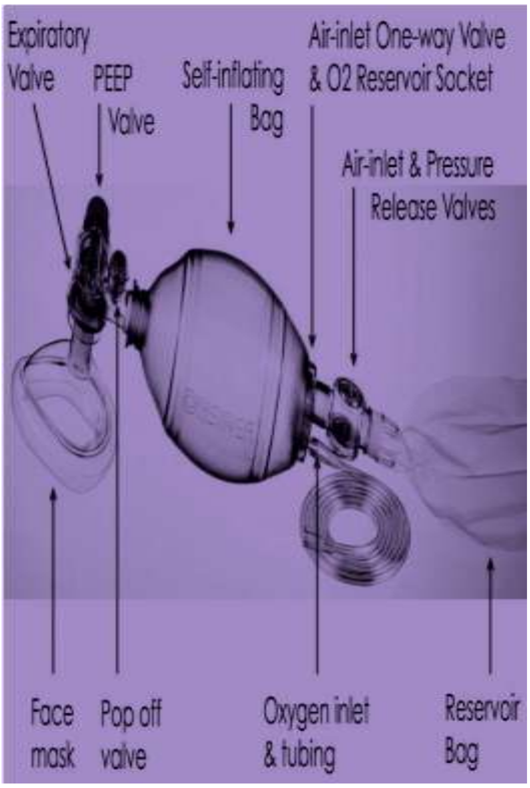

Fig. 4: Bag-valve Mask or Ambu Bag

Arduino Uno:
Arduino Uno is a microcontroller board developed byArduino.cc which is an open-source electronics platformmainly based on AVR microcontroller Atmega328.

Arduino Uno comes with USB interface, 6 analog inputpins, 14 I/O digital ports that are used to connect withexternal electronic circuits. Out of 14 I/O ports, 6 pins canbe used for PWM output.

Atmega328 microcontroller is placed on the board thatcomes with a number of features like timers, counters,interrupts, PWM, CPU, I/O pins and based on a 16MHzclock that helps in producing more frequency and numberof instructions per cycle.

For this prototype using only few channels. Addition ofpressure sensor and volume sensors will increase thesafety features. Also, by adding Wi-Fi or Bluetooth module it can be operate remotely using smartphone application.

Fig. 5: Arduino Uno R3

Motor Controller L298:

• Motor Controller is used to control the direction of DCmotor.
• It consists of an L298 motor driver IC which iscapable of rotating the motor in both clockwise andanti clockwise directions by switching its pins fromHIGH to LOW and vise versa.
• Required +12V, GND and +5V in order to power it up.So, we will design a voltage regulator which will stepdown 12V to 5V.
• Using L298 microcontroller, 2 DC motors can easilyoperate. So simply by adding another DC motor withambu bag setup can operate **2 ventilation system**atthe same time.

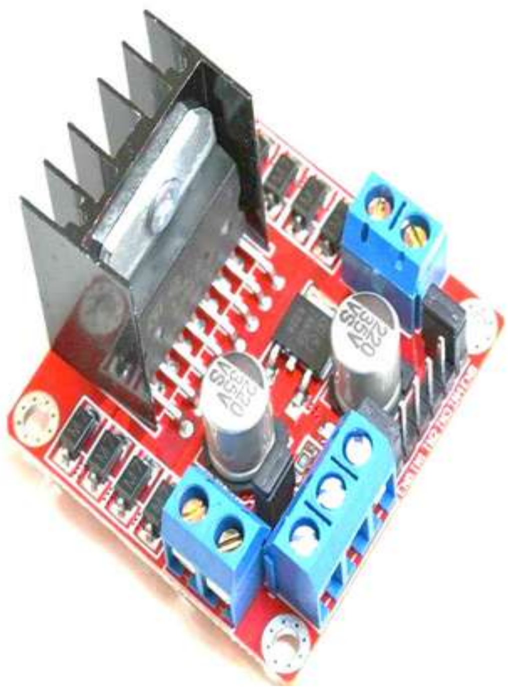

Fig. 6: Motor Controller L298

DC GearMotor:

• For this prototype used 12V DC gear motor of 7 kg/cm torquecapacity.
• Speed(RPM): 7-600RPM and 0.15A is suitable for proposeddesign.

Fig. 7: 12V DC Motor

Belt:

• Normally gear belt or nylon rope is suitable to transmit
rotational motion from motor shaft to the moveable arm placed
onambu bag.
• For this prototype used a nylon rope to hold the arm and
when motor start to rotate rope also start to make spiral to
give the arm horizontal movement.

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Fig. 8: Belt and Nylon Rope

Other Equipment's:
12V Battery and power adaptor, switch key, Arduino IDE software, jumper wires, card board for arm, etc.

Arduino Code Desigining:
Open the Arduino IDE software and go to Tools and select the Arduino board and the COM port properly.

Fig. 9: Arduino Code Desigining

Now, upload the source code for **2 sec clockwise and 3 sec anti clockwise** rotation to the Arduino UNO board. So that, it can complete 12 RR/ min as per our calculation. Code is also available in Arduino IDE website. Just past the code and edit the time value, connection pin number and motor speed set carefully.

Testing And Results:
After implementing of all setup and successful run of Arduino code operated several time to obtain result.
According to our uploaded source code motor will rotate **2 sec clockwise and 3 sec anti clockwise** continuously. So that, it can complete 12 Respiratory rate (RR)/min as per our calculation to provide acontinuous plate pressure and air flow for the pneumonia cases of COVID-19 patient lungs.

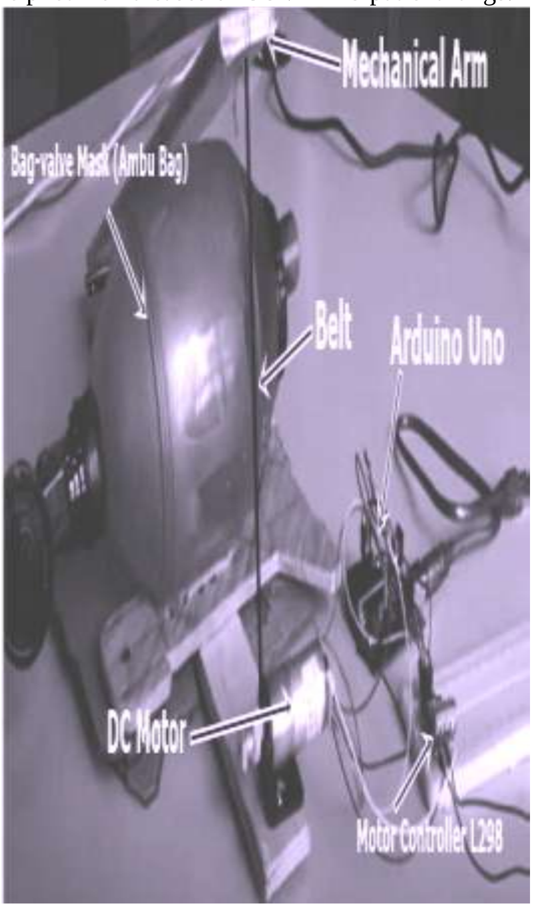

Fig. 12: Testing and result calculation for proposed ventilator machine

II. DISCUSSION AND CONCLUSION:

Designed and developed a prototype of automatic ventilator to support pneumonia cases for COVID-19 patients.

It has a controlled breath rate of 12 RR/min and 500-600 mL tidal volume. It featuresassist control and provide a constant air flow to the lungs.

Power requirement is very low and running for 3.5 hours on one battery charge at its most demanding setting. Battery backup also need to be checked.
It is low cost, portable, light weight and able to run 2 DC motors at the same time.

Further development includes pressure sensor, air flow meter, over pressure alarm andother safety features to make it more user friendly.

Advantages of Low Cost Mechanical Ventilator

- Can be used in under developing countries.
- Cost of the ventilator is minimized.
- Can be manufactured from locally available materials.
- Production time can be minimized.

Disadvntages of Low Cost Mechanical Ventilator

- Risk of Failure if not manufactured properly.
- Maintenance should be done at proper intervals.
- Too much local materials cannot be used since it deals with the patients life directly.

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