A low-cost, compact, open-source, face mask particle filtration efficiency test setup

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Version: Aug. 7, 2020

Introduction

The use of face masks, not just by health care workers, but the general populace has been universally recommended as a key intervention in reducing the spread of disease in the current COVID19 pandemic.[1] This had resulted in a wide variety of face masks from homemade cloth masks to surgical masks and N95 filtering facepiece respirators being available. A key issue is to determine the filtration efficiency of such facemasks, especially for small sub-micron-sized particles. For filters based on fibrous materials, and operating at filtration velocities similar to those encountered in human breathing, the minimum filtration efficiency occurs for ~0.3μm sized particles.[2] This is particularly important for N95 masks, where the particle filtration efficiency (PFE) for 0.3μm-sized particles is a critical metric. There are several masks that claim to be N95, but have failed to meet standard specification. Further, though N95 respirators are normally meant for single-use, the shortage of masks has led to several decontamination processes being developed include moist and dry heat treatment, hydrogen peroxide vapour, ozone, UV-C radiation etc.[3] It is important to check that such processes do not impact the filtration efficiency of the mask post treatment. However, even the simplest commercially available mask testing units cost upward of 10 thousand USD[4], and are not easily accessible in most low- and middle-income countries. Further, recent US FEMA emergency guidelines[5] restricting export of such equipment will impact the availability of such systems. Several groups around the world have been working on alternative low-cost mask testing setups.[6-9] Many of these rely on laser particle counters used for clean-room monitoring which are still in the 1000 USD range. A really low-cost "DIY" mask PFE testing system that is easy to fabricate and use even in resource-constrained settings would hence be extremely useful.

In this brief report we show how a low-cost, compact, particle filtration efficiency test setup can be made using relatively easily available components, in particular particle concentration sensor chips that are now widely and cheaply available for air pollution monitoring. We estimate that such a simple unit could be built for ~130 USD/10000 INR, including an oil-free diaphragm pump, and a standard medical nebulizer for generating a fine aerosol. (This cost would reduce significantly if one uses a simple vacuum cleaner, and just depends on the ambient particles in room air.) Our prototype uses a Plantower PMS7003 air quality monitor chip that is controlled via an ESP8266 WiFi micro controller unit. Air is sucked through the particle counter using a pump/vacuum cleaner, and the throughput of 0.3 μm sized particles (for N95) measured with and without a mask at the input. A simple HTML interface is used to read the particle counts and evaluate the filtration efficiency. All the construction details, diagrams, source codes for the micro-controller and interface are available open-source at the GitHub repository https://github.com/shescitech/TIFR_Mask_Efficiency.

We emphasize that the home-built prototype was made and tested on a small variety of masks available to us during the lockdown in Mumbai. While calibration tests against professional equipment would be needed to establish the accuracy of numbers, our preliminary data show that this prototype is capable of adequately qualifying the filtration performance of N95 respirators (we estimate a ±2% accuracy), and also comparing respirators prior to and after a decontamination process.

Design:

Any mask filtration efficiency test setup requires to subject a sheet of the mask material of fixed area (or the entire mask, typically mounted on a human face mannequin), to a flux of 0.3 μm sized particles (for N95) and measure the throughput of such particles across the mask. While commercial setups would have in-built aerosol generators for a desired particle size, there are typically enough residual sub-micron and micron-sized particles in room air itself that can be used. Hence any device that can count the number of particles in air can be useful to check transmission through a mask. Given the interest in air quality measurements, especially in polluted cities, air-quality- indicator (AQI) systems are now widely deployed. Most of these are designed to measure PM2.5 and PM10 levels (of 2.5 μm and 10 μm sized particles). However many such AQI systems are based on laser particle counter sensors (like the Plantower PMS 1003/5003/7003 series[10]) that actually provide measurements of particle counts at 0.3, 0.5, 1, 2.5, 5 and 10 μm as standard outputs. These sensors are optimized for the detection of 2.5 μm sized particles and have been extensively tested[11]. Though the sensitivity of the PMS 7003 at 0.3 μm is considerably less than at 2.5 μm, it is reasonable enough for reliable measurements. However, in any case the absolute sensitivity is *not* critical for a mask test application as the parameter of interest is a ratio of measurements. The filtration efficiency, η_{mask}, can be determined from the ratio of particles per unit time detected with, N_{mask}, and without the mask attached, $N_{ambient}$, as $\eta_{mask} = 1 - (N_{mask} / N_{ambient})$

Our mask PFE test setup uses a Plantower PMS7003 sensor that is controlled via an ESP8266 WiFi micro controller unit. (We used a Wemos D1 R2 WiFi capable ESP8266 based development board, however this could also be done through any WiFi capable IoT controller with an ESP8266 core for the Arduino IDE such as a Wemos D1 mini, NodeMCU etc.). The setup is externally powered via a standard USB port on the ESP8266 board. This is connected to the PMS7003 sensor using a 1.27mm pitch IDC connector, which supplies power and is also used for data transfer. A schematic of the setup and a photograph of the lab prototype are shown in Figs. 1(a) and (b), respectively. The PMS7003 is kept inside a small plastic box, with input and output provided via standard 6 mm tubes. We use 6 mm quick fit connectors all through the setup for ease of assembly. We use an oil-free diaphragm pump (HSV-1, High Speed Appliances, Mumbai) that provides a maximum flow of 30 lpm. The flow can be measured and controlled with a taper-tube flow meter. For most experiments we used a flow of 10 lpm*, similar to typical human breathing rates. We have also used a home vacuum cleaner, as well as a battery-operated portable vacuum cleaner and find that they can also be satisfactorily used for the PFE measurements. However, such vacuum cleaners for domestic use are not meant for heavy duty operation and could heat up after ~30 min of continuous use.

* We are aware of the ASTM test conditions for masks that specify a flow rate of 85 SLPM. However our setup is mainly aimed to be a tool for quick evaluation of mask PFE, e.g. to check if a claimed N95 mask really meets the specification, or to check before-and-after performance following decontamination treatments etc.

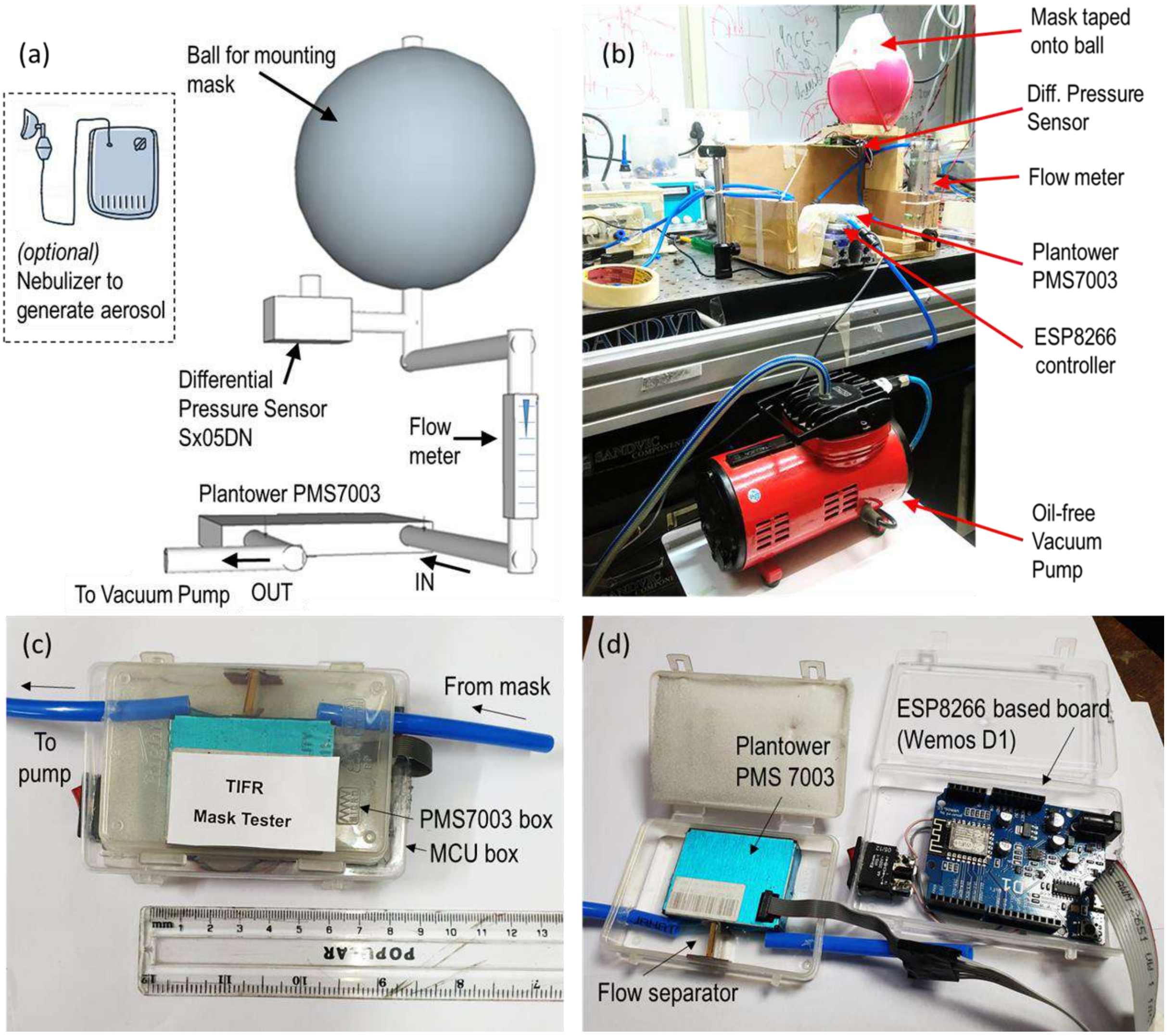

Fig. 1 (a) Schematic diagram and (b) photograph of the PFE test setup, (c) view of the air quality sensor chip and control unit in small plastic boxes kept atop each other in a compact configuration (b) opened up view showing the PMS7003 chip and the ESP8266 based MCU board. The box edges and connector ports are sealed with tape/hot-glue to ensure that the setup is airtight.

A more critical design issue is that these sensors are designed to sample ambient air (with a small internal fan) and do not have the ability to generate any suction pressure to draw air through a face mask. Thus, some other arrangement has to be made in order to force the air flow through the mask, and past the sensor. This was done using a vacuum cleaner in the initial tests, and eventually with a small diaphragm pump. It is of utmost important to ensure that the air being sucked through the mask is appropriately directed into the input port of the particle counter sensor, to enable reliable measurements to be made. Further the vacuum pump has to sample air at the output port of the sensor, and ensure that the air flow is such that it does not bypass the sensor. This can be conveniently achieved by using an appropriately sized divider plate that sits tightly against the PMS7003 sensor chip and the box. This serves as a barrier between output and input ports to prevent direct mixing, and ensures that the air flows through the sensor. (See part marked as flow separator in Fig. 1 (d)). It is also important that the PMS7003 sensor box and the input/output connectors are completely sealed to prevent any external air being sucked into the box. We used a combination of tape and hot-glue for this purpose.

While typical room air has enough particles of 0.3µm size to enable PFE measurements on N95 masks, air-conditioned laboratory environments often have filters that reduce the particulate count significantly. In that case a much better signal to noise ratio in the measurements can be achieved with intentionally enhanced particle counts in the local environment. This can easily be done using normal saline (0.9% NaCl solution) in a standard medical nebulizer. We have also tried using smoke from an incense stick which also works well, however the steady state count of particles is more stable with a nebulizer than a burning incense stick. We can obtain a relatively constant background level with the nebulizer kept about 5 m away from the test setup.

The codes required for programming the ESP8266 based MCU board to interface with the PMS7003 were written for the Arduino Integrated Development Environment (IDE) and allow the particle count data from the PMS7003 to be streamed to a local http web server. A python code is used to access this real time data and plot it, as well as apply the appropriate filters, analysis and PFE calculation tools. The data transmitted from the Arduino is visualized and analyzed through a simple html interface that allows various parameters to be changed, including the particle size channel, data acquisition rate, IP address etc. A snapshot of the mask tester user interface is shown in Fig. 2. To ease the calculation of the PFE an intuitive user interface with an in-built efficiency calculator has also been provided.

Fig. 2: Screenshot of the face mask efficiency tester. A drop down menu allows different particle size channels to be chosen. Clicking on the wrench icon pops up an advanced settings window allowing other options to be changed. Clicking on the efficiency button provides 4 vertical bars that can be moved to demarcate regions of particle count without and with the mask, and the calculated PFE is displayed. Similarly the data statistics marker proves two vertical bars to demarcate a region for calculating the average and standard deviation of particle counts.

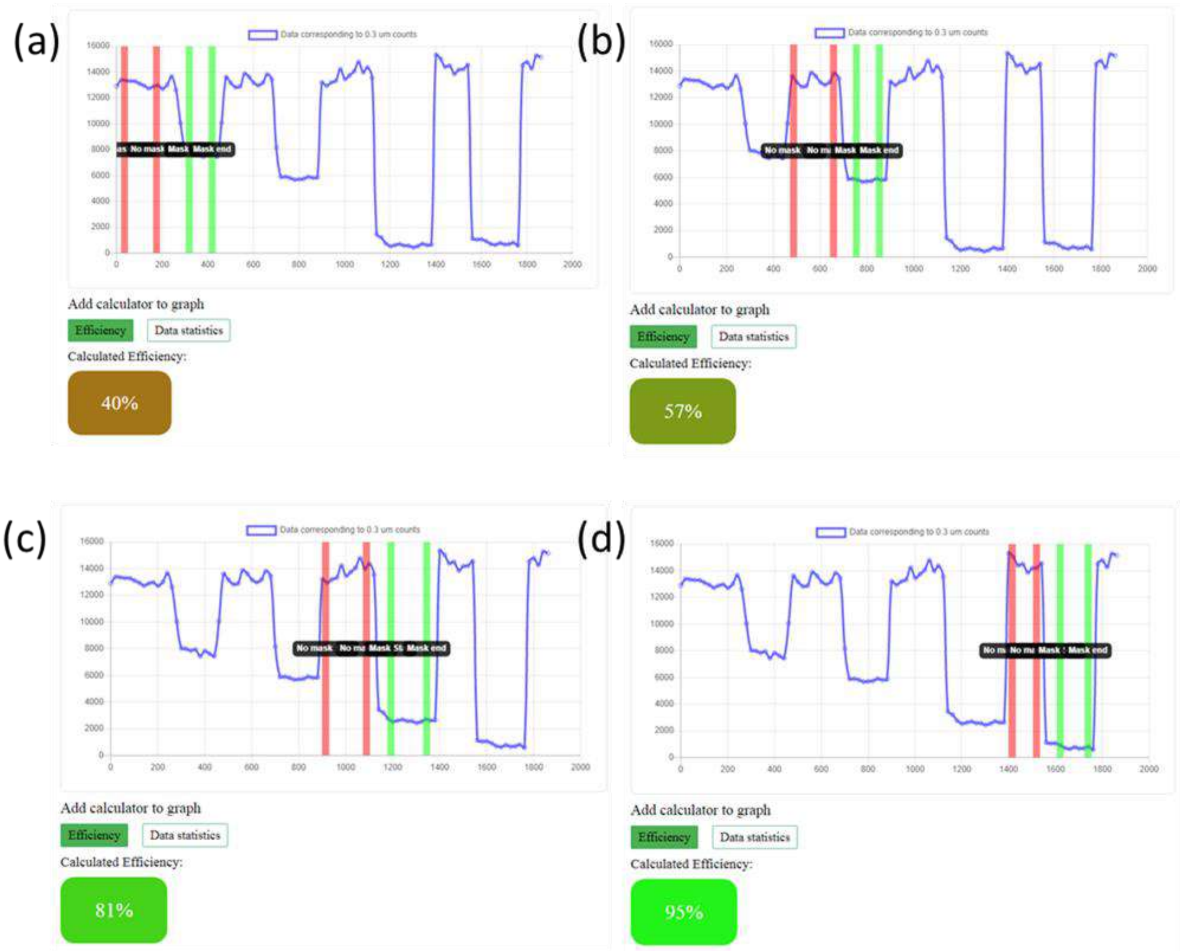

Fig. 3: Screenshots of efficiency calculation of data for 4 masks of progressively increasing efficiency showing the colour coding of calculated efficiency displayed.

Fig. 3 shows measurements of 4 masks of progressively increasing efficiency (40% to 95%). To make the visual display of information more intuitive, the background colour of the efficiency is colour coded from red for a poorly filtering mask to light green for the highest PFE values.

Another useful feature of our code is the ability to modify parameters (e.g. change WiFi name and password, acquisition rate in seconds etc.) via OTA (over the air) updates through the WiFi network without having to connecting the MCU physically to a computer. Detailed procedures are available in the relevant section of the GitHub repository.

The GitHub repository https://github.com/shescitech/TIFR_Mask_Efficiency has 4 sections:

- arduino – instructions and code to integrate the Plantower PMS7003 with any ESP8266 based board (Wemos D1 R2, Wemos D1 mini, Nodemcu etc) and stream the particle count data to a local http web server
- design – overall project design guide and pictures
- python – instructions and code to access to real time data from the particle counter
- web – instructions and code to visualize the particles count and calculate mask PFE, data statistics, save data and graphs, upload and view previous measurements etc.

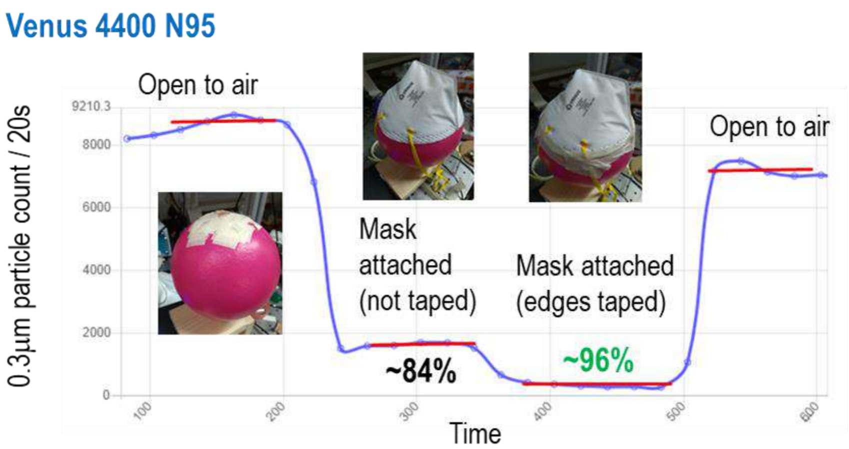

Fig. 4: Tests on a Venus V-4400 series N95 mask showing the importance of taping the edges to prevent ingress of particles from the side of the mask. The PFE increases from 84% to 96% on sealing the sides of the mask with paper tape.

As an example we show an interesting observation in Fig. 4 illustrating the importance of proper fit of the mask on a mannequin. In particular, we point out that the hard plastic ball used is spherical, and hence does not naturally fit perfectly well onto a typical mask especially in the region around the nose clip, and also at the seams (especially since some of these non-stitched masks have thick fused seams. Hence is there significant leakage of air from the sides of the mask which determines the ingress of particles, and unless the mask is well sealed to ensure that the only particles which enter are those passing through the mask material, quantitative in measurements are likely to give incorrect results! Note that one expects a far better fit on the contours of a human face, due to the shape of an N95 mask, the nose clip, and the softer nature of skin as compared to the hard plastic. Though the data exaggerates the nature of the problem, this is an important point with implications for practical use of masks as well. The best N95 mask, if improperly worn or ill-fitting can be dangerous in a real-world situation.

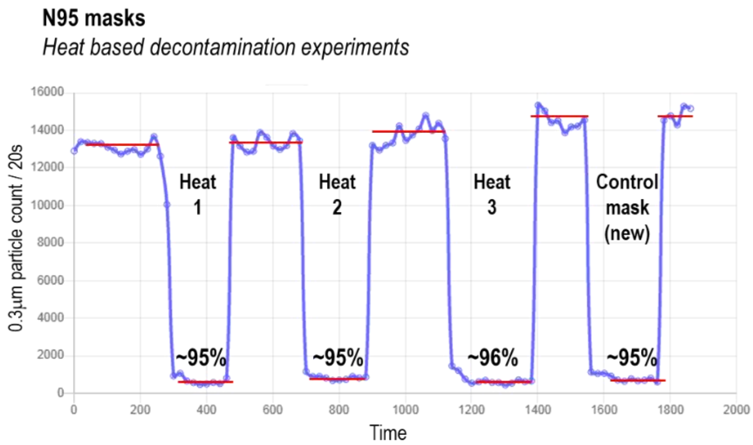

Fig. 5: Tests on series of heat-based decontamination experiments on N95 masks.

The ability of the setup to make relative measurements is also very useful as seen in the example in Fig. 5. Three N95 masks were subjected to different heat cycling experiments and their PFEs compared to that of a control (pristine) mask. Such quick measurements are essential while developing any protocol for decontamination and re-use, where masks much be checked for any change in their PFE pre- and post-treatment. For this a simple setup like our mask PFE tester is ideal.

Acknowledgements:

We acknowledge several useful discussions with the N95decon team (N95decon.org) especially the information on their Slack channel for solutions for LMI countries. We thank Tata Memorial Hospital, Mumbai for sending us many samples of N95/FFP2, and surgical masks for testing our setup. We acknowledge Ronak Sutaria, Respirer Living Sciences; A Azizur Rahman and Prajakta Dhumal, TIFR; and Sanjay Ingale, BMek, for various inputs, assistance and useful discussions.

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[1] https://www.who.int/emergencies/diseases/novel-coronavirus-2019/advice-for-public/when-and-how-to-use-masks
[2] K. W. Lee & B. Y. H. Liu, On the Minimum Efficiency and the Most Penetrating Particle Size for Fibrous Filters, Journal of the Air Pollution Control Association, 30, 377-381 (1980)
[3] A good summary is available at https://n95decon.org
[4] Used mask testers e.g. MITA 8120 from TSI or AccuFIT9000 from Accutec-HIS sell for >5000 USD on eBay!
[5] https://s3.amazonaws.com/public-inspection.federalregister.gov/2020-07659.pdf
[6] L.C. Marr, Virginia Tech. Univ., https://docs.google.com/document/d/1eFkaliSLbbFzLwOgnTLr3CTfdN3KrVxAbZbJLS86-4o/
[7] Prakash group, Stanford, https://docs.google.com/document/d/1zInS5npxCcTHxyG_4F2spCf274HL31bDbiNRcHQrvNI/

[8] A. I. Nazeeri, et al. An Efficient Ethanol-Vacuum Method for the Decontamination and Restoration of Polypropylene Microfiber N95 Medical Masks & Respirators, medRxiv 2020.04.12.20059709v2
[9] D. Provenzano, et al., Alternative Qualitative Fit Testing Method for N95 Equivalent Respirators in the Setting of Resource Scarcity at the George Washington University, medRxiv 2020.04.06.20055368
[10] http://www.plantower.com/en/
[11] M.L. Zamora, F. Xiong, D. Gentner, B. Kerkez, J. Kohrman-Glaser, K. Koehler, Field and Laboratory Evaluations of the Low-Cost Plantower Particulate Matter Sensor, Environ. Sci. Technol., 53, 838–849 (2019)