# Computational Investigation of The Exhalation Process with and Without Wearing a Protective Mask

Islam Ahmed Mohamed Mohamed El Sayed[1,*], Ahmed Farouk AbdelGawad[1]

[1] Mechanical Power Engineering Dept., Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt

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**ABSTRACT**

This paper shows different simulations of airflow patterns for the human face during exhalation with and without wearing a protective mask. The nasal airways were defined based on biological anthropology and medicine instructions. A three-dimensional body-manikin of African athlete of 1.8 meters tall was employed to the expiration (exhalation) flow study using ANSYS-Fluent software. There were two different mask models included in the flow simulations and were manufactured by means of 3D-printing technology. The two manufactured masks were designed using SolidWorks software. The study was carried out four times during the exhalation process of a human wearing the two masks and without wearing them. The velocity magnitudes were significantly different while wearing the mask in comparison to the cases of not wearing it. The results demonstrate the capability of using 3D-printed masks as a replacement of the traditional medical masks (i.e., N95 and surgical masks) with retaining the same functions of the protective mask. Thus, based on the present study and due to the great shortage of surgical and medical masks availability locally and globally, the 3D-printed masks might be a temporary solution to limit the vast spread of contagious diseases like the dangerous COVID-19 outbreak.

## 1. Introduction

### 1.1 Background

In recent years, both experimental and computational researches have been done to study the dispersion of aerosols and particles in different environments [1-7]. However, the spread of aerosols, and droplets generated during different human respiratory activities (e.g., inhalation and exhalation) has been of special interest. Exhalation in closed and crowded environments may cause dispersion of small airborne particles that might be produced from an infected patient or a contagious disease carrier such as SARS (Severe Acute Respiratory Syndrome) which started in China in 2003, MERS (Middle East Respiratory Syndrome) which was first reported in Saudi Arabia in 2012, recent COVID-19 (2019 novel coronavirus or "2019-nCoV"), and other infectious diseases that attack the respiratory system and lungs [8-12].

* Corresponding author.
E-mail address: eslam.elsayed@ejust.edu.eg

Wearing a face mask is certainly not an iron-clad guarantee that humans won't get infected. Viruses can also be transported through the eyes. Tiny viral particles, known as aerosols, can penetrate masks. However, masks are effective at capturing droplets, which is a main transmission route of coronavirus. Health care workers can be exposed to patients with infections. To minimize exposure to airborne infectious agents, health care facilities (e.g., hospitals and health care centres) use isolation rooms, negative pressure ventilation, air filtration and disinfection. However, in certain settings, administrative and engineering controls may not adequately protect health care workers from contaminated airborne droplets.

So, it is of great importance to study the transport and motion of the exhaled particles in the respiratory tract and even after exhalation process. Understanding the flow pattern of particles and droplets can aid in reducing infection rates of respiratory diseases.

*1.2 Exhalation Process Flow Simulation*

In the present study, CFD (Computational Fluid Dynamics) simulation models were developed for an adult African body-manikin with lungs of interior volume 2-2.5 liters of air with approximately inhalation time of 2 seconds and exhalation time of 3 seconds [13-15].

Learning the flow patterns in the realistic human nasal openings (nostrils) is important to predict the minimum distance that must be kept away from a disease carrier who does not wear a mask. Also, it is vital to emphasise that putting on a protective mask could prevent particles from travelling further. Wearing a mask not only hinders large particles from passing through filter layers, but also decelerates smaller particles and reduces their velocities and as shortens their travel paths. That is why there is a great necessity for a flow simulation of the human exhalation process.

Thus, CFD models are described in this paper for the human head and the full body with and without face masks. A human head, and a full-body manikin were imported and modified by adding the nasal cavities (nostrils) to be suitable for the simulation [16,17]. Meshing was done by the "Meshing tool" in ANSYS-Fluent software version 17.1. The minimum element size was 0.001 mm (i.e., 1 micron) with inflation rate of 1.2 and global mesh sizing of minimum at proximity and curvatures captures to ensure that the study is precise and the results are accurate.

*1.3 Present 3D-Printed Masks*

Concerning the present 3D-printed masks, the first mask was made from PLA (Polylactic acid) plastic material due to its availability and its low cost. PLA is the most widely used plastic filament material in 3D-printing. The second mask was decided to be made from PETG filament (Polyethylene terephthalate glycol), which is a thermoplastic polyester. PETG provides significant chemical resistance, durability, excellent formability for manufacturing, high flexibility to conform to any face size, suitability for variety of head dimensions [18-21].

This paper describes reliable, durable, and reusable 3D-printed face masks that might be useful for people and health care workers (i.e., doctors, nursing stuff) to reduce infection of COVID-19 outbreak. The prescribed masks were designed upon medical instructions, and world health organization (WHO) regulations.

*1.4 Calculation of Outlet Velocity from Nasal Openings*

Considering the anatomy of the human nose, Figure 1, the following assumptions are to be stated
 i.    No pressure losses due to friction in the interior path from the lungs to the nose tip.

ii. The nostril area is assumed to be circular with 1.0 cm-diameter.
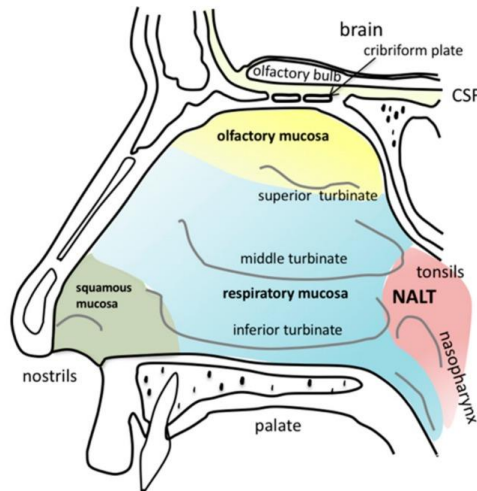iii. The discharge coefficient is not considered.



**Fig. 1.** Anatomy of the human nose [22]

Table 1 illustrates the Anthropometry with detailed dimensions of nostril for African, Asian, and European males and females [23].

**Table 1**
Detailed dimensions of nostril for African, Asian, and European males and females [23]

| Population | W. African | W. African | E. Asian | E. Asian | N. European | N. European | S. Asian | S. Asian |
|---|---|---|---|---|---|---|---|---|
| Sex | Male | Female | Male | Female | Male | Female | Male | Female |
| N[a] | 10,6,10 | 30,28,30 | 43,33,43 | 84,74,84 | 91,91,91 | 145,144,145 | 42,35,42 | 31,26,31 |
| Height (cm) | 179.89[b] (6.48) | 164.68 (8.61) | 173.02 (6.79) | 159.94 (6.23) | 181.00 (7.72) | 167.15 (6.70) | 173.91 (6.13) | 157.74 (6.72) |
| Melanin Index (% reflectance) | 59.23 (9.68) | 60.27 (11.34) | 31.42 (2.94) | 32.63 (2.94) | 26.71 (2.68) | 28.19 (2.60) | 38.50 (5.82) | 39.89 (4.72) |
| Nares width (mm) | 45.36 (2.74) | 39.50 (2.95) | 38.55 (2.28) | 34.35 (2.02) | 34.29 (2.42) | 30.91 (2.07) | 37.47 (2.59) | 33.20 (1.89) |
| Alar base width (mm) | 45.31 (2.61) | 40.57 (2.56) | 39.98 (2.31) | 36.60 (1.93) | 35.66 (2.53) | 33.00 (1.98) | 37.77 (2.57) | 34.33 (1.92) |
| Nasal height (mm) | 51.31 (2.36) | 49.15 (3.04) | 52.35 (2.52) | 48.76 (2.03) | 51.59 (2.64) | 48.62 (2.11) | 50.81 (2.34) | 47.31 (2.13) |
| Nasal ridge length (mm) | 46.31 (2.63) | 43.82 (2.76) | 47.14 (2.59) | 43.41 (2.24) | 47.82 (2.78) | 44.78 (2.37) | 46.59 (2.35) | 43.57 (2.47) |
| Nasal tip protrusion (mm) | 15.94 (1.44) | 14.43 (0.98) | 15.81 (1.35) | 14.47 (1.11) | 17.62 (1.25) | 16.43 (1.02) | 16.60 (1.23) | 15.68 (1.26) |
| External surface area (mm) | 1782.13 (122.92) | 1477.42 (167.39) | 1604.73 (154.02) | 1315.35 (100.95) | 1758.72 (153.36) | 1470.61 (118.68) | 1719.14 (134.48) | 1422.48 (122.86) |
| Nostril area (mm) | 70.17 (10.41) | 57.18 (9.75) | 57.59 (7.61) | 45.40 (4.77) | 54.46 (5.97) | 45.80 (5.13) | 60.83 (8.87) | 48.52 (6.48) |

Thus, based on the previous assumptions and Table 1, the following tabulated inputs (Exhalation time, nostril diameter, and the interior volume) and outputs (Area, flow rate, and velocity at exit) in Table 2 can be obtained.

**Table 2**
Input and Output Parameters of the Exhalation process to compute the exit velocity from the Nostril

| Input Parameters | | Output Parameters | |
|---|---|---|---|
| Volume occupied in lungs | 1.0 liter | Area | 0.8 cm$^2$ |
| Exhalation time | 3-4 sec | Volume flow rate | $0.333 \times 10^{-3}$ m$^3$/sec |
| Nostril diameter | 1.0 cm | velocity at the nostril exit | 2 m/s |

## 2. 3D-Printed Masks

*2.1 CAD Drawings and Basic Dimensions*

This section illustrates the details of the two manufactured masks, which were designed using SOLIDWORKS software version 2018. The design of the two masks was based on Anthropometry details that are described in Table 1 for an African male [23].

*2.1.1 Mask (1)*

For this mask, computations were limited only to the head of an adult male with an average head size. A close view of the mask is shown in Figure 2. Description of the human head with overall dimensions are shown in Figure 3.



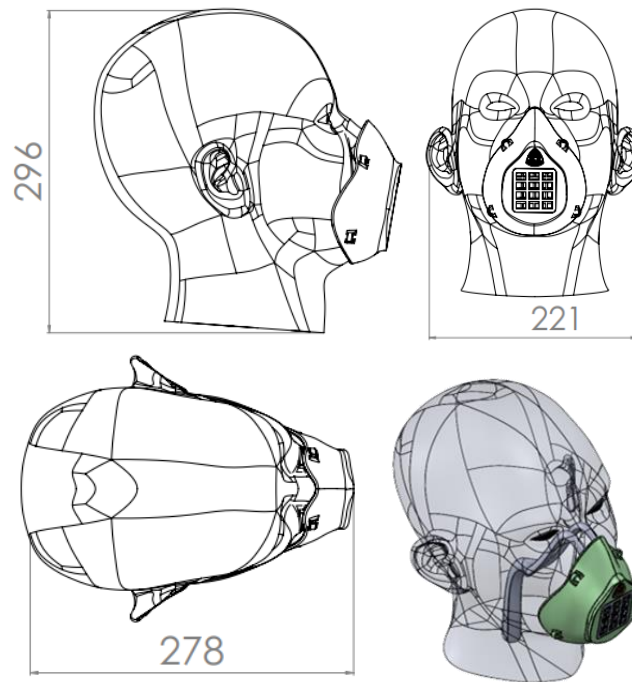**Fig. 2.** Assembly of the human head and Mask (1)

**Fig. 3.** Description of the human head with overall dimensions for Mask (1) (Dimensions in mm)

*2.1.2 Mask (2)*

For this mask, computations were extended to the whole body of an adult male with an average head size. A close view of the mask is shown in Figure 4. Overall view and dimensions of the human-body manikin for Mask (2) are shown in Figure 5.

It is noticed that, in Figure 5, some details; such as the hands with fingers were omitted as they do not affect the present study. It was found that considering the two hands increases significantly both the computational effort by the requirement of mesh refinement, and simulation run-time.



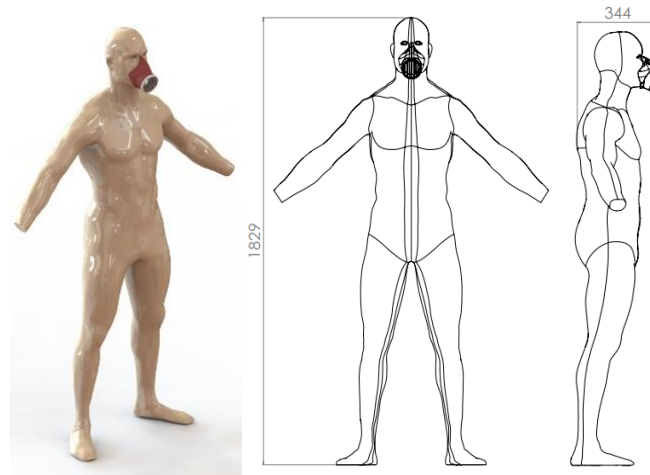**Fig. 4.** Assembly of the human head and Mask (2)

**Fig. 5.** Overall dimensions of the human-body manikin for Mask (2)

As shown in Figure 4 and Figure 5, the second mask was equipped with a screw cap to simplify the filter replacement and in the same time maintains the necessary tighten.

## 2.2 Manufacturing of Masks

3D-printing or additive manufacturing technology is most suited for such applications of the present work. 3D-printing enables the production of complex shapes using less material than traditional manufacturing methods [24-27]. To be printed, the two manufactured masks were designed using SOLIDWORKS software version 2018, then converted into G-code using MakerBot software version 2.8.

Several thermoplastic materials (filaments) can be used in this technology as can be seen in Table 3, which gives a brief comparison between them. The material requirements for such job may be listed as (1) cheap, (2) elastic, (3) durable, and (4) no health hazard.

**Table 3**
Comparison between the most common thermoplastic materials that used in 3D-printing [28]

| No. | Type | Advantages | Disadvantages |
|-----|------|------------|---------------|
| 1 | ABS | - Tough<br>- Common<br>- Non-toxic | - High melting point<br>- Unpleasant fumes |
| 2 | PLA | - Easy to print<br>- Biodegradable<br>- Cheapest | - Degrade over time<br>- Rough texture |
| 3 | PVA | - Water soluble<br>- Fairly easy to print | - Expensive<br>- Risk of toxic fumes |
| 4 | Nylon | - Tough<br>- Inexpensive | - High temperature |
| 5 | HDPE | - Easy to dissolve<br>- Lightweight | - High temperature |
| 6 | PETG Flexible Filament | - Produces flexible products<br>- Lightweight | - Printer tinkering |

Thus, PLA filament was selected for the Mask (1) because of its very low cost, and availability in the local market. Figure 6 shows the printed Mask (1). For Mask (2), Figure 7, PETG flexible filament was chosen due to its high flexibility, which satisfies two main goals

i.     Mask can easily conform to the features of any face.
ii.    Mask ensures no existence of possible gaps between the face and the mask.



**Fig. 6.** 3D-printed Mask (1)



**Fig. 7.** 3D-printed Mask (2)

*2.3 Manufacturing Considerations of Masks*
*2.3.1 Material*

As can be seen in Figure 6 and Figure 7, the two printed masks were tested for real operation. Thus, to be suitable for different face sizes and features, it is necessary to select a very flexible and soft material for 3D-printing such as "PETG Flexible Filament" of Mask (2). PLA material of Mask (1) was not flexible enough to conform to the face details, which caused some air gaps and as a result, Mask (1) is not fully protective.

*2.3.2 Cost*

It is somehow expensive for 3D-printing of masks. However, 3D-printing produces complex shapes using less material than traditional manufacturing methods. Moreover, 3D-printing is capable of producing products (masks) that are more complicated than other manufacturing methods.
The mask cost is divided into two parts, namely

i.     Raw material cost: It depends on the type of material and the corresponding weight in grams, e.g., 1 gram of PLA costs 2 EGP.

ii.    Machining or machine time cost: It depends on the type of the 3D-printer and operator pricing. Technicians specify definite cost (in EGP) for each minute of the 3D-printing.

## 2.3.3 Other manufacturing techniques

When there is no big catastrophic challenge such as coronavirus, other production techniques may be suggested. Plastic-injection molding by using one die is a very time saver and suitable for mass production. Also, vacuum dies (molding) may be utilized in mass production of masks.

Another manufacturing method is the use of composite materials, which is relatively cheap, to produce the required masks. However, there are health hazard concerns of glass and carbon fibers that should be considered.

## 3. Computational Simulations
### 3.1 Computational Aspects

The computations were carried out by ANSYS-Fluent software version 17.1. To clearly demonstrate the effect of the two masks, the computations covered four cases as shown in Table 4.

**Table 4**
Computational investigated cases

| Case No. | Mask No. | Description | Nostril velocity (m/s) |
|---|---|---|---|
| 1 | 1 | Breathing without mask | 2 |
| 2 | 1 | Breathing with mask | 2 |
| 3 | 2 | Breathing without mask | 2 |
| 4 | 2 | Breathing with mask | 2 |

Although the magnitude of the exhalation velocity is small and due to the complexity of the flow passage, the flow was treated as turbulent. The flow was considered steady, and incompressible. k-$\varepsilon$ model, with standard wall function, was adopted as the turbulence model. Also, gravity effect was considered.

The computational domain was a parallelepiped with enough dimensions to guarantee full analysis of the exhalation flow. The computational meshes were constructed by tetrahedral elements. Careful consideration was really paid to get mesh-independent solution. The number of elements of mesh was increased, with required refinements, until no further change of solution was noticed. The number of mesh elements was 1,000,823 and 1,420,921 for Mask (1) and Mask (2), respectively.

Figure 8 to Figure 10 show the computational mesh for the different cases with and without masks. The mesh elements were concentrated and refined at the human head and body, and mask.
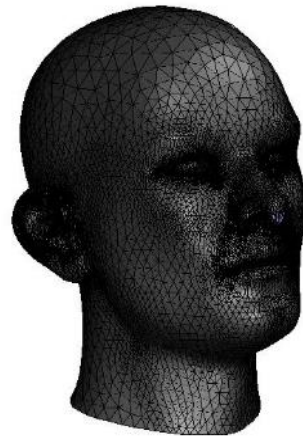
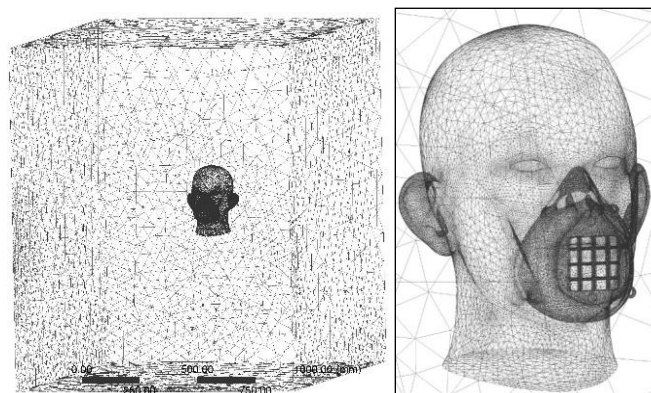**Fig. 8.** Meshing of human
head without Mask (1)



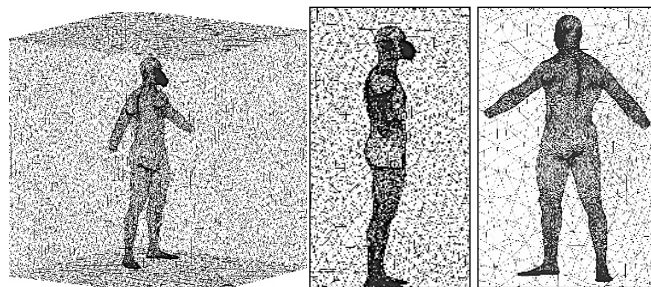**Fig. 9.** Doman and human head meshing with Mask (1)



**Fig. 10.** Different views of the meshing of the domain
and human body with Mask (2)

## 3.2 Results and Discussions

In the present study, the main criterion to judge the effectiveness of the mask is the strength of the exhalation flow represented by the velocity values in front of the human head.

### 3.2.1 Mask (1)

Figure 11 and Figure 12 show two views of the flow streamlines and velocity magnitudes of the exhalation flow of the human head without Mask (1), case (1), and with Mask (1), case (2), respectively, at nostril velocity of 2 m/s.

When comparing Figure 11 and Figure 12, it is clear that wearing Mask (1) causes a noticeable reduction in the exhalation velocity out of the nose. This is a very good indication that Mask (1) weakens the exhalation flow, which means that the possibility of infection is reduced.
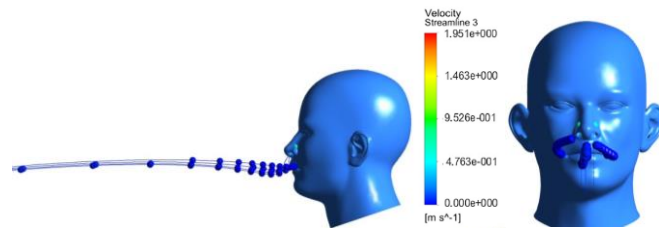


**Fig. 11.** Flow streamlines and velocity magnitudes for human head without Mask (1), case (1)
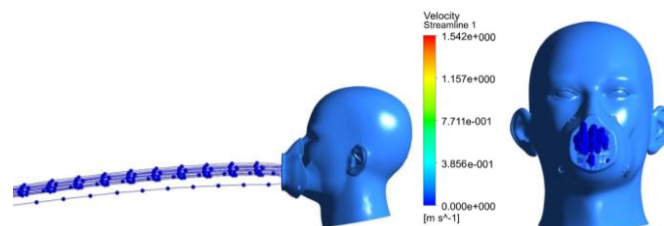


**Fig. 12.** Flow streamlines and velocity magnitudes for human head with Mask (1), case (2)

Figure 13 shows four close views of the flow streamlines of the exhalation flow of the human head without Mask (1), Figure 13(a) case (1), and with Mask (1), Figure 13(b) case (2), respectively.
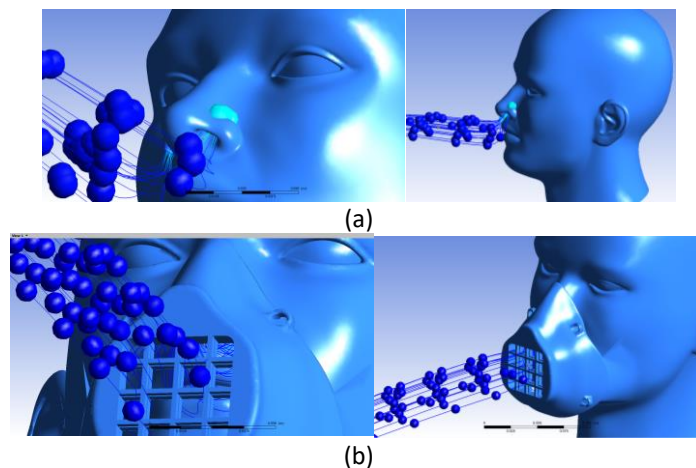


(a)



(b)

**Fig. 13.** Close views of the flow streamlines of the exhalation flow of the human head without and with Mask (1); (a) without Mask (1), (b) with Mask (1)

*3.2.2 Mask (2)*

Figure 14 and Figure 15 show two views of the flow streamlines and velocity magnitudes of the exhalation flow of the human body without Mask (2), case (3), and with Mask (2), case (4), respectively, at nostril velocity of 2 m/s.

Again, when comparing Figure 14 and Figure 15, it is obvious that wearing Mask (2) causes a small reduction in the exhalation velocity out of the nose. This is a good indication that Mask (2) weakens the exhalation flow, which means that the possibility of infection is reduced. Also, the pattern of the exhalation flow differs when wearing Mask (2).
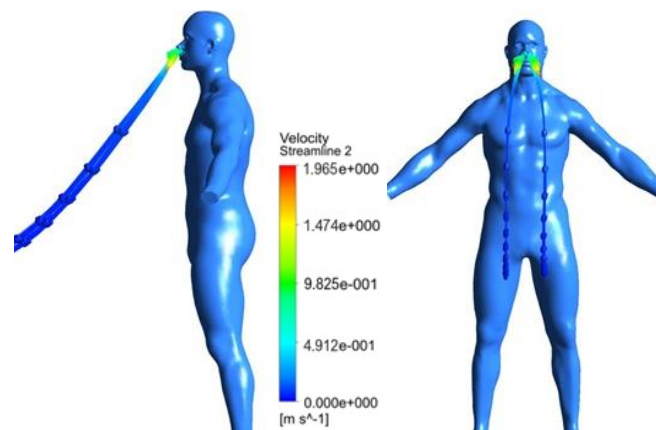


**Fig. 14.** Flow streamlines and velocity magnitudes for human body without Mask (2), case (3)
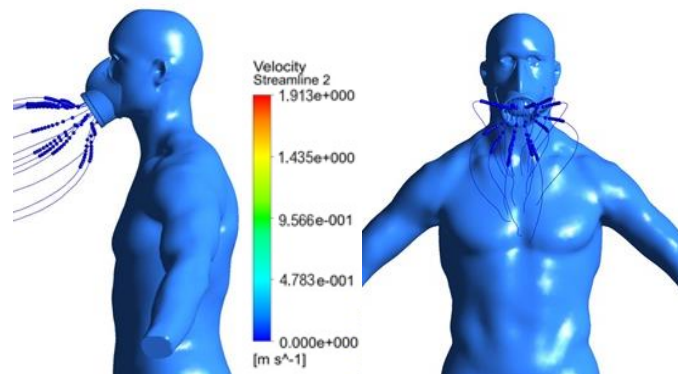


**Fig. 15.** Flow streamlines and velocity magnitudes for human body with Mask (2), case (4)

Figure 16 shows four close views of the flow streamlines of the exhalation flow of the human head without Mask (2), Figure 16(a) case (1), and with Mask (2), Figure 16(b) case (2), respectively.
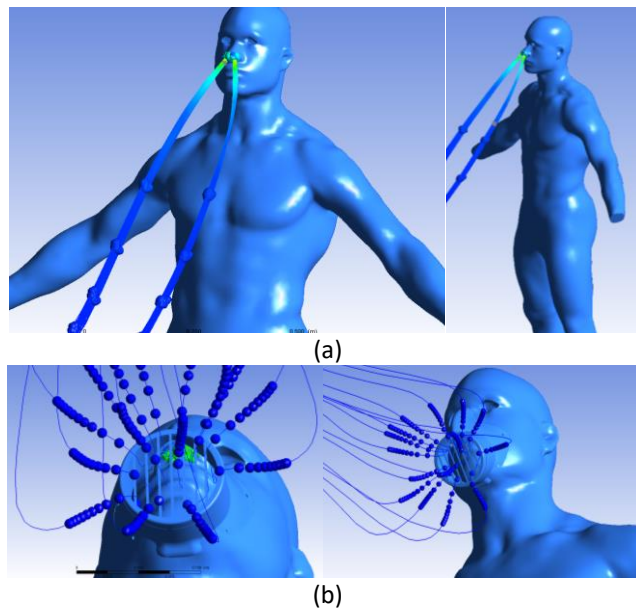
(a)



(b)

**Fig. 16.** Close views of the flow streamlines of the exhalation flow of the human head without and with Mask (2); (a) without Mask (2), (b) with Mask (2)

### 3.2.3 Comparison between Mask (1) and Mask (2)

Based on the results of the two previous sections, a comparison between the two masks can be carried out. Figure 17 shows a comparison between the magnitudes of the maximum velocity (Vwm) for the exhalation flow, just out of the nose, with and without Mask (1) and Mask (2).

It is clear from Figure 17 that the reduction of the maximum velocity due to Mask (1), case (2), is better than the reduction of Mask (2), case (4). This is may be attributed to the obvious differences in the shape and structure of the two masks.

Figure 18 shows a comparison between magnitudes of the velocities (Vm) for the exhalation flow, just out of the mask, for the two masks.
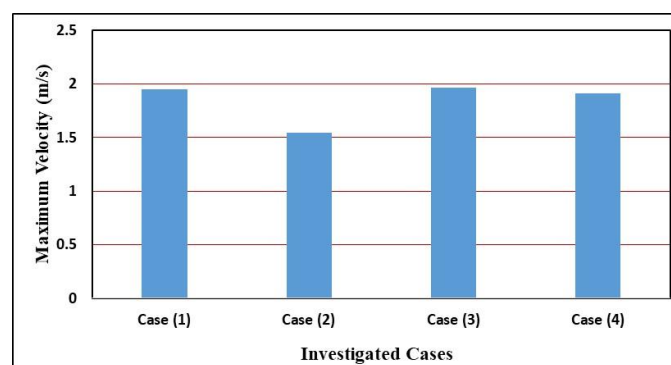


**Fig. 17.** Comparison between magnitudes of the maximum velocity (Vwm) for the exhalation flow, just out of the nose, with and without Mask (1) and Mask (2)
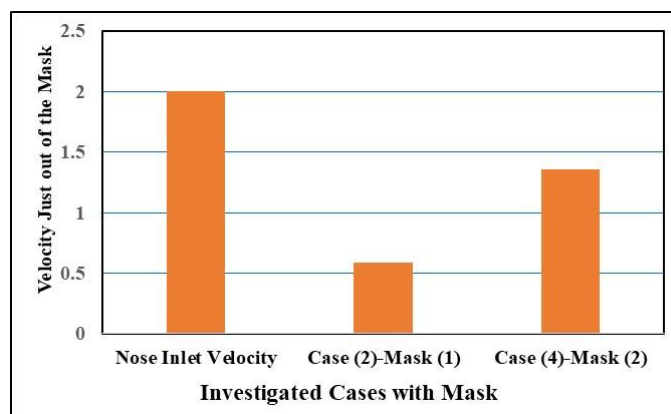
**Fig. 18.** Comparison between magnitudes of the velocities for the exhalation flow, just out of the mask, for the two masks

Again, Figure 18 ensures that the reduction of the velocity due to Mask (1), case (2), is better than the reduction of Mask (2), case (4).

The percentage velocity reduction (Pr) may be calculated from the following equation

$$P_r = [(V_{wm} - V_m)/V_{wm}] \times 100 \tag{1}$$

Thus, the percentage velocity reduction (Pr) is 62.1% for Mask (1), and 29.2% for Mask (2), repectively. However, this also indicates that it is more difficult to breathe using Mask (1) than using Mask (2).

Consequently, when choosing the suitable mask, a compromise should be made between the ease of breath and the reduction of breath velocity, which means less spread of possible infection.

## 4. Conclusions

The present paper demonstrates investigation of the exhalation flow patterns with and without wearing a protective mask. Two different masks were manufactured and considered for computational simulation. Based on the above results and discussions, the following concluding points can be stated

   i. Wearing masks has greatly affected the flow patterns exiting from nostril during the exhalation process.
   ii. The change of the flow pattern and velocity reduction depends greatly on the mask shape and structure.
   iii. Wearing masks results in the reduction of the velocity values in front of the human head, which means that masks considerably weaken the exhalation flow. Reduction reaches values of 62.1%.
   iv. From one point of view, Mask (1) may be prefered over Mask (2) due to reduction of the velocity values in front of the human head, which means weaker breathing flow with less infection probability.
   v. From another point of view, Mask (2) may be better than Mask (1) due to the flexible material of Mask (2), which enables the mask to fit completely to the face. Also, it enables easier breathing.
   vi. When looking for a suitable mask, a compromise should be made between the ease of breath and the reduction of breath velocity, which means less spread of possible infection.

vii.    Production cost of masks by 3D-printing is somehow higher than other production techniques. However, 3D-printing gives a quick and temporary alternative solution to cover the high shortage or lack in surgical and traditional masks.

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