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Finite element analysis over transmission region of coronavirus in CFD analysis for the respiratory cough droplets

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ABSTRACT

The pandemic outbreak of COVID-19 is worldwide now which requires a novel solution to control the fast-spreading virus. The coronavirus analysis over the contaminated area and its speed of transmission if examined can prevent the spread of COVID-19. A wide range of such problems could be simplified through finite element analysis for a better solution. Many computational fluid dynamics problems could be solved by the finite element method (FEM) effectively by utilizing finite elements. A remarkable linear triangular element meshing over the transmission region between the individuals has been generated by triangular unstructured meshes to analyze the velocity of the virus. The flow intensity of the coronavirus has been analyzed within the standard specified distance recommended by WHO between two individuals at 1.83 m to hinder the spread of COVID-19. Extended work has fabulously extracted the element and nodal information from the discretization region. Moreover, it has been effectively utilized to simplify the numerical solutions of FEM and improve its efficiency to a larger extent. We have discretized the region of transmission of respiratory cough droplets carrying coronavirus from an infected person and the intensity and the speed of the transmission have been computed. The velocity of the transmission of coronavirus has been analyzed by solving an elliptical partial differential equation (PDE) over the region around the mask of an infected individual at a specified distance of 1.83 m. Infectious transmission of COVID-19 in different environmental conditions is of numerous complexities to work on and analyze the growth of the infectious coronavirus. Mathematical models formulated for respiratory cough droplets carrying coronavirus can be very efficiently simplified through FEM when the information of the velocity of flow and existence of the coronavirus at the particular stage of transmission region is known. The present study of different temperatures and analysis of wind factors during the transmission process can help to reduce the infection risk between individuals if the recommended specified distance is maintained within the individuals. It is very helpful to formulate and implement a suitable guideline for this pandemic time.

1. Introduction

This outbreak of the unexpected virus attack of coronavirus in the year 2019 has drastically changed the whole world [1–4]. The infectious disease came into existence widespread in many parts of the country. A variety of inventions and discoveries are required to control the spread of this infection from an infected person to a normal person [5]. The region surrounded by an infected person can unknowingly carry the virus through wind, coughing, sneezing which would be transmitted to an uninfected person. The region through which the virus gets transmitted can reduce the intensity of the virus or drastically increase its trans-

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mission depending on the environmental factor. The virus SARS-CoV-2 ( Severely Acute Respiratory Syndrome) transmits through the infected person’s cough [6] drops while speaking or coughing with a mask and without the mask [7]. Usage of the mask can reduce the risk to a larger extent than by an infected person without the mask. The transmission of the virus SARS-CoV-2 occurs in both the region around an infected person with a mask and without a mask.

There were many myths due to unavailable facts regarding the spread of the virus between the individuals. Indeed, many disposable respirators came into practice to disinfect the cycle of virus growth. An active introduction of N95 with better protection layers claimed to protect the virus from getting infected. There was a sudden increase in the usage of N95 masks and subsequently, its demand also raised along with PPE (Personal Protective Equipment). The combined efforts of the better-quality respirators and the study of the impact of the virus SARS-CoV-2 in the transmission region can result in many innovative results [7] to control the spread of the virus.

Many airborne diseases are caused due to transmission of infectious bacteria and viruses present in the environment. The present situation of spreading COVID-19 is also associated with the transmission of coronavirus through the air [8–10]. Moreover, an infected person who coughs with the mask and without the mask could also have a possibility of spreading the disease to another person through the air. It’s an avoidable situation in the present scenario but the crucial conditions can be reduced with individuals’ understandings. The carrier droplets in sneezing [38,48] and coughing from an infected can initiate the spread of the COVID-19 and many respiratory diseases [32,35–36].

The impact of the air quality is another factor responsible for the speedy growth of the coronavirus. Emission of air pollutants to the atmospheric layer due to the pollutants like black carbon and nitrogen dioxide is caused by the impact of the traffic flows in major cities [8]. This unprecedented impact of pollutants reduces the air quality [8–10]. The air quality of a few countries and the fast spread of the disease has been discussed in [8–11]. There is a potential risk factor on water bodies as well in the transmission of coronavirus. The potential risk has been analyzed for the spread of the virus in water bodies via environmental factors [12–14,40]. A model has been framed and the multiple linear regression together has been used to evaluate the spread of the risk factor in a few typical rivers in Hubei [14]. The probability of adverse effects in human beings due to this risk factor has been discussed in [15–16].

Reference [48] depicts the numerical modeling [21,28,39] of the distribution of the virus when an infected person performs human acts such as coughing [38] and sneezing. The microbial pathogens carrying the virus when exhaled during the transmission process can cause violent respiratory diseases [30]. By examining different parameters of microbial droplets such as velocities, size distribution, and injection angles of these droplets, a maximum infectious area has been predicted. The work has been correlated with the governing incompressible Navier Stokes equation given by Equation (1) and (2):

\[
\rho \frac{\partial u_i}{\partial t} + \rho u_i \frac{\partial u_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \mu \nabla^2 u_i + \rho g i, j = 1, 2
\]  

and

\[
\frac{\partial u_i}{\partial x_j} = 0
\]

where \(u_i\) denotes the velocity component of virus in \(x\) the direction of flow, \(\rho\) is the flow density, \(P\) is the pressure, \(g\) the component of gravitational acceleration in the \(x\) direction, and \(\nabla^2\) is the Laplacian operator. Neglecting the compression and viscous dissipation, the equation for conservation of thermal energy is given by Equation (3):

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p u_i \frac{\partial T}{\partial x_i} = k \nabla^2 T
\]

where \(T\) is temperature, the fluid-specific heat, and \(k\) is the fluid thermal conductivity. The unknown terms such as velocity, pressure, and temperature i.e., \(u_1, u_2, P\) and \(T\) respectively can be expressed in terms of interpolation formulas over each finite element which can be accomplished by the shape functions. The estimated solution fields take the form of Equation (4):

\[
u_i = \{N_i\}^T \{u_k\}
\]

\[
P = \{N_i\}^T \{p_k\}
\]

\[
T = \{N_i\}^T \{T_k\}
\]
These non-linear equations Equation (1) – (3) when simplified with finite element method reduces to Equation (5):

\[ [k][u] = [F] \]  

The component entries can be expressed in the system of linear equations as given by Equation (6):

\[
\begin{bmatrix}
{k^{n_n}} & 0 & 0 \\
0 & {k^{n_2}} & 0 \\
0 & 0 & {k^{n_1}} \\
\end{bmatrix}
\begin{bmatrix}
{u_1} \\
{u_2} \\
{u_3} \\
\end{bmatrix}
= 
\begin{bmatrix}
{f^1} \\
{f^2} \\
{f^3} \\
\end{bmatrix}
\]  

(6)

Applying the boundary conditions while computing fluid flow in a region requires a major criterion that is the conservation of mass. This conservation of mass of the system could be enforced directly by many methods which have been performed by various researchers [17–18]. Incompressible continuity equation gets reduced to the form [18] as given in Equation (7):

\[ \nabla^2 \phi = -D \]  

(7)

The solution of the potential function \( \phi \) represented by Equation (7) satisfies the conservation of mass in the velocity field produced. Fortunately, it provides convergence characteristics for many problems for which it has been applied [18]. In the present work, it has been simplified over the transmission (between the individuals) region of coronavirus with the intensity of coughing and sneezing of an infected person.

3. Transmission region of the coronavirus between individuals

The places which are experiencing cold weather and preparing to face winter climate may go through major challenges of the spread of coronavirus. The impact of the COVID-19 pandemic still needs investigations in terms of the aerial habitats. The persistence of the virus on the surfaces and the spread of the virus through aerial habitats could control influence to a greater extent. Correlation analysis between the epidemic and meteorological data can be seen in many present studies related to COVID-19 [19–20].

In this most infectious environmental context, triangular meshing in the region of active transmission of the virus is an effective adjunct. The present proposed methodology can be effectively incorporated in the present extensive pandemic requirement to disinfect the flow of the virus and to prevent its further growth and function in the transmission region. Consider the transmission region between the individuals to be a rectangular region of 1.83 m length and 1 m breadth. This region requires the study [37, 43] and further investigation of the growth of the coronavirus.

The maximum transmission takes place in this region from an infected person to an uninfected person. The rate of transmission is considered more without mask [7] than with mask by the infected person.

The complexity of the human airways and the breathing process limit the application of in vitro measurements to only two consecutive branches of the human airway. Herein, in-depth information on in vitro experiments and state-of-the-art reviews on various computational fluid dynamics (CFD) applications and finite element methods on airflow and aerosol motion in both healthy and obstructed human airways are provided [21].

In computational fluid dynamics applications, the airflow motions in a healthy and blocked airway of human beings can be reviewed through finite element methods. These experiments can be evaluated within vitro experiments. A complex human airway and the process of breathing in human beings can restrict the applications dealing with in vitro measurements [16]. These measurements are impractical experimentally and very difficult to calculate. Dispersions models are mathematically created and analyzed numerically for various motions and their impact can be seen in [5,16,21].

4. Subparametric transformation for meshing the transmission region using triangular elements

The regular and curved triangular elements used in meshing with parabolic arc matching curved boundaries and its mathematical formulation are available in the literature [22]. Each unmapped element from \((x,y)\) a Cartesian coordinate system is mapped to a standard right-angled isosceles triangle, in \(\xi\) and \(\eta\) the natural coordinate system \((\xi, \eta)\).

The interpolation function of Lagrange’s considered for any field variable \(u\) (say) which governs a physical problem is given by Equation (8):

\[ u = \sum_{i=1}^{[(n+1)(n+2)]/2} N_i^{(n)}(\xi, \eta)u_i \]  

(8)

where \(N_i^{(n)}(\xi, \eta)\) represents the shape functions of the specific triangular element of order \(n\) at the node \(i\). In the present work, the quadratic type of triangles has been considered by replacing \(n\) with 2. The shape functions for a triangle element of quadratic type have been provided in Equation (9):

\[ N_1^{(2)} = [-\xi + 2\xi^2], \]

\[ N_2^{(2)} = [-\eta + 2\eta^2]. \]

Fig. 1. Mapping of a triangular element of quadratic type to a standard form [22].
\[ N_2^{(2)} = \left[ 1 - 3\xi - 3\eta + 2\xi^2 + 4\xi\eta + 2\eta^2 \right]. \]

\[ N_4^{(2)} = 4\xi\eta, \]

\[ N_5^{(2)} = \left[ 4\eta - 4\xi\eta - 2\eta^2 \right]. \]

\[ N_6^{(2)} = \left[ 4\xi - 4\xi\eta - 4\xi^2 \right]. \]  

The transformation of the discretizing element from a physical coordinate system to a local coordinate system, i.e., from a Cartesian to a natural system in terms of \((x, y)\) is given by Equation (10):

\[ t = \sum_{i=1}^{(n+1)(n+2)/2} N_i^{(m)}(\xi, \eta)t_i(t = x, y) \]  

A well-known scheme of equidistance spacing has been followed along the two straight sides (Fig. 1). The standard formulae of dividing the straight-line segments with the specified ratio have been implemented on these straight sides of the discretizing element. To contemplate with the plane analytic geometry, Equation (10) reduces to Equation (11):

\[ t(\xi, \eta) = t_1 + (t_1 - t_3)\xi + (t_2 - t_3)\eta + \frac{a_i^{(4)}(t)\xi\eta}{3} + \frac{1}{3} \sum_{i,j=1,(i,j)} a_i^{(4)}(t)\xi^i\eta^j, (1 \leq i, j \leq 3, t = x, y) \]  

The subparametric transformation equations map the global to the local coordinate system for a straight regular side Equation (12) and the curved side Equation (13) is given by:

\[ t = t_1 + (t_1 - t_3)\xi + (t_2 - t_3)\eta + 2(t_4 - t_1)t^2 \]  

In the quadratic type, the elements used for discretization will take the value \(n = 2\). The coordinates on the curved side of the discretizing element of quadratic type are spanned by three coordinates, they are \(t_1, t_2, \) and \(t_4\), in such a way that \(t_4\) lies on the curved side. The transmission region has been discretized by finite triangular elements and subparametric transformation of parabolic arcs has been incorporated for better results. Subparametric transformation on higher order finite meshing over different domains have been successfully implemented for various applications [22–27].

5. Results and discussions

5.1. Triangular meshing over the transmission region by using MATLAB

Considering the region of transmission from one person to another person be maximum between the curved and the straight sides. The flow intensity of the virus has been studied in both cases (with mask and without mask [7]) as shown in Fig. 2. The maximum transmission region has been discretized by the proposed
Fig. 4. Transmission region discretized using quadratic elements.

Fig. 5. (a) Linear meshes over the transmission region. (b) Linear meshes over the transmission region with nodal data of finite elements. (c) Quadratic meshes over the transmission region. (d) Quadratic meshes over the transmission region with nodal data of finite elements.
method using linear triangular elements and elements of quadratic type by MATLAB. Precise coordinate location data can be extracted from the proposed method. The nodal data and the elements implemented in the present novel meshing can be deduced easily through the present scheme of parabolic arcs.

Maintaining a social distancing of 1.83 m [30] distance and more from an infected person is the ultimate remedy to hinder the growth of the coronavirus [7]. It could prevent the decomposition of the virus on another person and break the flow region of virus transmission. The pressure exerted on each droplet of cough containing the virus could be hampered by maintaining more distance than the recommended distance between two individuals. Figs. 2-4 represent the discretization of the transmission region over the mask of an individual at a distance of 1.83 m. Fig. 5 shows the meshing over the transmission region using simple linear and quadratic elements respectively.

The virus present in cough droplets is the main cause of spread from an infected person’s coughing or sneezing [48]. The disease can stop spreading when awareness among the individuals is followed by every citizen. The nodal data of the present meshing can analyze the position of the virus and its intensity which in turn is helpful to analyze the minimum safe distance that has to be maintained between individuals, the quality of mask to be worn such as porous medium, accurate size, appropriate material, etc.

5.2. Mesh quality

Mesh convergence can be attained with the present approach of mesh quality. The results are compatible with the refined mesh sizes used for discretization over the transmission region. The discretization process has been carried out with different mesh sizes for analyzing its convergence criteria. During quadratic order triangle meshing [24] the standard element size used provides the same flow intensity of the virus over the region than the more refined element sizes. Hence, this states the mesh convergence which concludes that one of the parameters of mesh quality is attained.

In finite element modeling [41], mesh convergence is one of the major factors. The mesh quality of this work is much more precise.
when compared with other software which performs meshes up to quadratic order elements. The Jacobian ratio is one of the mesh convergence criteria. The disproportionality between a certain standard element and an ideally fixed shape element is regulated by the Jacobian ratio. Since the Jacobian ratio varies between $-1$ and $1$, an element when presented with the Jacobian ratio near to 1 is an ideal element. The ideal element relies on the kind of element type used. The present approach of subparametric transformation of mapping the ideal element to an actual standard element from the parametric coordinate system to the global coordinate system inspects the element type. During the finite element solutions [23–28] using higher order mesh elements, the determinant of the Jacobian matrix for the integration points which is also termed as Gauss points is evaluated at every element. The Jacobian ratio is represented by Equation (14):

$$\text{Jacobian ratio} = \frac{\text{Minimum of } |J| \text{ at every element's Gauss points}}{\text{Maximum of } |J| \text{ at every element's Gauss points}}$$

(14)

The value of the determinant of the Jacobian matrix when approaches near to one predict a convergent solution to the system and if the value is zero it gives a distorted element. For the number of elements obtained in both cases i.e., linear and quadratic element discretization considered in the present approach for different mesh sizes, the determinant of the Jacobian matrix is obtained close to 1. It concludes that the accuracy of the flow intensity of the virus over the transmission region is correlated much precisely with quadratic elements than the lower-order elements.
5.3. Flow analysis of the velocity of virus in the transmission region

The coronavirus getting emitted or exhaled from the infectious person is the main cause of spreading to an uninfected person. The virus which has been transported in the air would be present in the air at the maximum distance of 1.83 m from the infected person [7]. The statistical study [28–30, 39, 42, 48] of coronavirus transported in the air over coastal regions depicts the importance of awareness [41] on it. The biological air sampling technique [31] has been introduced by [21] for the study of the transport of viruses in the air. The effect of the virus present in the air has not been analyzed with many correlated factors in the literature. The presence of a virus at each stage of transmission between individuals can be precisely correlated with the transmission region considered in the present work. The intensity of the flow of the virus gets reduced or vanishes while moving away from an infected person.

The factors affecting the transmission of the virus are the flow rate and the intensity with which it gets transmitted, temperature [17], the direction of the transmission, the size distribution of the coronavirus and the virus droplets, and many more. The position of the molecules containing the virus can be easily analyzed from the present meshing scheme. The node positions and the coordinate of each discretized element can be extracted from the present meshing technique in Fig. 6. The present scheme incorporates the subparametric transformation of parabolic arcs introduced by earlier researchers with curved triangular discretization [22–27]. The curved boundary over the mask or the face of an individual or the region around the individual itself when considered as a curve, the curved at one side of the triangle is utilized at the boundaries as
discretization elements. The subparametric transformation of parabolic curves has been implemented for the discretization of transmission regions where the complexity arises to simply a PDE over those regions.

The transmission of the coronavirus through air depends on the intensity of coughing and sneezing by a human wearing with or without the mask. The transmission of the virus from an infected person is more without using a mask compared to wearing a mask. This transmission of the virus has been analyzed for different scenarios based on the intensity of coughing and sneezing by an infected person.

The transmission region considered in the present work is a standard social distance of length 1.83 m and breadth of 1 m. A semicircle of radius 0.5 is assumed to be the mask or the area around the face or the area around an infected person. Dirichlet's boundary conditions have been applied to the boundaries of the transmission region of the virus. On the curved boundary of the transmission region, Neumann's boundary condition has been applied which indicates the flow rate intensity of human activity. The flow rate intensity has been increased depending on the intensity of the coughing or sneezing of an infected person, to analyze the velocity component of Equation (1) in the transmission of coronavirus along the x-direction. Applying the boundary conditions on the transmission region, an elliptical PDE [18] in Equation (7) has been simplified with the finite element method using subparametric transformation of parabolic arcs. The velocity of the transmission of the virus in the transmission region is analyzed by solving Equation (1) – (3) by FEM using parabolic arcs. When the input source flux in Equation (7) is considered as 2, the solution data is plotted by the contour graph shown in Fig. 7. The maximum

![Fig. 9. The flow intensity of the virus at D = 6 over the transmission region.](image)

![Fig. 10. The flow intensity of the virus at D = 8 over the transmission region.](image)
populated region of the virus has extended up to 0.45 m distance away from an infected person. The next Fig. 8 indicates the maximum transmission till the distance of 0.7 m when the source flux is taken as 4. Consequently, the source data at different values have been analyzed at 6, 8, 10, 12 in Figs. 9, 10, 11, and 12 respectively. The maximum transmission of the virus at the positions 0.9 m, 1 m, 1.2 m, and 1.5 m has been observed for the input source data 6, 8, 10, 12. The transmission from the emitter will be more due to environmental factors [27,30–31] such as wind, humidity, etc. Hence the maximum transmission region of the virus considered is within 1.83 m between the individuals. The receptor if maintained at a standard distance from the emitter can avoid getting exposed to the virus. The quality of the mask used by the emitter is also a factor contributing to the spread of the virus. This scheme provides the complete information of the nodes and elements utilized in the discretization of the transmission region and the precise flow intensity of the virus.

In Fig. 7, the flow rate has been analyzed at 0.45 m from an infected person and around the face mask along x-direction when source data is increased. It has been observed at D = 4, the virus present in the maximum range of transmission region is up to 0.7 m from the infected person as shown in Fig. 8. In this case, the solution of the velocity component of Equation (7) is very close to 0.9 m when the flow intensity is considered as D = 6 as shown in Fig. 9.

Here, the PDE solution shows the output intensity at 1 m away from an infected person when the input source data is increased to 8, in Fig. 10. In this case, when the infected person has more intensity in the natural activity such as coughing and sneezing process, the existence and flow of the virus can be supposed to be for a longer time. In turn, can cause an impact to a larger extent on the uninfected person [33–36].

The consequent increase can be seen in the contour solution of Equation (7) as the increase in source flux. The solution data observed is very close to 1.2 m and 1.5 m away from an infected person with the source flux at 10 and 12 respectively Figs. 11 and 12.

### 5.4. Computation of temperature and analysis of wind conditions over the transmission region

Laplace equation governing a variety of equilibrium physical phenomena such as temperature distribution in a two-
dimensional flow has been considered here over the transmission region. To illustrate the numerical solution of the Laplace equation, we consider the distribution of temperature in a two-dimensional region, where the temperature is maintained at a particular value along the four boundaries (i.e., Dirichlet-type boundary conditions). The Laplace equation, for this case, is written as Equation (15):

\[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \]  

The numerical solution of temperature distribution represented by the Laplace equation (14), has been plotted for in the contour graphs in Figs. 13 and 14.

The temperature distribution of the transmission region under consideration at normal boundary conditions has been computed. The boundary temperature is considered at a normal room temperature of 30 degrees and 40 degrees respectively while simplifying the PDE for Dirichlet’s conditions. The contour graph for the temperature distribution has been plotted over the transmission region at different temperatures.

The transmission of the coronavirus is associated with many parameters like the intensity of natural activity during the coughing and sneezing process [38]. The same could be extended with the environmental parameters such as wind conditions Fig. 15 and can be discussed by considering a specific boundary condition associated with the transmission of coronavirus.

5.5. Wind conditions

The cough droplets carrying the virus can affect both adults and children having different heights. In [38] the normal height
assumed is 1.63 m where the adults and children will be at risk of having shorter heights. The mass reduction of the cough droplets is seen at nearly around 2 m and completely vanishes as it reaches 6 m as stated in [38]. In the computation of the flow intensity in the transmission region of virus present on the cough droplets, the intensity of the droplets could be seen reducing before 1.83 m as computed in Figs. 10 - 15.

Wind conditions can enhance the transmission up to 6 m long or more distance based on the different wind speeds. The diameter of the cough droplets decreases with time from 111 μm to 82 μm for several conditions of wind. With the increase in wind speed, the diameter of the cough droplets has been observed reducing. This reduction of the droplets is due to the wind’s shear rate being at the higher side which seeds up the evaporation of the droplets [38]. Hence, the height of the different adults and children can have a varied analysis depending on the environmental conditions.

6. Conclusions

The rate of increase in the intensity of an individual’s coughing and sneezing [34,48] enhances the spread of the coronavirus faster and to a larger area in the transmission region. The existence of the virus in the transmission region for a longer period and the larger area occupied by it has an impact on the transmission process of the disease to another person. The intensity of the flow of the virus in the transmission region 1.83 m (6 feet) [30] via the velocity component of the flow of the virus has been precisely computed by simplifying an elliptical PDE by FEM. The present triangular meshing over the transmission region of the coronavirus provides an appropriate solution for the velocity of the coronavirus spread in an incompressible flow region. The transmission of coronavirus at different temperatures and wind conditions is also efficiently analyzed within the transmission region [30].
The present study can help in analyzing the intensity of virus flow at different environmental conditions such as wind conditions, the air humidity of the environment, the critical area of transmission of the virus from an infected person. It is helpful in the CFD analysis for the respiratory cough droplets transmission. To envisage the relative existence of the virus location and the growth cycle during a transmission process, the present FEM analysis assists efficiently. It is advantageous to frame the required guidelines of the safety measures to prevent the spread of COVID-19 between human beings and to cultivate a gentle awareness between the individuals.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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