Airborne Fluid Dynamic(Sneeze) Simulator

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Figure 1: Airborne Transmission of Coronavirus[5]

ABSTRACT

In early 2020, a novel and extremely contagious virus named Coronavirus-19 (Covid-19) broke out worldwide. Research shows that the virus is mainly transmitted through droplets generated when an infected person coughs, sneezes, or exhales.

Here we implement an airborne fluid dynamics(sneeze) simulator that estimates the behavior of an in-compressible, homogeneous fluid under the Navier-Stokes equations that simulates virus transmission. Specifically, we simulate virus different spread paths by adjusting external factors such as velocity, pressure, temperature and density. This enables us to study how the virus reaches when people breath, sneeze and cough.

In addition, we aim to simulate and test the situation where humans wear masks and sneeze to see how particles' trajectory changes when obstacles(masks) are present. As a result of mask simulation, we an effective prevention of virus spread thus proved it is crucial to wear masks in outdoor activities to protect ourselves and other people.

KEYWORDS

computer graphics, fluid dynamic simulation, particle simulation, sneeze

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1 INTRODUCTION

1.1 Background

The coronavirus COVID-19 is affecting 209 countries and territories around the world and two international conveyances. People in N.Y. and S.F. are forced to take shelter in place. Until April 9th, 14,802 people lost their lives because of this virus in the U.S., and 88,538 people died around the world. However, there are still many people who choose to neglect the existence of this dangerous virus and refuse to use face masks to protect themselves and other people. Thus, we wish to create a 2D fluid dynamics simulator to simulate the situations of people breathing, coughing, and sneezing. We hope to use this project to activate their awareness about how severe this disease is. It will be difficult to mimic the real dynamics for the spreading particles in these situations because of the complexity of the simulation. Thus, we will first implement a 2D fluid dynamics simulator based on Navier-Stokes equations and other reference projects. Then, we will try to utilize the actual data from researches about human coughs and sneezes for a real simulation.

1.2 Goal

Our goal of this project is to simulate the spread of particles in the air. We will then simulate if wearing masks makes any difference in the process of social networking. Hopefully, we could finally apply different materials on masks and simulate the positive effects of wearing masks against virus spreading.

The baseline of this project is to simulate the process of particle(virus) spreading. Through rendering fluid dynamics simulation, we will be able to see the virus' travelling path, velocity, and spreading time frame. In this part we will apply the Navier-Stokes equations and use GLSL fragment shaders to perform the physics calculations on the GPU.

If we get ahead of our schedule, we hope to simulate the fluid particles with some kind of barriers (to simulate masks). We would like to show the huge differences of particles' travelling path under situations with and without masks. We want to achieve this since ultimately we want to remind people of ways of protecting themselves from the Covid-19 virus and other airborne diseases.

We will measure our final result by both time and space complexity. We will also compare our fluids path with real-life airborne particle's travelling path to reveal the differences and consistencies. By the end of this project, we will be able to see the spreading paths of particles with different sizes in the air, we will also answer the ultimate question, that whether people should wear masks under airborne and direct contact diseases.

2 RELATED WORKS

2.1 A study in droplet dispersion, heat and mass transfer

Aliabadi et al. developed a Computational Fluid Dynamics simulation of near-field cough and sneeze droplet dispersion and heat and mass transfer.[6] By considering various sources of variability in cough processes and ambient relative humidity, they simulated the motion of coughs in a quiescent background. They take humidity as a important factor since it affects the evaporation process and further affects the size of the droplets, which results in changes in vertical drop speed and axial penetration force.

2.2 Cough simulators

Zhang et al. established a Lagrangian model of droplet trajectories, and simulated cough in a predetermined ambient flow field.[9] Parshina-Kottas et al creates a 3-D simulation of cough spreading using research data from the Kyoto Institute of Technology by computing the movements and separation of various sizes of droplets produced by coughs.[8]

3 OUR WORK

To simulate the behavior of fluids, we need to find a way to represent the physical properties at a certain time spot. We used 2D fields to represent the various velocity,temperature and density at different positions in the grid. After locating the fluids, We applied Navier-Stokes Equations in our calculation of forces, velocity, density, pressure. Combining these factors together gives us a complete simulation of fluid particles transmitting in the air.

Besides fluids, we also simulated the movement of droplets generated when people sneezing. Each droplet is considered as an independent object, they do not interfere with each other and there are no other constraints. We take Gravity, Air Friction and Buoyancy into consideration, compute the external force and update velocity and position each time step using modified Euler method. In particular, the radius and mass change over time due to evaporation effect.

Moreover, we added some barriers to the space as a simulation of masks. The fluids and droplets would be absorbed, bounced back or pass through the mask based on the velocity and position.

3.1 Navier-Stokes Equations

Navier-Stokes Equations is used to describe the motion of incompressible and homogeneous fluid.

$$\frac{\partial u}{\partial t} = -(u \cdot \nabla)u - \frac{1}{\rho}\nabla p + v\nabla^2 u + F \tag{1}$$

3.1.1 Advection. The first term in equation 1 represents the advection field along the fluid's velocity field. Since the velocity causes the fluid to transport particles with the flow, we need to constantly use this term to update not only velocity, but also density and temperature which is affected by changes in velocity.

3.1.2 Pressure. The second term in equation 1 represents the pressure of fluids, which is calculated as force per unit area. We keep track of pressure because particles of a fluid move around each other, once adding force to one part, other parts of particles would also got "squished". Specifically, we used the Poisson Equation to solve for pressure.
In order to quantify pressure, we will apply the Poisson-pressure equation.

$$x_{i,j}^{k+1} = \frac{x_{i-1,j}^k + x_{i+1,j}^k + x_{i,j-1}^k + x_{i,j+1}^k + \alpha b_{i,j}}{\beta} [7] \tag{2}$$

Where a and b are constants, $a = -(dx)^2$ and $b = 4$. To solve this equation, we run 50 iterations and apply this equation to each position until convergence. Then $x_{i,j}$ represents the pressure at position (i,j).

3.1.3 Diffusion. The third term in equation 1 is named viscosity, which is a measure of how resisting a fluid is to flow. Since we are simulating particles in air where viscosity is virtually zero, we do not considerate viscosity and left it out of our implementation.

3.1.4 External Forces. The fourth term encapsulates acceleration due to external forces applied to the fluid. In our case, it refers to the (in most cases, horizontal) force where human sneezes the particles out of their mouths. During the transmission paths, gravity and buoyancy also count as external forces in the vertical direction.

$$f_{buoyancy} = (-\kappa d + \sigma(T - T_0))[7] \tag{3}$$

Where κ is a constant mass scale factor, σ is a constant scale factor, T is the temperature and T_0 is the ambient temperature.

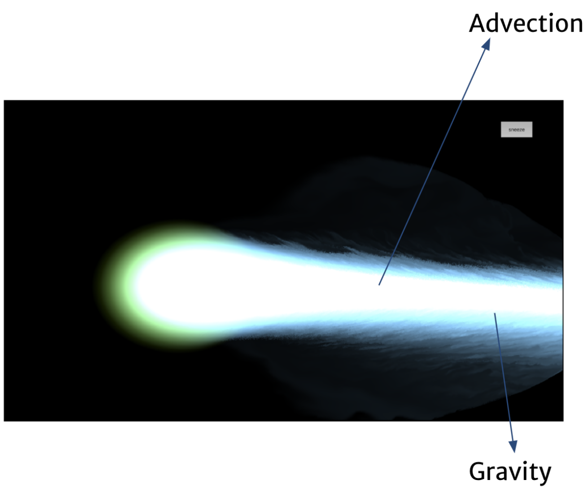

Figure 2: Our simulation of advection and gravity

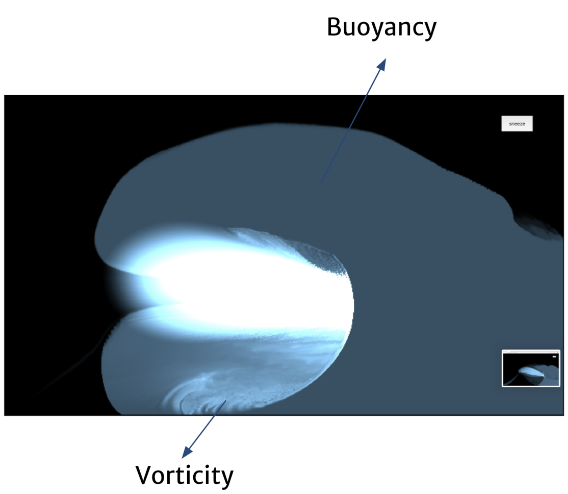

Figure 3: Our simulation of vorticity and buoyancy

3.2 Modified Euler

$$x^{t+\Delta t} = x^t + \Delta t \dot{x}^t + \frac{(\Delta t)^2}{2}\ddot{x}^t \tag{4}$$

Euler’s method is a commonly used iterative method for particle simulation. It is inaccurate since the speed and acceleration do not remain constant within a single time slot. Errors accumulate each time step and increases as the time step increases. Even if we use the modified version to make more accurate calculations, it is still not stable enough.

But in our simulation, since each particle is independent, and there is no force between particles, the external force is only affected by the particle itself and the surrounding environment. In this case, there won’t be btoo much bias, and the Modified Euler method is sufficient. To compute the acceleration, we considered three types of external forces.

3.2.1 Gravity.

$$f_g = mg \tag{5}$$

Where g is the gravitational acceleration constant, $m = \rho V$, and $V = \frac{4}{3}\pi r^3$.

3.2.2 Air Friction.

$$f_{drag} = -\frac{1}{2}C\rho_f A v^2[2] \tag{6}$$

Where C is the drag coefficient that represents the drag of an object in a fluid environment. We used smooth sphere to simulate droplets, the commonly used C is 0.1. [4]ρ_f is the air density, A is the cross-sectional area and v is the velocity. The direction is opposite to the velocity direction.

3.2.3 Buoyancy.

$$f_{buoy} = \rho_f V_f g[3] \tag{7}$$

Where ρ_f is the air density, V_f is the volume of displacement air, which is equal to the particle volume.

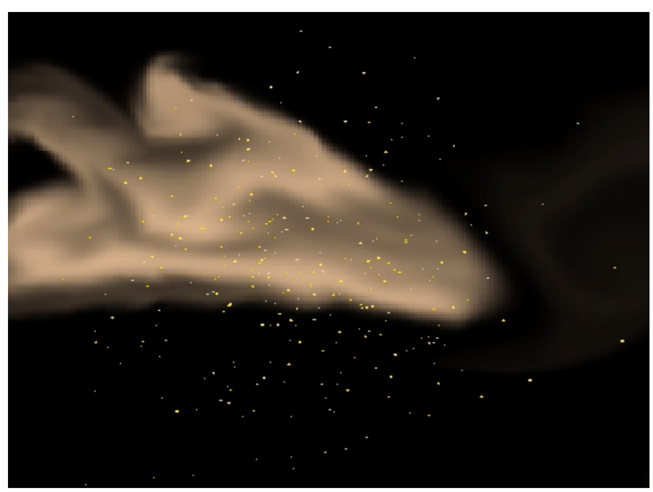

Figure 4: Our simulation of droplets

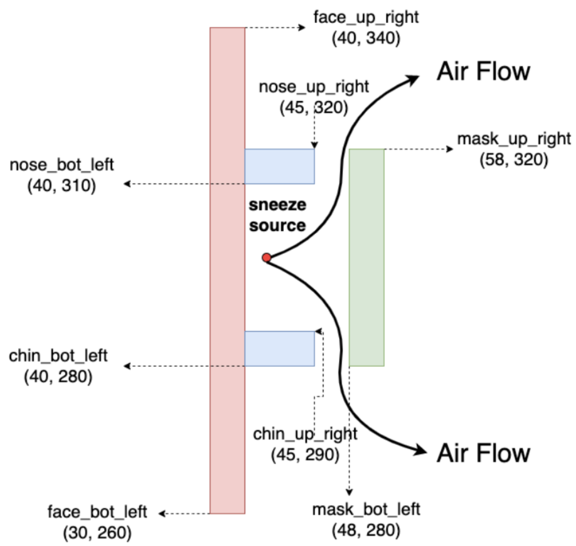

Figure 5: Our simulation of mask

3.3 Mask Simulation

The mask simulation is done by constructing a few blocks in front of the human face in the scene, which resembles human's face, nose, chin and the mask itself. These blocks are calculated in scale with the human face. We set the center between nose and chin to be human's mouth, which is the source of the air flow. When a human sneezes, the air flow is split by the mask to vertical flows and they escape from gaps around nose and chin. Most of the droplets will either be bounced back by the mask, or got absorbed in the mask, while only very few made it to pass through the mask.

To be more specific, we set the fluid density at the blocked position to be 0, and set the velocity to be opposite to the last position's velocity to simulate the bounce.$last_p = current_p - v * \delta t$. If the velocity is small and $last_p$ is still in the blocks, we set the velocity to be 0, which means that the fluid is absorbed by the mask. If the velocity is extremely large, the fluid will pass through the mask.

3.4 Environment and Settings

3.4.1 Environment. We used MacOS Catalina as the operating system, JavaScript and HTML as programming language, and lastly, three.js in WebGL as the graphics library.

3.4.2 Settings. We set the number per sneeze at 500, and the size of each droplet is randomized around $0.2mm$ and $0.4mm$. In addition, the droplets' initial density at $1kg/dm^3$, and initial velocity at 50m/s [1] which resembles the real world scenario. The droplets are ejected in the shape of a semi-circle with radius $0.15m$ away from the mouth when the human sneezes, the movement in the air depends on the net forces afterwards.
In buoyancy force calculation, we set κ, the constant mass scale factor as σ, the a constant scale factor as 0.08.

3.5 Results and Future Research

3.5.1 Results. We noticed that when wearing a mask, the airflow from human mouth is mostly split to two flows and can escape from the gap between face and nose, and the gap between face and chin. However, most of the droplets are blocked(absorbed) by the mask and stopped spreading instantly. This proves that wearing a mask is a very effective way to reduce virus spread, and is very crucial in outdoor activities given the current situation.

With masks of level 3, which are defined as masks that used in high risk of fluid exposure, more particles will get filtered by thus less droplets will get away. For example, the N95 masks, the mask is designed to be tighter thus aligns more with human's face, thus the gaps around nose and chin are also smaller. Changing these external factors will slightly change the trajectory of droplets, and we can see an obvious boost in preventing the spread of virus.

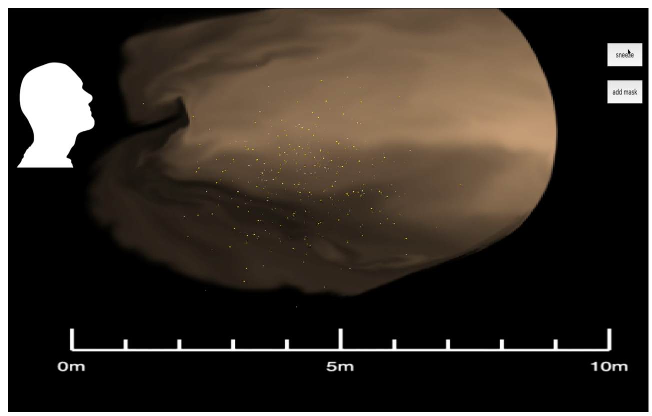

Figure 6: Sneezing without wearing a mask

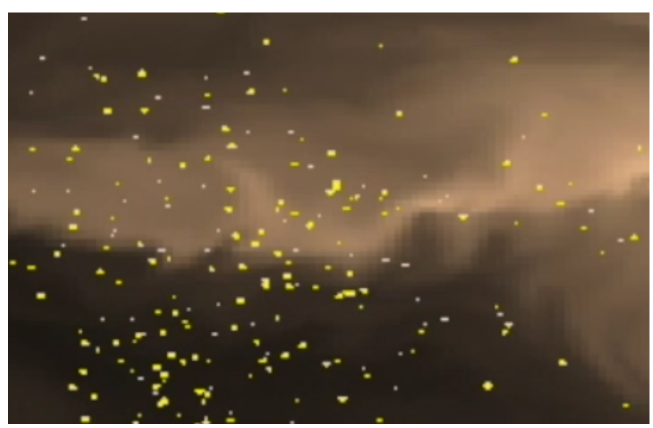

Figure 7: Close-shot of droplets

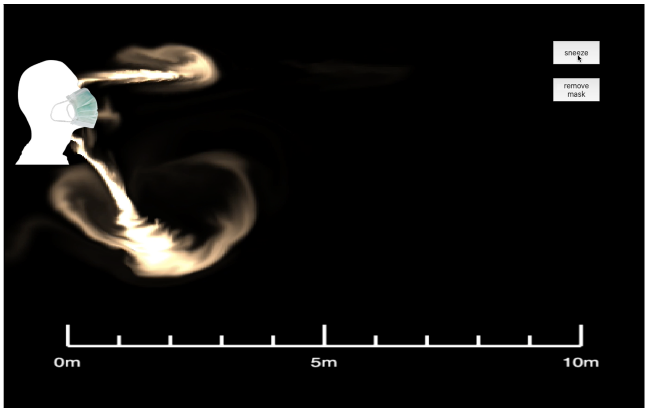

Figure 8: Sneezing with a mask

3.5.2 Future Research. For future research, it's possible to add more environmental characters such as humidity, since it will affect the evaporation rate and thus influence the volume and mass of droplets. Moreover, cross effects of each environmental characters is also a crucial part, the air pressure, temperature and density of air are related and change across time. The movement of droplets will also affect the movement of the fluid, we now compute them separately, but it is possible to merge them as a whole.Besides, we can use different shapes and densities of blocks to simulate and compare various types of masks.

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