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Article

Simulation of smoke dispersion and air pollution dynamics

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Abstract: A hybrid model approach is proposed to address the limitations of traditional physical and empirical models in simulating smoke diffusion and depicting gas pollution. This method integrates the semi-Lagrangian method for smoke modeling, with the k-d tree algorithm enhancing computational efficiency. To enhance smoke simulation details, a fluctuating wind field generated by the linear filter method is incorporated into the external force term to refine smoke particle trajectories. The rendering process employs a bidirectional projection function combined with actual smoke textures to mitigate the issue of particle visibility and to significantly enhance the visual fidelity of smoke diffusion. Additionally, an optimized Gaussian plume model is utilized to bridge the gap between physical and empirical models, while a pollution attenuation formula and refined Perlin noise are applied to enrich the global gas pollution details and to increase the realism of pollution dynamics. The method also incorporates an improved time axis algorithm to overcome the issue of static gas pollution color, enabling the depiction of dynamic and gradual pollution changes. Experimental results validate the effectiveness of this approach in generating realistic and dynamic gas pollution scenes in real-time.

Keywords: smoke diffusion; gas pollution; physical model; empirical model; gaussian plume model

1. Introduction

Gas pollution is one of the common pollution in life, including fuel combustion, tail gas emission, industrial pollution, etc. Among them, the gas pollution caused by smoke diffusion has a great impact on daily life. Therefore, simulating gas pollution has important practical significance and broad application prospects. On the one hand, it is difficult to capture the smoke details because the smoke diffuses rapidly with time; on the other hand, it is difficult to establish a relationship between smoke diffusion and gas pollution, which is worthy of in-depth study.

In recent years, smoke simulation has been the focus of research at home and abroad. Since the method of simulating smoke motion was proposed by Stam [1] and Fedkiw et al. [2] in 2003, smoke simulation has been more and more widely used. The method of using physical models can usually truly show the details of smoke. Xie et al. [3] synthesized high-resolution smoke with real details through neural network training of low-resolution smoke, and applied it to different physical models, but its neural network training time is too long to achieve real-time; Tang et al. [4,5] proposed an improved spatial adaptive vortex restriction method to generate clear vortices.

Smoke details; in the aspect of smoke path, the improved finite difference method is used to solve the N-S equation to speed up the solution, and the attraction and driving force are introduced to realize the large-scale smoke path simulation. The smoke and gas pollution simulation based on empirical model can quickly reach the real-time state, but it sacrifices the details of smoke and lacks realism. Lu et al. [6] proposed a spherical fog rendering model, which combined with traditional Perlin noise to render hierarchical fog in real time through HDR; Guo et al. [7] used Perlin noise to generate heterogeneous density distribution texture, and then used MRF model combined with atmospheric scattering perspective to evaluate rendering and draw heterogeneous fog image.

Therefore, this paper proposes a method of mixing empirical model and physical model to plot the dynamic gas pollution caused by smoke diffusion. Firstly, the smoke trajectory is optimized for the physical model, and the smoke particles are drawn based on physical rendering to improve the diffusion details; secondly, the relationship between smoke diffusion and gas pollution is established according to the air pollution theory, and the realistic and dynamic gas pollution is simulated according to the optimized empirical model.

2. Smoke simulation based on physical model

In order to simulate the real smoke diffusion, the driving force in the semi Lagrangian method is improved, the vortex calculation process is optimized, and the real smoke effect is generated by combining the physical illumination model.

2.1. N-S equation construction physical model

Using semi Lagrangian method to simulate smoke particles can more realistically calculate the smoke diffusion movement. The momentum conservation equation and mass conservation equation are:

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

$$\nabla \cdot u = 0 \tag{2}$$

where u is the velocity field of incompressible fluid, ρ is the fluid density, p is the pressure, v is the viscosity coefficient, f is the fluid resultant force term, ∇ and F is the gradient operator.

In the fluid resultant force term, the smoke simulation details are increased by introducing the vortex binding force. The calculation formula of the vortex field is:

$$\omega = \nabla \times u, \tag{3}$$

of which, × Represents a convolution operation. The generated vortex field is substituted into Equation (1) to obtain the vorticity conservation equation:

$$\frac{\partial \omega}{\partial t} = (\nabla u) \cdot \omega + (u \cdot \nabla)\omega + u\nabla^2\omega + \frac{1}{\rho}\nabla \times f。 \tag{4}$$

According to Biot Savart formula, the velocity field is updated by the vortex field to realize the physical movement of real smoke particles.

2.2. Introduce k-d tree to improve calculation efficiency

After introducing vortex, the iteration of velocity field will be affected by multiple vortices, and the amount of calculation will increase significantly. K-d tree is introduced to reduce the amount of computation. Compared with octree, k-d tree has obvious advantages in spatial division, and the simulation efficiency is significantly improved.

Set the distance threshold according to the k-d tree segmentation point. If the distance from the particle to the segmentation point is less than the threshold, calculate the impact of each vortex on the particle's velocity field within the distance threshold. The formula for calculating the impact of a single vortex on the environment is:

$$u = \frac{1}{4\pi}\int \frac{\omega \times r}{r^3} \mathrm{d}v。 \tag{5}$$

In order to simplify the calculation, the vortex is regarded as a point, which is transformed from integral to summation, and the velocity field can be approximately expressed as:

$$u = \frac{1}{4\pi}\sum_{i=1}^{N} \frac{\omega \times r_i}{{r_i}^3}。 \tag{6}$$

$$\omega = \sum_{i=1}^{N} \omega_i \tag{7}$$

$$L = \sum_{i=1}^{N} L_i\, \omega_i \tag{8}$$

In the calculation process, if the distance from the particle to the vortex is greater than the threshold, the vortex is regarded as a single vortex structure, while multiple vortex clusters less than the threshold are used to calculate the vortex position L by vector sum

2.3. Improve external force items to improve sports details

In the process of calculating the external force, the vortex force alone can not provide more details. This paper improves the smoke diffusion trajectory by improving the wind force.

The wind in the space is usually V_m composed of V_w downwind, cross wind V_h and vertical wind. Using Kaimal spectrum as the wind speed spectrum expression can better show the autocorrelation characteristics of the wind field than the height independent Davenport power spectrum. Therefore, in the calculation of wind speed, the pulsating wind is solved by Gauss process, and the expression of $V(T)$ is obtained.

$$v(t) = -\sum_{k=1}^{p} \boldsymbol{\psi}_k (t - k\Delta t) + \boldsymbol{N}(t) \tag{9}$$

where p is the order of AR model, ΔT is the time step of simulated wind speed ψ_k time history, is the autoregressive matrix coefficient of AR model, and $n(T)$ is the independent random process vector. According to the random vibration theory, the correlation function is obtained by using Wiener sinchin formula and the expected operation. R_N the specific calculation formula is:

$$\boldsymbol{R}_N = \boldsymbol{R}(0) - \sum_{k=1}^{p} \boldsymbol{\psi}_k \boldsymbol{R}(k\Delta t) \tag{10}$$

Through R_N Cholesky matrix decomposition, the random wind speed vector with time interval can be obtained, which can be brought into the wind term to improve the smoke trajectory.

2.4. Realistic rendering of smoke particles

As a non-uniform medium, smoke will produce scattering and reflection when light passes through it, as shown in **Figure 1**. Considering the real-time problem, the real smoke texture is combined with the physical bi-directional reflection distribution function to render more realistic smoke particles.

In this model, the outgoing emissivity is $L_0(v)$ equal to the product of the emissivity integral in all incident directions, the BRDF value, and the cosine value. The formula for calculating the outgoing emissivity is:

$$L_0(v) = \int_{\Omega} f(I, v) \times L_i(I)(nI)\, \mathrm{d}\omega_i, \tag{11}$$

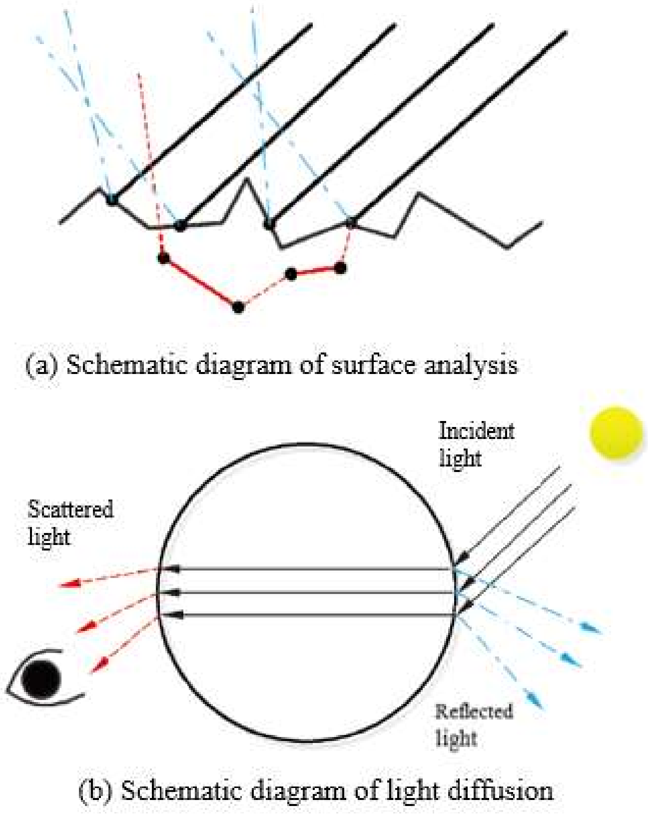

Figure 1. The scattering and reflection of light.

The reflection term usually consists of subsurface scattering and reflection. The calculation formula of subsurface scattering is:

$$f(I,v)=\frac{C_{\text{base}}}{\pi}\left(1+(F-1)(1-nI)\right)^{5}\cdot\left(1+(F-1)\ (1-nv)^{5}\right) \quad (12)$$

of which, $F = 0.5 + 2r(hI)^2$.

Calculation of highlights using Torrance sparrow micro panel model

$$f(I,v)=\frac{F(I,h)\,G(I,v,h)\,D(h)}{4(n,I)\ (n,v)} \quad (13)$$

The $F(I,h)$ Fresnel reflection model is used to deal with the ratio of reflected light to $G(I,v,h)$ incident light, the shadow $D(h)$ masking function and the normal distribution function.

3. Gas pollution dynamic simulation

Considering the real-time, the method based on empirical model is used to simulate gas pollution, establish the relationship between smoke diffusion and gas pollution, and draw the real and dynamic pollution.

3.1. Build the relationship model between smoke and gas pollution

The pollutant height consists of the smoke cloud lifting height and the particle height. The smoke cloud lifting height is assigned according to the smoke particle height. The particle height adopts a linear height field. In order to build the relationship between smoke diffusion and gas pollution, the smoke modeling is combined with the air pollution theoretical model. In this paper, gaussian plume pollution model is introduced

$$X(x,y,z,t,k,H)=\frac{\exp(k)\,Q}{2\pi\, u\sigma_y\sigma_z}\exp\left(-\frac{y^2}{2{\sigma_z}^2}\right)\cdot \left\{\exp\left[-\frac{(z-H)^2}{2{\sigma_z}^2}\right]+\exp\left[-\frac{(z+H)^2}{2{\sigma_z}^2}\right]\right\} \quad (14)$$

where, is $X(x,y,z,t,H)$ the concentration in the vertical wind direction of *X* meters, the cross wind direction of *Y* meters, and *Z* meters away from the ground at time *t*, *q* represents the intensity of the pollution source, *h* is the effective height of dust, *u* is σ_y, σ_z the fluctuating wind speed, and is the horizontal and vertical diffusion coefficient of particles. Increase the pollution factor *K* and optimize it as an exponential function to realize the gradual change effect of pollution concentration. For different pollution changes, rendering into different degrees of gas pollution.

3.2. Optimize pollution attenuation formula and add pollution details

Considering the real-time performance, the screen technology based on empirical model is used for rendering. Firstly, the concentration change gradient is obtained according to the pollution concentration attenuation formula, and the calculation formula is

$$f=\exp\left[-\left(\int_{y_{\text{base}}}^{y}X_t\,\mathrm{d}t\right)^{2}\right] \quad (15)$$

Due to the irregularity of gas pollution diffusion, the rendering of Equation (15) produces less details. Therefore, the classification noise optimized based on 3D Perlin noise is adopted, and the wind speed factor is introduced to generate the dynamic gas pollution effect. The specific calculation formula is

$$Y_{\text{noise}}(x, y, z) = \frac{\sum_{n=1}^{m} N(xf^n, yf^n, zf^n \cdot \boldsymbol{v}_p(x, y, z, t))\, p^n}{\sum_{n=1}^{m} p^n} \tag{16}$$

where, m is the frequency multiplier, f is the frequency, p $v_p(x, y, z, t)$ is the amplitude, representing the fluctuating wind field at P, generating a real pollution attenuation formula.

3.3. Dynamic computing ambient light

The optimized pollution concentration attenuation formula can improve the details, but the color cannot change dynamically with time. To solve this problem, the optimized time axis algorithm is introduced to generate dynamically variable smoke. The calculation formula of ambient light at different times is

$$C_{T_{\text{current}}} = \frac{1}{2}\left[1 - \cos\left(\frac{T_{\text{current}} - T_0}{T_{\text{total}} - T_0}\right)\pi\right] C_{\text{inc}} \tag{17}$$

where, C_{inc} represents the "value color" of the ambient T_0 light, represents the initial time (i.e., The early morning T_{current} initial time), represents the T_{total} current time, and represents the overall time. According to the smooth transition of negative cosine function, the ambient light at different times is $C_{T_{\text{current}}}$ calculated.

In addition, transparency coefficient is introduced λ, the pollution color is dot multiplied with the illumination color to obtain the final real illumination, as shown in Equation (18), and then the real dynamic gas pollution scene is rendered.

$$C = f(C_{T_{\text{current}}} + C_{\text{light}}) + \lambda(1 - f)\, C_f \tag{18}$$

4. Realization of smoke diffusion and gas pollution simulation

4.1. Overall program framework

The overall program flow chart of this paper is shown in **Figure 2**.

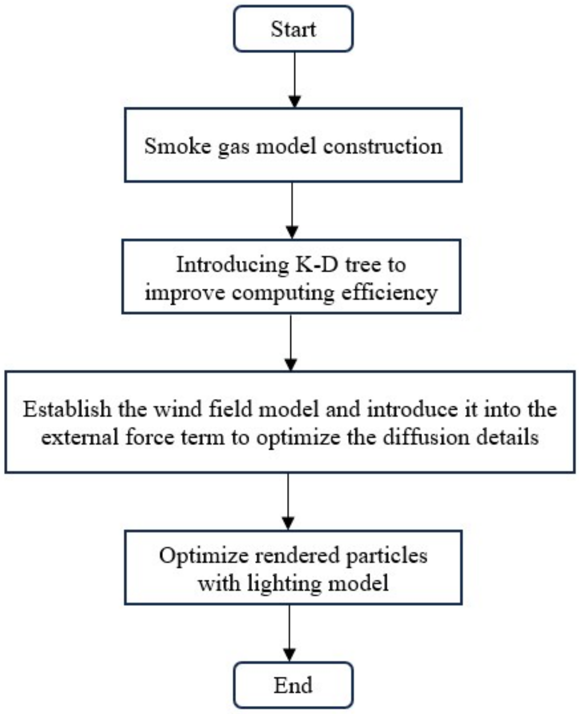

Figure 2. Overall program flow chart.

4.2. Experimental results and analysis

The dynamic gas pollution simulation system based on Windows system and unity3d platform is used in this experiment. The hardware environment is: Intel Core i7-4790 CPU 3.60 ghz, 16 g, and NVIDIA geforce GTX 750ti graphics card.

Figure 3a,b shows the comparison of smoke diffusion between document [3] and this method. **Figure 3a** shows the experimental effect of using the time-dependent generation model to solve the fluid flow problem in reference [3], with a mesh resolution of 256 × one hundred and eighty × 180, although only a single time step is used, the frame rate is only 0.0008 FPS, and real-time rendering is not possible. This method can generate a large number of diffusion details on a real-time basis. **Figure 3c,d** shows the comparison between the method in literature [4] and that in this paper. **Figure 3c** shows the improved spatial adaptive vortex restriction method used in reference [4] to simulate smoke, with a grid resolution of 64 × eighty-six × 64. The details of smoke diffusion are not obvious enough. In this paper, the method of texture and physical rendering model is used to simulate the smoke color and lighting more realistic. **Figure 3** shows the comparison between the real picture and the large-scale scene in which the method in this paper is applied to ensure that the simulated smoke is real and natural in the real-time state.

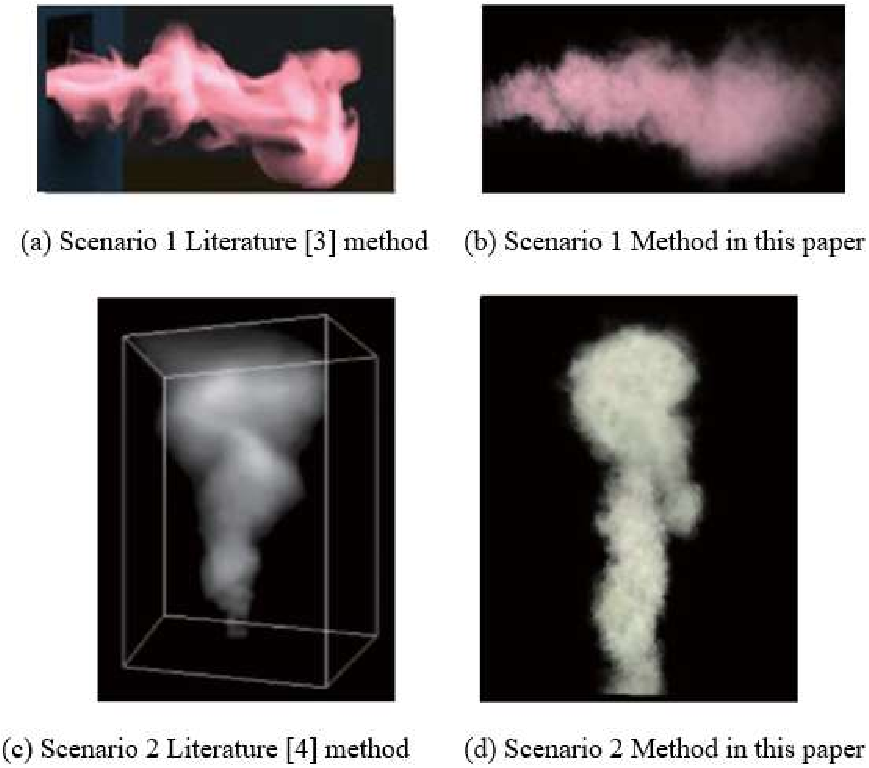

Figure 3. Comparison with literature [3,4] and real smoke.

Figure 4. Missile smoke wake comparison experiment.

Figure 4 shows the comparison experiment of missile smoke wake diffusion. Among them, **Figure 4a** is a real picture, **Figure 4b** is the method of literature [5], and **Figure 4c** is the method applied to the smoke path direction by this method. Through comparison, it can be seen that the optimized physical model method in this paper is more natural and flexible than that in literature [5], and the wake diffusion effect is more obvious, which is closer to the real picture effect.

Figure 5 shows the gas pollution simulated by the optimized empirical model. The simulation results are compared by substituting different pollution factors into the gas pollution simulation. The figure shows the gas pollution simulation under the pollution factor k = 0, 0.4 and 1 respectively, which can obviously compare the gas pollution with different gradients produced by different pollution factors, and the effect is obvious.

(a) k=0 (b) k=0. 4 (c) k=1

Figure 5. Experiment on the influence of pollution factors on smoke pollution.

(a) T=6 (b) T=13 (c) T=20

Figure 6. Optimized timeline algorithm experiment.

Figure 6 shows the dynamic changes of smoke diffusion and gas pollution with the time axis at the time of $T = 6$ in the morning, $t = 13$ at noon and $T = 20$ at night. The light interpolation calculation color at different times shows the light and dark effects of gas pollution.

In order to test the efficiency of dynamic pollution simulation, **Table 1** lists the comparison of experiments in this paper and some literature data. The particles and meshes in the table refer to the number of particles or mesh size used in the literature to simulate the smoke effect. Among them, it is obvious that this algorithm can significantly improve the simulation details and ensure the real-time performance.

Table 1. Frame rate statistics for different experimental scenes.

Experimental diagram	Particles/mesh	Frame rate/fps
Figure 3a [3]	256 × 180 × 180	0.0008
Figure 3b	30,000	72.6
Figure 3c [4]	64 × 86 × 64	27.6
Figure 3d	30,000	72.6
Figure 3f	90,000	55.2
Figure 4b [5]	-	45.2
Figure 4c	30,000	86.2
Figure 5	60,000	40.3
Figure 6	90,000	36.2

5. Conclusion

In this paper, a method for dynamic pollution simulation of smoke diffusion is proposed. Firstly, the semi Lagrangian method is used to calculate the particle trajectory, and the k-d tree is used to improve the calculation efficiency. The fluctuating wind model based on Kaimal spectrum is introduced and combined with the real physical illumination to avoid the particle sense and improve the smoke diffusion details at the same time; in addition, the smoke diffusion is combined with the optimized Gaussian plume model, and the improved empirical model and Perlin classification noise are used to generate more real gas pollution; the optimized time axis algorithm is adopted to solve the problem that the pollution color cannot change dynamically, and greatly improve the pollution realism. The experimental data show that this method can realize the real-time simulation of gas pollution under smoke diffusion. In the future work, it is necessary to further study the interaction between gas pollution and environment.

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