PHYSICAL SIMULATION OF WOOD COMBUSTION BY USING PARTICLE SYSTEM

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August, 2010

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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In computer graphics, the most challenging problem is modeling natural phenomena such as water, fire, smoke etc. The reason behind this challenge is the structural complexity, as the simulation of natural phenomena depends on some physical equations that are difficult to implement and model. In complex physically based simulations, it is required to keep track of several properties of the object that participates in the simulation. These properties can change and their alteration may affect other physical and thermal properties of object. As one of natural phenomena, burning wood has various properties such as combustion reaction, heat transfer, heat distribution, fuel consumption and object shape in which change in one during the duration of simulation alters the effects of some other properties.

There have been several models for animating and modeling fire phenomena. The problem with most of the existing studies related to fire modeling is that decomposition of the burning solid is not mentioned, instead solids are treated only as fuel source.

In this thesis, we represent a physically based simulation of a particle based method for decomposition of burning wood and combustion process. In our work, besides being a fuel source, physical and thermal affects of combustion process over wood has been observed. A particle based system has been modelled in order to simulate the decomposition of a wood object depending on internal and external properties and their interactions and the motion of the spreading fire according to combustion process.

Keywords: Solid models, physically based modeling, fire simulation, wood combustion, wood decomposition.

ÖZET

ODUN YANMASININ PARÇACIK SİSTEM TABANLI FİZİKSEL SİMÜLASYONU

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Bilgisayar grafiğinde, en karmaşık sorun, su, ateş, duman ve benzeri doğal fenomenlerin modellenmesidir. Bu karmaşanın ardındaki neden yapısal olup, doğal fenomen simülasyonlarının, uygulanması ve modellenmesi zor olan fiziksel denklemlere dayanmasıdır. Karmaşık fiziksel simülasyonlarda, simülasyona katılan cismin çeşitli özelliklerinin kayıt altına alınması gerekmektedir. Bu özellikler değişebilir ve bunların değişimi, cismin diğer fiziksel ve termal özelliklerini etkileyebilir. Doğal fenomenlerden biri olan odun yanması da, yanma reaksiyonu, ısı aktarımı, ısı yayılımı, yakıt tüketimi ve cisim şekli gibi çeşitli özelliklere sahiptir ki simulasyon süresince bunların herhangi birindeki değişim, bazı diğer özelliklerin etkilerini değiştirir.

Ateş fenomeninin modellenmesi ve hareketlendirilmesini içeren bir çok model bulunmaktadır. Ateş modellenmesi ile ilgili var olan çalışmaların çoğundaki sorun, yanan katı cismin parçalanmasına değinilmemiş olunması, bunun yerine katı cismin sadece yakıt kaynağı olarak kullanılmasıdır.

Bu tezde, yanan odunun parçalanması ve yanma sürecinin parçacık tabanlı yönteme dayanan fiziksel simulasyonunu sunuyoruz. Bu çalışmamızda, odunun yakıt kaynağı olmasının dışında, yanma sürecinin odun üzerindeki fiziksel ve termal etkileri gözlemlenmektedir. Odun cisminin içsel ve dışsal özellikleri ve bunların etkileşimlerine dayanan parçalanma, ve yanma sürecine göre belirlenen ateş yayılım hareketi simülasyonu için parçacık tabanlı sistem modellenmiştir.

Anahtar sözcükler: Katı modeller, fiziksel modelleme, ateş simülasyonu, odun yanması, odun parçalanması.

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To my family,

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Chapter 1

Introduction

Motivation

In computer graphics, complex physical simulations have important role in creating realistic graphical applications. Many complex physical simulations require modeling of different number of natural phenomena. To provide realism, the level of accuracy is retrieved by keeping the track of all the details of all physical phenomena. However, in computer graphics it is not preferred. Instead, the physical model is simplified and a simple simulation is used to implement the physical model.

One of the significant complex physical phenomena is fire modeling. In [2–16], many researchers have proposed several approaches to model and render fire propagation. However, in these fire models, none of them has emphasized the decomposition of burning solid. Instead, they only treated solids as fuel source, as in [17].

In computer graphics, object deformation has been widely used in simulations. As [18], some of them have not been applied to physical applications, they only used to deform purely geometric techniques; others such as [19–21] have been applied to physical simulations in order to change the shape of an object depending on physical principles.

One of the deformable objects that has been widely worked on is wood. It has a complex chemical structure. Effects of physical and thermal combustive reactions have different affects on wood object. In literature, there is a significant amount of research that has been done in order to understand the chemical, physical and thermal combustion mechanism of wood. Some of these studies have worked on the complete combustion phases of wood [22, 23]. Some of them focus on subprocesses such as drying, pyrolysis, char gasification, or thermal conductivity and thermal diffusivity values that trigger the combustion reaction of wood [24–30].

Although there are many significant studies in areas of complex physical simulations such as fire construction and propagation, wood combustion and object deformation; there has not been any approach yet that combine all of these together.

In this thesis, we have focused on physically based simulation of wood combustion by using particle system. In our work, not only a simple simulation will be presented, but by generalizing the approach presented in [24], we will model a real combustion process and its graphical simulation depending on oriented particle system approach. During the combustion process, hot volatiles are produced. Depending on the gas production, we will propagate fire. Moreover, decomposition of wood object will be analyzed according to the real combustion reaction equations. Additionally, since our simulation depends on physics, we will also model falling behavior of wood object under combustion depending on physical and thermal changes. Thus, our aim is merging all above areas in order to simulate a real wood combustion process as a complex physical simulation.

Outline of the Thesis

- *Chapter 2* presents a comprehensive investigation of the previous work on Particle Systems, Wood Structure and Combustion, Fire and Object Deformation.

- *Chapter 3* explains our proposed system, physical simulation of wood combustion by using particle system in detail.

- *Chapter 4* contains the results of an experimental evaluation of the proposed physical simulation of wood combustion by using particle system.
- *Chapter 5* concludes the thesis with a summary of the current system and future directions for the improvements on this system.

Chapter 2

Background

This chapter is mainly divided into four sections. In the first section, historical information for particle system model-technique to model our system is briefly explained. The second section presents wood in general and mainly two subsections structure of wood and combustion of wood are presented. The third section briefly explains the different approaches for fire simulation. Finally, approaches related to different representations of object deformation are presented.

2.1 Particle System

Particle Systems were first used in computer graphics by Reeves in 1983 [31]. He defined a particle system model as "a cloud of primitive particles" for modeling of "fuzzy objects" such as fire, smoke, clouds and water. These fuzzy objects do not have smooth, well-defined and shiny surfaces, instead their surfaces are irregular, complex and ill-defined. In his work, Reeves analyzed the dynamic and fluid changes especially in shape and appearance of these objects.

The representation of particle systems differs in three basic ways from the representations normally used in image synthesis.

- An object is represented by "clouds of primitive particles" that define object volume, instead of a set of primitive surface elements such as polygons or patches that define object boundary.
- A particle system is not a static entity. Its particles change form and move along time. New particles are "born" and old particles "die".
- An object represented by particle system is not deterministic, since its shape and form are not completely specified. Instead, stochastic processes are used to create and change an object's shape and appearance.

While modeling fuzzy objects, particle system model has several advantages over classical surface oriented techniques.

- By specifying a particle as a point in 3D space, it is a much simpler primitive than a polygon which is the simplest element of surface oriented representations. By using particle system model, more of the basic primitives can be processed and more complex images can be produced in the same amount of computation time.
- The particle system model is procedural and controlled by random numbers. Therefore, in order to obtain highly-detailed model, it is not required to have more human design time as it is necessary in surface based systems.
- Finally, particle systems model objects are "alive". It is difficult to represent the complexity level of primitives by surface based modeling techniques.

A particle system is a collection of many minute particles that represent a fuzzy object. Each particle in Reeves particle system has attributes that directly or indirectly effect the behavior of the particle or ultimately how and where the particle is rendered. Over a period of time, particles are generated into a system, move and change form and finally die out of the system depending on values of particle attributes. A simple algorithm defined by Reeves is as follows:

- New particles are generated into the system.

- Each new particle is assigned its individual attributes.
- Any particle that has existed for a predetermined time is destroyed.
- Remaining particles are moved and transformed according to their dynamic attributes.
- Active particles are rendered in a frame buffer.

The approach above was later extended by Reeves and Blau [32], Fournier and Reeves [32], Sims [33], and many others to model such diverse phenomena as trees and grass, ocean spray, fireworks, waterfalls, fire, snowstorms and explosions. In Reeves [31] and Sims [33] fire and waterfall models, particles move under the influence of force fields and contraints but do not interact with each other.

Reynolds [34], in his work on flocking behavior, greatly enhanced the power of the particle system as a modeling tool. He proposed the idea of coupling the particles so that they interact with each other as well as with their environment, and demonstrated that it is possible to exploit simple local rules of interaction between large numbers of simple primitives to produce complex aggregate behaviors.

Miller and Pearce [35], Terzopoulos et al. [36], and Tonnesen [37] all explored coupled particle systems as a way to model liquid-like and melting materials. Miller [38], Szeliski and Tonnesen [39], and van Wijk [40] proposed particle interactions that are a function of direction, producing deformable sheets and surfaces of particles. Our own interest is representing a particle system based model of wood combustion by considering both internal and external interactions of each particle.

2.2 Wood

The use of wood as a fuel source for heating is as old as civilization itself. Historically, it was limited in use only by the distribution of technology required to make a spark. The burning of wood is currently the largest use of energy derived from a solid fuel biomass. Wood heat is still common throughout much of the world.[41]

2.2.1 Wood Structure

Wood instead of being a relatively solid material like a steel or concrete, is basically composed of many tubular fiber units or cells, cemented together. In Figure 2.1, annual ring which is a layer of wood cells added to a tree trunk or stem during one growing season is shown in vertical cross-section. Each annual growth ring is composed of an inner part called earlywood (springwood), which is formed early in the growing season, and an outer part, called latewood (summerwood), which is formed later.

Figure 2.1: Annual Rings of Wood [1]

Mainly, wood is divided into two different types as softwood and hardwood. Hardwoods have more complex structure than softwoods. The most significant feature separating hardwoods from softwoods is the presence of pores or vessels. Therefore, hardwoods shown in Figure 2.2 have less resin and burn slower and longer, whereas softwoods shown in Figure 2.3 burn quickly [1].

Type of wood, whether it is hardwood or softwood, burned in the combustion process is important for the heat value and the energy efficiency. Therefore, in our simulation, we modeled an oak which is a hardwood.

Figure 2.2: Hardwoods: Ash, Red Oak, White Oak, Beech and Hickory

Figure 2.3: Softwoods: Eastern White Pine, Sugar Pine, Tamarack, Larch and Spruce

2.2.2 Wood Combustion

Understanding the mechanisms and processes involved in the combustion of wood forms the basis of developing more efficient combustion systems. Many researchers have developed several numerical methodologies for the complete combustion of wood, while others have focused on some of the specific sub-processes involved such as heat transfer, pyrolysis, char and external gas phase processes etc. A detailed computational model of wood combustion has been developed by Bryden [22]. This wood combustion model handles full range of sizes and moisture contents with or without external combustion. This work was extended by Bryden et al. [23] to examine the effect of wood size, moisture content and temperature on the rate of pyrolysis and formation of tar, volatiles and char.

Porteiro et al. [24] presented a mathematical model including most known sub-processes involved for the simulation of a single particle's thermal degradation under combustion condition. The model uses a novel discretization scheme and combines intra-particle combustion processes with extra-particle transport processes, including thermal and diffusional control mechanisms.

Thunman and Leckner [25] have worked on the effective thermal conductivity which is one of the most important parameters of modeling thermal conversion of wood. The variation in thermal conductivity with temperature and conversion of the wood has to be considered in the progress of combustion. They derived a model to calculate the effective thermal conductivity in parallel and perpendicular to the fibres, applied to different stages of combustion of wood.

Thunman et al. [26] have developed a simplified model for the combustion of solid fuel particles that is relevant for particle sizes and shapes. Typical shapes (spheres, finite cylinders, and parallelepipeds) are also considered. The model treats the particle in one dimension. The model only requires the transfer of heat and mass to an element of its external surface in order to describe the conversion inside a fuel particle. According to their work, when modeling a large combustion system, it is a great advantage that the conversion is related to the external surface, because the model does not have to be limited to just a single particle. In fact, it can handle the conversion of a solid phase in a computational cell, where the conversion is related to surface area per unit volume, instead of the surface area of a single particle. The model shows satisfactory agreement with measurements performed on more than 60 samples of particles of different sizes, wood species, and moisture contents.

In [27], the influence from structural changes, heat transfer properties of dry wood and pyrolysis mechanism on the pyrolysis of large wood particles were studied. A model of wood pyrolysis was modified to include structural changes.

Bruch et al. [28] represented a computer model to describe the conversion of wood under packed-bed conditions. The packed bed is an arrangement of a finite number of particles, typically sized between 5 and 25 mm, with a void space left between them. Each particle is undergoing a thermal conversion process, which is described by a one-dimensional and transient model. Within the single-particle model, heating, drying, pyrolysis, gasification and combustion are considered, whereby each particle exchanges energy due to conduction and radiation with its neighbours. Because of the one-dimensional discretization of the particles, heat transfer and mass transfer is taken into account explicitly.

Another work related to thermal decomposition is represented by Peters and Bruch [29]. In their work, a flexible and stable simulation method is presented to predict the thermal conversion of wood particles. A combination of several subprocesses which overrates different properties and sizes represents the global process of thermal conversion. This approach allows for simultaneous processes e.g. reactions in time and covers the entire range between transport-limited (shrinking core) and kinetically limited (reacting core) reaction regimes. Thus, the model is applicable to simulate sufficiently accurate the thermal decomposition of each particle in a packed bed, of which the entire conversion is regarded as the sum of all particle processes.

According to Ragland and Aerts [30], detailed computer modeling of combustion processes requires accurate property values. Fuel properties for combustion analysis of wood can be conveniently grouped into physical, thermal, chemical, and mineral properties. In their approach, they reviewed existing property data on wood which are required for the analysis of combustion systems and to suggest properties that need further quantification.

2.3 Fire

Simulating fire phenomena has an important role in computer graphics applications such as entertainment, visual simulation, battlefield visualization, and even landscape design. However, the visualization and animation of fire is challenging problem. Many researchers have carried out different approaches to model and render the dynamic behavior of fire.

A good survey has been given by Nielson and Madsen [2]. Over a decade ago, Perlin [3] presented a noise-based method to model fire in which fractal perturbation is used to simulate its turbulent movements. His approach is easy to implement, whereas fire front propagation or external effects such as wind cannot be described by his approach.

Inakage [4] represented a model of a simple laminar flame which was texture mapped onto a flame-like implicit primitive and then he traced as a volume-based model. He used a physical model to emit light in the regions of combustion. However, his model is computationally expensive and deals with still images rather than multiple animated flames.

In [5], Takahashi and Chiba combined a user defined vortex-based velocity field and a 2D fuel map to describe the movement of fire. They used a gridded representation of the space, where each grid cell contains a certain amount of fuel gas and heat. Fire itself is modeled by placing geometric primitives around particle trajectories, which are influenced by a vector field.

Stam and Fiume [6] presented a similar model in three spatial dimensions for the creation, extinguishing and spread of fire. The spread of the fire is controlled by the amount of fuel available, the geometry of the environment and the initial conditions. They use a map covering the object defining the amount of fuel and temperature on every point on the object. Their velocity field is predefined, and then the temperature and density fields are advected using an advection-diffusion type equation. They render the fire using a diffusion approximation which takes into account multiple scattering.

Foster and Metaxas [7] presented a method for simulating turbulent gas and fire. Qian [42] used a front tracking method to simulate infinitely thin premixed flame surface, which is explicitly represented by connected marker points.

Recently, Nguyen [8] presented a method based on the Navier-Stokes equations to model fuel with hot gaseous products. By using the level set method to track the moving flame surface they produced realistic looking turbulent flames.

Bukowski and Sequin [9] integrated the Berkeley Architectural Walkthrough Program with the National Institute of Standards and Technology's CFAST fire simulator. The integrated system creates a simulation based design environment for building fire safety systems. An application of physically accurate firelight, and the impact of different fuel types on the color of flames and the scene they illuminate is given in the work of Devlin and Chalmers [10].

Accurate ray casting through fire using spatially sparse measured data rather than simulated data was discussed by Rushmeier [11] using radiation path integration software documented in [12].

In Siegel's approach [13], fire animation is done using turbulent wind fields and rendering is based on warped blobs. The approach is costly and user controls are not so flexible and intuitive.

Perry and Picard [14] have a similar representation as a velocity spread model from combustion science to propagate flames. They reuse the same polygons used for modeling to spread the fire. The flame front is represented by a set of particles, adding new particles as the front expands.

Beaudin [15] use a similar but more accurate flame front technique to model the spreading of the flames. They guarantee that the boundary lies on the object, unlike the work of Perry and Picard [14]. They plant the root of the flame skeleton on the surface and displace the skeleton with the air vector field. They use an implicit surface representation to dress up the flame skeletons during the rendering. Their method is fast, interactive, and allows for quick preview, but lacks accurate air and smoke motion inside the simulation volume.

Melek and Keyser [16] used a modified interactive fluid dynamics solver to describe the motion of a 3-gas system. They simulate the motion of oxidizing air, fuel gases, and exhaust gases. The burning process is simulated by consuming fuel and air based on the amounts of fuel and air inside each grid cell. The combustion process produces heat, and they model the resulting spread of temperature through the system. The heat distribution induces convection currents in the air, causing the flame to take the appropriate shape. By modeling heat distribution, they also simulate the spread of fire to and self-ignition in other combustible solids.

Zao and Wei [17] introduced a method for fire propagation and burning consumption of objects represented as volumetric data sets. Advantages of using volumetric data sets are having high quality results, convenience of implementation and computation, and usability of arbitrary objects. A volumetric fire propagation model is based on distance field which is defined as the distance of any point in space to the nearest surface of the object. Shell volume is another term commonly used. It stores the densities of all voxels. When using values of a shell volume model, distance field is generated for fire propagation around a voxel object based on voxel densities. Using a technique called enhanced distance field representation, fire-front points are guaranteed to stick to the virtual surface while propagating. This propagation method can be easily applied also to polygonal objects. A shell volume is employed that rapidly generates narrow bands, which are then used in a fast marching method to create the distance field for volumetric data for any given isovalue. In this model, the object burning consumption by modifying the fuel property of object voxels and remove burnt voxels from the rendering.

Additionally, there has been many thundering works about high-speed combustion phenomena such as explosions [43] and [44]. Musgrave [43] concentrated on the explosive cloud portion of the explosion event using a fractal noise approach. Neff and Fiume [44] model and visualize the blast wave portion of an explosion based on a blast curve approach.

Yngve [45] proposed a solution for the compressible version of the fluid flow equations, modeling the shock waves created by explosions. In their model the propagation of an explosion through the surrounding air is used as a computational fluid dynamics based approach to solve the equations for compressible, viscous flow. Their system includes two way coupling between solid objects and surrounding fluid, and uses the spectacular brittle fracture technology of the work of Brien and Hodgins [46]. While the compressible flow equations are useful for modeling shock waves and other compressible phenomena, they introduce a very strict time step restriction associated with the acoustic waves which makes the solution computationally expensive [46].

2.4 Object Decomposition

In computer graphics and animations, deformable objects have been widely used especially in animation of clothing, facial expressions and human or animal characters. In [47], many mathematical and computational techniques are examined for modeling object deformation in computer graphics applications.

Many applications do not necessarily apply the physical principles. They are only based on purely geometric techniques which are computationally more efficient. Basically, curves and surfaces are required to model deformation of an object. It can be provided by Bezier curves, double-quadratic curves, B-splines, rational B-splines, and non-uniform rational B-splines (NURBS). These methods can be represented by both planar and 3D curves and have related 2D patches in order to specify surfaces. In these representations, the curve or surface is represented by a set of control points. The shape of the objects are adjusted by moving control points to new positions, by adding or deleting control points, or by changing their weights.

One of the significant method in order to deform an object is Free-form deformation (FFD). It provides not only adjusting individual control points but also a higher and more powerful level of control. By changing the space values in which the object lies, free-form deformation method can alter the shape of object. Free-form deformation technique can be applied to many graphical representations such as points, polygons, splines, parametric patches, and implicit surfaces. Sederberg and Parry [18] developed a technique for deforming the solid geometric models by using free form deformation techniques. Their method could be applied to quadratics, CSG based models, parametric surface patches or implicit objects with derivative continuity.

Mass-spring models are used to model simulations of physical principles which are not represented by purely geometric techniques. It is a physically based technique used to model deformation of objects. An object is modeled as a collection of point masses connected by springs in a lattice structure. Mass-spring systems have been used especially in facial animations. Terzopoulos and Waters

[19] were the first to apply dynamic mass-spring systems to facial modeling. They constructed a three-layer mesh of mass points based on three anatomically distinct layers of facial tissue which are the dermis, a layer of subcutaneous fatty tissue, and the muscle layer respectively.

Continuum models are more accurate physical models that treat deformable objects as a continuum: solid bodies with mass and energies distributed throughout. Separating the model from the method used to solve has an important role. Models can be discrete or continuous but the computational methods used to solve the models are ultimately discrete. The equilibrium of a model acted on by external forces is considered by the full continuum model of a deformable object.

General finite element method (FEM) is used to find an approximation for a continuous function that satisfies some equilibrium expression such as the deformation equilibrium expression. In FEM, the continuum, or object, is divided into elements joined at discrete node points. A function that solves the equilibrium equation is found for each element. The solution is subject to constraints at the node points and the element boundaries so that continuity between the elements is achieved. Finite element method has limitations because of the computational requirements. It is difficult to apply real time systems. Because the force vectors and mass matrices should be computed for each integration over the object which is costly. Therefore, it is preferred to apply only small deformations. Gouret and Thalmann [20] used FEM to model interactions between the soft tissues in a human hand and a deformable object. They use 3D elements with linear interpolation functions and a dynamic formulation to animate the interaction. Chen and Zeltzer [21] used 20-node brick elements with parabolic interpolation functions to model deformation of muscles and other objects.

Chapter 3

Proposed System

In this chapter, our work for simulating the combustion process of a piece of wood by using particle system model is presented.

We have divided our system into three main sections as "Wood", "Fire" and "Falling Down of Wood under Combustion". In the first section, our main object, wood is explained in detail. The latter section, fire construction and propagation is discussed. In the final section, falling behavior of wood under combustion is examined.

3.1 Wood

This section is mainly divided into three subsections. In the first subsection, modeling structure of wood is briefly explained. The latter subsection includes decomposition process of wood in detail. Moreover, in the third section, our wood simulation and implementation approach is presented.

3.1.1 Wood Modeling

Wood is even more structurally advanced because it is actually a multi-layered, fdament-reinforced, closed-end tube [1]. In our work, wood is designed as a multi-layered structure in order to be consistent with the wood structure in real. Each layer which is counted to determine the age of the tree as in real-wood model, is a particle system composed by rings and each ring is a collection of particles in our implementation. A particle is denoted as P_{ijk}, where i indicates layer number, j indicates ring number and k indicates the particle index. The width of the wood is determined by the number of nested layers, $\sum i$, and the height of the wood is determined by the number of lined up rings, $\sum j$. In Figure 3.1, 5-layered wood model is shown in order to highlight the layered structure. In Figure 3.2, 20 rings of a layer are shown to denote the rings used in wood structure. The wood model presented in this thesis has 7 layers and each layer has 43 rings. In each ring, 360 particles are positioned. Totally, our wood model consists of 10x43x360 (108360) particles.

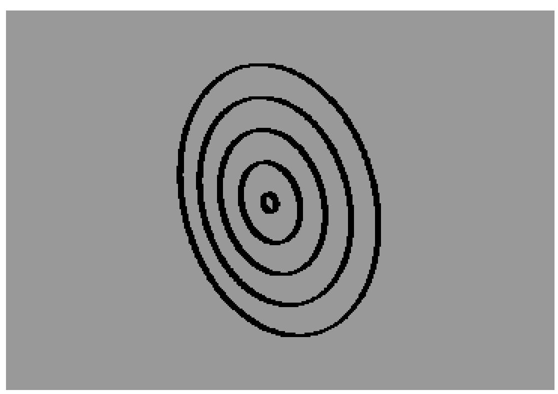

Figure 3.1: Layers of Wood Model

Modeling combustion of wood requires adequate knowledge of wood properties. In general case, properties of wood can be conveniently grouped mainly into physical and thermal properties. Physical properties of wood required for combustion process include wood density, particle size, internal and external surface area per unit volume, porosity, and color. Besides, additional physical properties are hold in our wood model in order to be used while combustion process is activated. These are position, life span, ignition time and velocity explained as

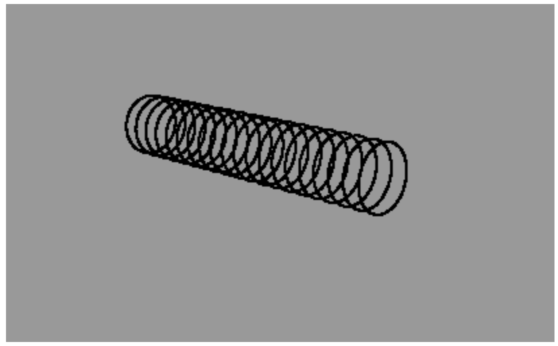

Figure 3.2: Rings of Wood Model

below. The significant thermal properties of wood for combustion analysis include specific heat of wood, the thermal conductivity of wood and thermal diffusivity of wood. In order to hold all properties required for combustion reaction, each particle in our representation has the properties below.

Physical Properties:

- Color: is a physical property that changes according to combustion process. Depending on changes in thermal properties, color of each particle has been darkened, especially in phase of high-temperature drying.
- Size: is a physical property that specifies the dimension of each particle. Depending on the increase in size, storage capacity for heat also increases.
- Density: is another physical property of each wood particle. Total value of particle density consists the density of wood. Porosity is needed for detailed modeling of pulverized wood combustion. Therefore, in our work it is not specified as a particle property, instead it is used as a helper property to determine the degree of particle density.
- Position: is a physical property that holds the location of a particle. It specifies the selected particle's layer and ring coordinates. By having a multi-layered structure, each particle in our system has to keep its layer number and ring number.

- LocalCoordinate: is a physical property that holds particle's local coordinate frame (relative to the global frame (X, Y, Z)) in a vector representation which adds 3 new degrees of freedom (co-planarity, co-normality and co-circularity)to each particle's state.

- Life: is a physical property that specifies the life time of the particle. If life time of a particle ends, then the particle will die out.

- Velocity: is a physical property that holds speed value and direction of wood particle's speed as a vector representation. Initially, before wood starts to burn, velocity of each particle is set to zero in a Cartesian coordinate system. Velocity property is also affected by changes in thermal properties.

- Char: is another physical property that denotes if the particle will burn or not. In our simulation, not all wood particles are burned. Some of them behaves as char, ash etc. This will be defined in following sections in detail.

- Spark: is an incandescent particle, especially one thrown off from a burning substance. This is specified as a physical property in our wood modeling according to the above definition to determine whether the selected particle will be a spark or not during the combustion process.

- Fired: is a physical property that defines if the particle reaches a fixed amount of heat, 'Fired' property is set and spark particle starts its motion.

Thermal Properties:

- Heat: is the most significant thermal property that holds the temperature of each particle. Specific heat depends on temperature and moisture content, not the density of wood.

- Thermal Conductivity: is a property that is specified as the measure of the ability of wood to transfer heat. The thermal conductivity of wood increases depends on changes in density, moisture content and temperature of wood. In our wood modeling, each particle's thermal conductivity property defines the rate of heat transfer among neighboring particles.

- Thermal Diffusivity: is a thermal property that controls the capability of a wood particle to hold or release heat.

Each particle that has all the above physical and thermal properties consist our particle based wood model.

3.1.2 Wood Combustion

The general process of wood combustion is extremely complex and includes various physical, thermal and chemical reactions and sub-processes. Several mathematical models have been developed for the complete combustion of wood particles while some of them have been focused on the specific sub-processes of wood combustion such as drying, pyrolysis, char gasification, etc. In our approach, we have adapted one of the mathematical models including most of the specific sub-processes - drying, pyrolysis and charring- for simulation of a single wood particle degradation under combustion conditions described in [24]. Instead of using the formulas and approach for combustion described in [24] identically, we have inspired from their approach and on the basis of this study, we have generalized a method for any combustible particles in our wood model.

In [24], researchers have assumed that if the particle and external conditions are isotropic, every point at a determined radial distance from the surface of the particle will be in the same degradation. Hence at any specific distance from the centre of the particle, defined as r, a control volume dV is defined. The control surface $G(r)$ is defined as the surface placed at a predetermined position r, which is related to the control volume as in Eq. 3.1

$$dV(r) = G(r)dr \tag{3.1}$$

A set of equations with an initial and boundary conditions are described in order to specify heat transfer, convective and diffusive mass transport inside a particle. In the following general differential equation, the conservation of mass, type and energy inside the particle is described as:

$$\frac{\partial}{\partial t}(\psi_i, \varphi_i) + \frac{1}{G(r)}\frac{\partial}{\partial r}(G(r)\psi_i u \varphi_i) = \frac{1}{G(r)}\frac{\partial}{\partial r}\left(G(r)\Gamma_i \frac{\partial \varphi_i}{\partial r}\right) + S_i \qquad (3.2)$$

where Γ_i is the diffusion coefficient, ψ_i is the generalized densities, φ_i is the dependent variable and S_i stands for the source/sink term. In Eq. 3.2, from left to right, each term stands for rate of increase in control volume, net rate of decrease due to convective transport, net rate of increase due to diffusion across boundaries of the control volume and net rate of creation inside the control volume.

According to immediate outflow and thermal equilibrium between gas and solid inside the control volume, the velocity of gases passing through a control surface placed at a distance r from the center of the particle at any given time is:

$$u(r) = \frac{1}{G(r)\rho_G}\int_a^b - \left[\dot{\omega}_h''' + (1-\chi)\dot{\omega}_p''' + (1+\zeta)\dot{\omega}_c'''\right] G(r^*)dr^* \qquad (3.3)$$

where χ stands for char yield during pyrolysis and ζ stands for the amount of oxygen consumed during char oxidation. Each reaction term is intrinsically negative as it represents the evolution of each solid type that are moisture, wood and char, inside the control volume over time. By simplifying Eq. 3.3, we have calculated velocity of gas of each particle in order to use while modeling fire propagation.

Boundary conditions at the surface of the particle depend on two internal thermal properties. These are rate of thermal conductivity of the wood particle and thermal diffusivity of each wood particle.

Thermal conductivity is a measure of the rate of heat flow through one unit thickness of a wood particle subjected to a temperature gradient. It varies in wood depending on emittance, particle density, moisture content, temperature and the type of gas enclosed in the wood particle. Thermal conductivity increases markedly with increasing moisture content bring about as twice as high at 100 per cent moisture content as it is at 10 per cent. In Eq. 3.4, effective thermal conductivity, λ, depending on change in temperature is calculated by addition of external radiative heat flux of the particle to the total value of convective heat transfer coefficient, control surface area and change in temperature in this area.

$$\lambda^* \left(\frac{\partial T}{\partial r}\right)_{r=R} = \dot{Q}_{rad} + hS(T_g - T_{r=R}) \tag{3.4}$$

Symmetry conditions for heat and mass transfer are also applied at the particle's centre. In Eq. 3.5, thermal diffusivity which is the diffusional mass transport of oxygen inside the particle depends on the availability of oxygen on the particle surface, which at the same time depends on the balance between diffusional mass transfer through the gas-solid inter-phase and chemical reaction at the surface. The Chapman-Enskog theory was used for determining the transport properties, while the specific heat, conductivity and viscosity of the gases involved have been calculated using expressions derived from the literature.

$$D^* \left(\frac{\partial Y_o}{\partial r}\right)_{r=R} = k_m \left[Y_{o\infty} - (Y_o)_{r=R}\right] \tag{3.5}$$

In our work, thermal conductivity and thermal diffusivity are calculated as defined in Eq. 3.4 and Eq. 3.5 to be used in heat transfer and heat diffusion processes.

The work of Porteiro et al. [24], they mainly specified three distinct precursor reactions for combustion process as drying/vaporization of water, pyrolysis/devolatilization and gasification of char. For particle size of interest, vaporization and devolatilization are thermally controlled while char conversion can either be kinetically or diffusionally controlled depending on operation conditions.

In the following sections, we briefly explain their approach for each combustion reaction and how we have adapted them to our work.

3.1.2.1 Drying

Vaporization of water is the pre-combustion stage of each wood particle to be burned. Water in wood normally moves from higher to lower layers of moisture content which supports the common statement that "wood dries from the outside in", which means that the surface of the wood must be drier than the interior if moisture is to be removed. Drying can mainly be divided into two phases: movement of water from the interior to the surface of wood, and removal of water from the surface.

The surface particle of wood reaches to the moisture equilibrium with the surrounding air soon after drying begins. This is the beginning of the development of a typical moisture gradient, that is the difference in moisture content between the inner and outer layers of wood. The surface of wood particle tends to reach moisture equilibrium with the surrounding air if the air circulation is fast enough to evaporate water from the surface as fast as it comes to the surface. If the air circulation is too slow, a longer time is required for the surfaces of wood particle to reach moisture equilibrium.

The rate at which moisture moves in wood depends on the humidity of the surrounding air, the steepness of the moisture gradient, and the temperature of each wood particle. The lower the humidity, the greater the capillary flow. Low humidity also stimulates diffusion by lowering the moisture content at the surface, thereby steepening the moisture gradient and increasing diffusion rate. The higher the temperature of the wood particle, the faster moisture will move from the wetter interior to the drier surface. Drying rate is also affected by thickness in which drying time increases with thickness and at a rate that is proportional to thickness. [48]

Moisture evaporation was considered to occur at 373 K and to be thermally controlled. Any heat transmitted to a moist zone that has reached its evaporation temperature will therefore be fully involved in evaporation until local moisture has been completely evaporated. Furthermore, no recondensation of steam is admitted, nor is the flow of steam towards the centre of the particle. By knowing that during drying the temperature of the control volume is constant, and that no flow of gas enters the control volume from beneath, as pyrolysis below 373 K can be ignored, the energy balance leads to the reaction rate for drying as in Eq. 3.7:

$$Moisture \xrightarrow{k_4} WaterVapour \tag{3.6}$$

$$\dot{\omega}_h'''(r) = \begin{cases} -\frac{1}{G(r)|\Delta H_h|}\frac{\partial}{\partial r}\left(G(r)\lambda^*\frac{\partial T}{\partial r}\right) \\ 0 \end{cases}$$
$$if\ T \geq T_{evap} \quad and \quad \rho_h > 0. \tag{3.7}$$

In Eq. 3.7, $G(r)$ stands for area of control surface, ΔH_h stands for reaction enthalpy, λ stands for thermal conductivity which is calculated according to Eq. 3.4 and set to thermal property value of particle. We have adapted parameters of Eq. 3.7 to our drying procedure. Surface control area, $G(r)$, has been calculated depending on value of *Size* property of particle. In our approach, we have set the value of reaction enthalpy, ΔH_h, as a constant. Coordinate of each particle to dry, r is hold by *Position* property of particle in our approach. If a particle's temperature T is hold as *Heat* property of each particle that is greater than or equal to evaporation temperature T_{evap} = (373K) and drying density, ρ_h, is greater than zero, then reaction process for drying will begin.

As the basis of [24], we have extended the physical process performed for drying a wood particle as drying a wood that has been formed by many wood particles. The graphical implementation will be explained in section 3.1.3.1 in detail.

3.1.2.2 Pyrolysis

Ignition and combustion of wood is mainly based on the pyrolysis phase. Pyrolysis is defined as the thermal decomposition of materials - in our case, wood - in the

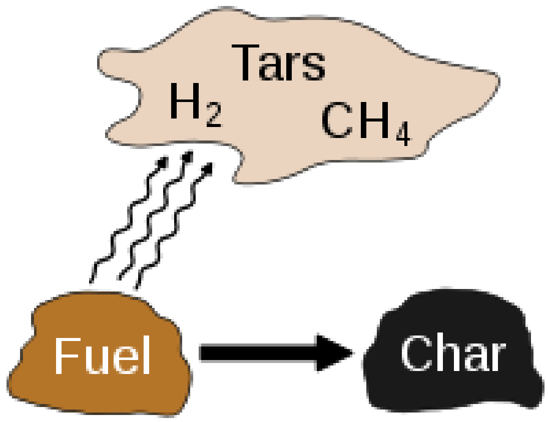

Figure 3.3: Simple sketch of pyrolysis chemistry

absence of oxygen or when significantly less oxygen is present than required for complete combustion. Pyrolysis has been considered by three parallel reactions for the transformation of wood into gas, tar and char as shown in Eq. 3.8 and Figure 3.3 schematically.

$$DryWood \begin{cases} \xrightarrow{k_1} Gas \\ \xrightarrow{k_2} Tar \\ \xrightarrow{k_3} Char \end{cases} \tag{3.8}$$

The general changes in wood structure that occur during pyrolysis phase are listed as below [49]:

1. Heat transfer from a wood particle, to increase the temperature inside the fuel
2. The initiation of primary pyrolysis reactions at this higher temperature releases volatiles and forms char
3. The flow of hot volatiles toward cooler solids results in heat transfer between hot volatiles and cooler unpyrolyzed fuel
4. Condensation of some of the volatiles in the cooler parts of the fuel, followed by secondary reactions, can produce tar

5. Autocatalytic secondary pyrolysis reactions proceed while primary pyrolytic reactions (item 2, above) simultaneously occur in competition

6. Further thermal decomposition, reforming, water gas shift reactions, radicals recombination, and dehydrations can also occur, which are a function of the process's residence time/temperature/pressure profile.

Net reaction rate of a wood particle during pyrolysis phase is given in Eq. 3.9.

$$\dot{\omega}_p''' = -\rho_w \sum_{i=1}^{3} k_i \exp\left(-\frac{E_i}{R_0 T_p}\right) \tag{3.9}$$

In order to start pyrolysis reaction, the most significant parameter, pyrolysis temperature, (T_p), has to be reached. Particle density (ρ_w), mass transfer coefficient (k_i), ideal gas constant (R_0) and activation energy value (E), have to be known. Mass transfer coefficient (k_i), ideal gas constant (R_0) and activation energy value (E) are all constant parameters in our implementation. In our approach, while pyrolysis temperature (T_p) is reached by particle temperature (T) hold in property ($Heat$), thermal decomposition of wood object will be started. We will explain our graphical approach in section 3.1.3.1.

3.1.2.3 Charring

Charring is a chemical process of incomplete combustion of a solid when subjected to high heat. The resulting residue matter is called "Char". Charring can be either a deliberate and controlled reaction used in manufacturing or it may be the result of naturally occurring processes as in our case. By the action of heat, charring removes hydrogen and oxygen from the solid, so that the remaining char is composed primarily of carbon.

The char net reaction rate for a wood particle is given in Eq. 3.10. Under combustion conditions, char reaction is normally controlled by the diffusion of oxygen from the bulk. The charring rate of wood is also very sensitive to the presence of inorganic impurities, such as fire retardants, because they affect the chemical kinetics of the pyrolysis process.

$$\dot{\omega}_c''' = -k_c \exp\left(\frac{-E_c}{R_0 T_c}\right) \rho_G Y_o \frac{M_c}{M_{O_2}} S''' \qquad (3.10)$$

In order to begin charring reaction, temperature (T_c), required to begin charring has to be reached. Same as in pyrolysis phase, particle density (ρ_G), mass transfer coefficient (k_c), ideal gas constant (R_0) and activation energy value have to be known. Additionally, rate of char weight (M_c) to oxygen weight (M_{O_2}) is required to char combustion process. Surface area of a particle (S), is required to calculate the rate of charring material. In section 3.1.3.3, graphical representation will be explained in detail.

3.1.3 Wood Simulation

Our system is mainly a simulation for combustion of a wood object. It allows us to visualize physical and thermal effects that change shape and internal structure of wood. Our simulation works by generating an animation frame per time step. For generating the animation frames, for each wood particle, physical and thermal equations required to implement real combustion reactions specified in Section 3.1.2 are calculated respectively, and their updated positions and orientations are determined for each frame. This process is repeated until all the desired frames of animation - combustion of whole wood - are generated.

As mentioned in Section 3.1.1, our wood object generation routine is fairly simple. As we explained in previous sections, it is formed by nested layers and ordered rings that are composed by particles. Hence, in order to simulate graphically, necessary phases for combustion such as heat transfer, heat diffusion and decomposition are carried out by particles. Therefore, interaction between particles, transfer of each property information among particles are highly important to simulate combustion process. Before explaining graphical implementation of each combustion reaction as subsections, we describe our approach to flow of necessary information among particles.

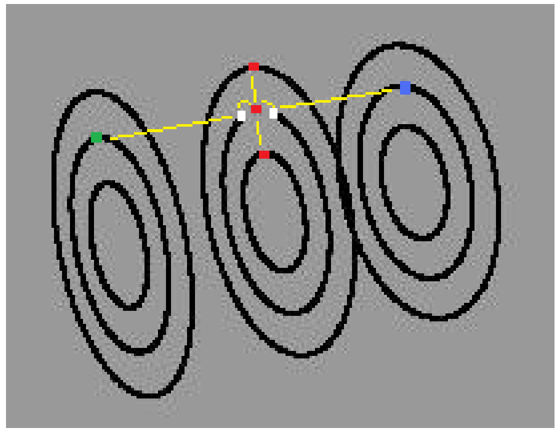

Figure 3.4: Control flow of information among particles

In Figure 3.4, enlarged graphical wood model is represented by 3 layers and 3 rings for each layer to show flow relations among particles. To make more explicit description, we have assumed that each red, green, blue and white points represents a particle schematically. Green particle (P_{21g_0}) is in 1^{st}ring of 2^{nd} layer. Red particle, (P_{22r_0}), in between the white particles is in 2^{nd} ring of 2^{nd} layer. Also, white particles, ($P_{22w_{360}}$) and (P_{22w_1}) are in 2^{nd} ring of 2^{nd} layer. Upper red particle, (P_{12r_0}) is in 2^{nd} ring of 1^{st} layer and lower red particle, (P_{32r_0}) is in 2^{nd} ring of 3^{rd} layer. Finally, blue particle, (P_{23b_0}) is in 3^{rd} ring of 2^{nd} layer. All these colored points specified as particles are neighbor particles of middle red particle in order to specify flow of required property information. White particles are radial-neighbor particles, upper and lower red particles have same x-coordinates values with middle red particle called as y-neighbor particle and, green and blue particles have same x-coordinates values with middle red particle called as y-neighbor particle. Required property values are calculated and compared with these neighbor particles to determine how property information is transferred between them. This procedure is repeated for each combustion reaction until all particles will be processed. This approach is generalized in Algorithm 1. This will be extended for each combustion process in the following subsections in detail.

Although Algorithm 1 suggests that initially P_{i00} is fired, by generalizing this initialization as our proposed system provides, the combustion process can be started from any desired wood particle by triggering the required property values of desired wood particle. In order to explain our approach clearly, we

Algorithm 1 General algorithm for property value transfer

```
1. Set property value of P_i00 as initial value to the result of
   calculation done related to reaction equation
2. For each P_ijk from layer number 0 to i-1
   2.1 For each P_ijk from ring number 0 to j-1
   2.1.2 For each P_ijk from particle index 0 to k-1
             2.1.2.1 Calculate necessary reaction equation results
                     for radial , x and y neighbor particles.
             2.1.2.2 Compare property value of P_ijk with
                     radial , x and y neighbor particles.
             2.1.2.3 Update property value of each radial ,
                     x and y neighbor particles.
```

have defined three different wood combustion types as *Left-Side Combustion*, *Middle Combustion* and *Multiple Combustion*. In *Left-Side Combustion*, we have triggered the particle P_{000} which is the 1^{st} particle found in 1^{st} ring of 1^{st} layer. In *Middle Combustion*, we have triggered the particle P_{0220} which is the 1^{st} particle found in 21^{th} ring of 1^{st} layer. Finally, we have triggered particles P_{000} and P_{0330} which are the 1^{st} particle found in 1^{st} ring of 1^{st} layer and the 1^{st} particle found in 32^{th} ring of 1^{st} layer respectively. During the following sections, with graphical illustrations, we have given examples of each three wood combustion type for the wood combustion processes.

3.1.3.1 Heat Transfer

Heat is begun to be transferred while wood particles reach to the pyrolysis temperature, by applying a pyrolysis process at every simulation time step. However, before this combustion phase, as it is mentioned in Section 3.1.2.1, a pre-combustion stage, drying, is applied to vaporize water included in wood structure. In our approach, we have represented drying of each wood particle by darkening its color. *Color* property of each wood particle is changed orderly according to net reaction rate value calculated depending on appropriate conditions given in Eq. 3.7. If combustion has not been started yet, wood particles will not be decomposed in this stage. The procedure in the drying phase is summarized in

Algorithm 2. The graphical representation of drying phase for wood combustion types, *Left-Side Combustion*, *Middle Combustion* and *Multiple Combustion* have been displayed in Figure 3.5.

Algorithm 2 Procedure for drying phase

```
1. Set Size, Position, Thermal Conductivity, Heat of P_ijk,
   1.1 If Heat of P_ijk >= T_evap and Density of P_ijk > 0
       1.1.1 Calculate net reaction rate for drying in Eq.3.7.
       1.1.2 Set Color of P_ijk to dark color.
   1.2 If Heat of P_ijk < T_evap or Density of P_ijk <= 0
       1.2.1 Color of P_ijk is NOT set.
2. Pass to each radial,x and y neighbour particles of P_ijk,
```

Pyrolysis phase is the main stage when heat is transferred to trigger thermal decomposition of wood object. During pyrolysis, some of the solid fuel found in each wood particle is converted into fuel gas. Thus, particle shrinks during heterogeneous phase of combustion. Particle shrinkage is computed throughout the process. Decomposition of a wood object will be explained in section 3.1.3.2 in detail. To make pyrolysis more clear, the procedure in the pyrolysis phase is summarized in Algorithm 3. The graphical representation of pyrolysis phase for each wood combustion types has been illustrated within the decomposition of wood in Figure 3.6.

3.1.3.2 Decomposition

While organizing our decomposition process, we have adopted the techniques described in [39], *Surface Modeling with Oriented Particle System* approach. Although techniques for deformable objects such as spline models and deformable surface models have been very successful in creating and animating such deformations, these methods either require the discretization of the surface into patches (for spline surfaces) or the specification of local connectivity (for spring-mass systems) and required highly significant amount of preprocessing before using surface model. Instead of using such an explicit modeling technique, we have also developed our particles as *oriented particles* by adding *LocalCoordinate* property

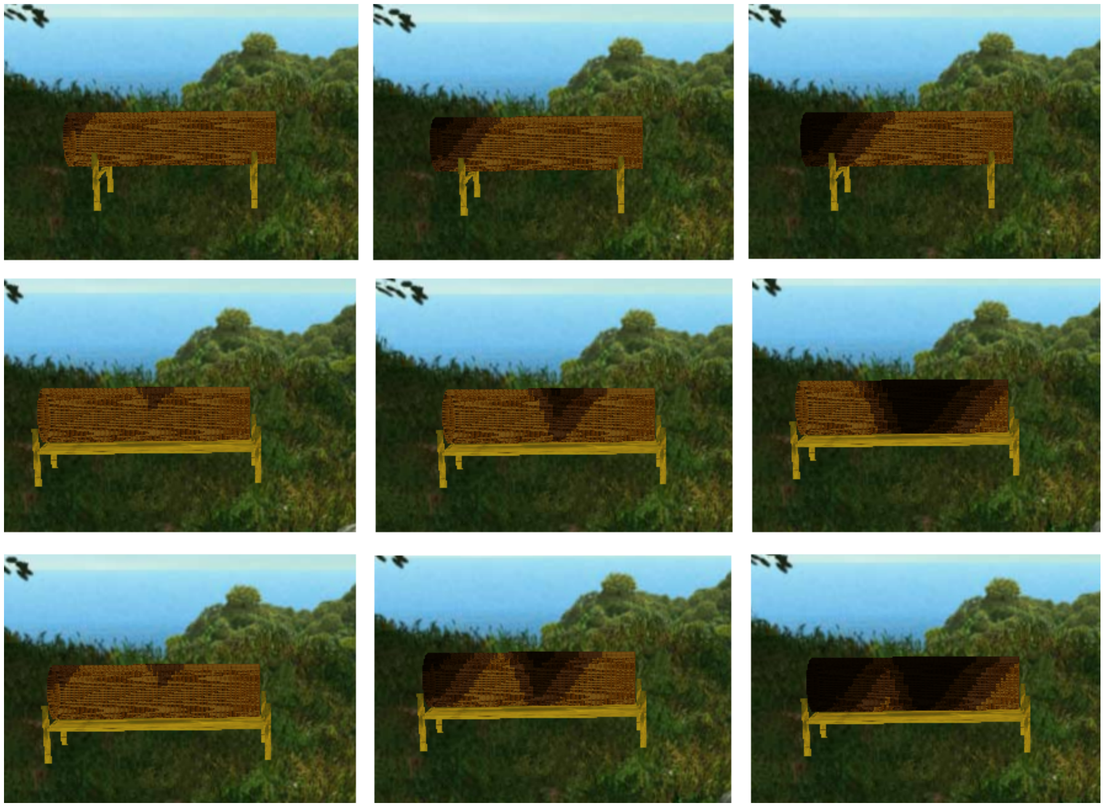

Figure 3.5: Drying Phases of Left-Side Combustion, Middle Combustion and Multiple Combustion

as a vector representation.

Each particle has a local coordinate frame which is updated during the simulation. New interaction potentials are designed which favor locally planar or locally spherical arrangements of particles. These interaction potentials are used in conjunction with more traditional long-range attraction forces and short-range repulsion forces which control the average inter-particle spacing.

Surface model composed by *oriented particles* shares characteristics of both deformable surface models and particle systems. Like traditional spline models, it can be used to model free-form surfaces and to smoothly interpolate sparse data. Like interacting particle models of solids and liquids, surfaces can be split, joined, or extended without the need for re-pararnetrization or manual intervention [39]. Thus, in our work, we have chosen to model our wood object by combination of *oriented particles*.

Algorithm 3 Procedure for pyrolysis phase

```
1. Set Size, Position, LocalCoordinate, Velocity, Heat of P_ijk
   to initial values,
2. Increase Heat for each time step,
   2.1 If Heat of P_ijk >= T_p and Density of P_ijk > 0
       2.1.1 Calculate Thermal Diffusivity of P_ijk according to
       Eq.3.5.
       2.1.2 Calculate Thermal Conductivity of P_ijk according to
       Eq.3.4.
       2.1.3 If Thermal Diffusivity > 0 and Thermal Conductivity > 0,
            2.1.3.1 Calculate net reaction rate for pyrolysis in Eq.3.9
            2.1.3.2 According to reaction rate calculated in 2.1.3.1,
                    set new Size, Velocity, Position and
                    LocalCoordinate values of P_ijk that will
                    be used in decomposition.
3. Pass to each radial,x and y neighbor particles of
   P_ijk to calculate 2.1.3.1.
```

In order to force particles to behave as surface-like structure, potential functions are described. In [39], potential functions *co-planarity*, *co-normality* and *co-circularity* are substituted as *local coordinates* of each particle. In our work, each particle has *Position* and *LocalCoordinate* properties that denote particle position and particle orientation of local coordinate frame respectively. Therefore, decomposition of each particle is calculated according to new *LocalCoordinate* property value that is defined by integration of potential functions and rate of shrinkage that affects particle's size depending on pyrolysis phase. Detailed explanation related to potential functions can be found in [39]. The graphical representation of decomposition for wood combustion types, *Left-Side Combustion*, *Middle Combustion* and *Multiple Combustion* have been displayed in Figure 3.6.

3.1.3.3 Char Production

After all particles have reached their pyrolysis temparature, decomposition of wood starts. During this process, some particles have completed their assigned life times and have transformed into a new form, called char. Other particles have continued to convert their fuel gas to volatiles in order to propagate fire.

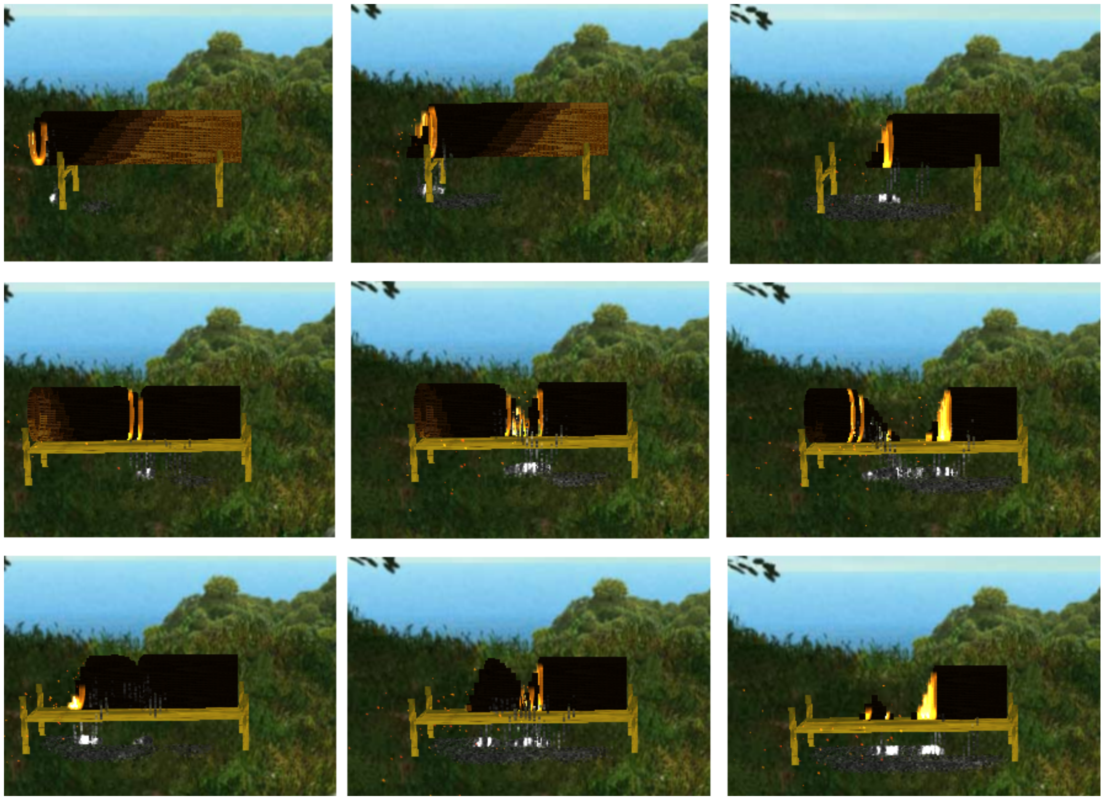

Figure 3.6: Decomposition of Left-Side Combustion, Middle Combustion and Multiple Combustion

It is defined in section 3.2 in detail. After required threshold heat value for charring has been reached, char production has been started. In our algorithm, if particle life time *Life* has ended, property *Char* is set as true, otherwise set as false. The procedure for charring phase is summarized in Algorithm 4. The graphical representation of char produced is displayed in Figure 3.7.

3.2 Fire

In this section, we will explain fire construction and fire propagation. As it is mentioned in previous sections, throughout pyrolysis phase, depending on changes in physical and thermal properties of a wood, solid fuel found in some wood particles have started to char and remaining particles have converted into fuel gas to propagate fire.

Algorithm 4 Procedure for charring phase

```
1. Set Size, Life, Position, Thermal Conductivity, Heat of P_ijk,
   1.1 If Heat of P_ijk >= T_c and Density of P_ijk > 0 and
       Life of P_ijk = 0
       1.1.1 Calculate net reaction rate for charring in Eq.3.10.
       1.1.2 Set Char of P_ijk as TRUE.
   1.2 If Heat of P_ijk < T_c or Density of P_ijk <= 0
       Life of P_ijk > 0
       1.2.1 Char of P_ijk as FALSE.
2. Pass to each radial, x and y neighbour particles of P_ijk,
```

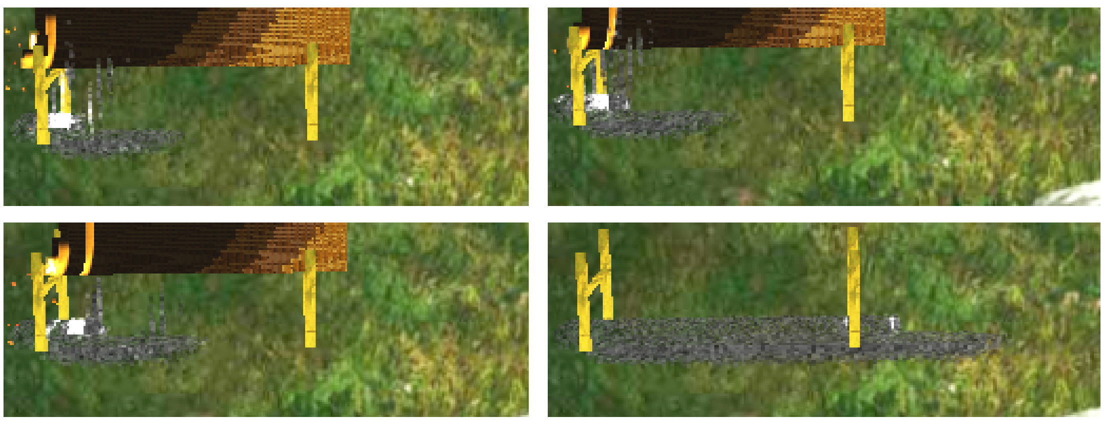

Figure 3.7: Char Production in Proposed Wood Model

Each wood particle is a potential fuel source and wood particles passed drying phase are named as active fuel source particles. Active fuel sources emit fuel gas density according to the result of rate for passing velocity of gas in Eq. 3.3, into the radial neighbor, x-neighbor and y-neighbor wood particles at every time step. Potential fuel sources can later self-ignite and become active fuel sources. Every wood particle has a pyrolysis temperature. When a wood particle reaches its pyrolysis temperature, it becomes a fuel source. Since self-ignition temperature of the fuel is much smaller than pyrolysis temperature, by having enough air in the system, the resulting fuel gas starts burning when it mixes with air.

As mentioned in section 3.1.1, in our implementation, fire model has also specific physical properties to model the propagation. These are as follows:

Physical Properties:

- Color: is a physical property that specifies the starting color of fire particles which comes out from emitter.
- FadeColor: is a physical property that specifies the final color of fire particles that is shaded by using interpolation.
- FadeTime: is a physical property that defines how fast fire particles die.
- Life: is a physical property that specifies the life time of fire particle. If life time of a fire particle ends, then fire particle will die out.
- Velocity: is a physical property that holds speed value and direction of fire particle's speed as a vector representation.
- Position: is a physical property that holds the location of a fire particle.

In our simulation, we have used a simple fire implementation. Mainly, after initializing above fire particle properties according to values determined by internal combustion processes of wood, we have located the beginning position of fire particles at specified locations. At every time step, according to speed of volatility calculated in Eq. 3.3, new *Position* of each fire particle has been interpolated.

In same approach has already been applied while determining the colority of fire particles. At first, we have visualized fuel gas as yellow and flame as red. The intensity in *Color* from yellow to red is changed depending on interpolation process applied according to density of gas (ρ_G) found in fire particles. As in real process for wood burning, not only yellowish-red flames are produced, also some white smokish flames are produced. To make it similar, in our implementation these flames are already implemented. The type of flames depends on gas density rate in each wood particle that triggers fire propagation. Graphical representation of yellowish-red and white smokish flames are illustrated in Figure 3.8.

Additionally, in real wood combustion process, some tiny and incandescent particles called sparks are rapidly thrown off from burning wood. We have also

Figure 3.8: Fire and Smoke Propagation in Proposed Wood Model

implemented sparks in our simulation shown in Figure 3.9. *Spark* property of wood particle determines whether the selected particle will be a spark or not during the combustion process. It is set according to *Heat* property of each wood particle. If *Heat* property of a wood particle has reached threshold temperature value for sparking and *Fired* property is set, then selected wood particle is specified as spark and starts its defined motion. Motion is determined according to *Velocity* property.

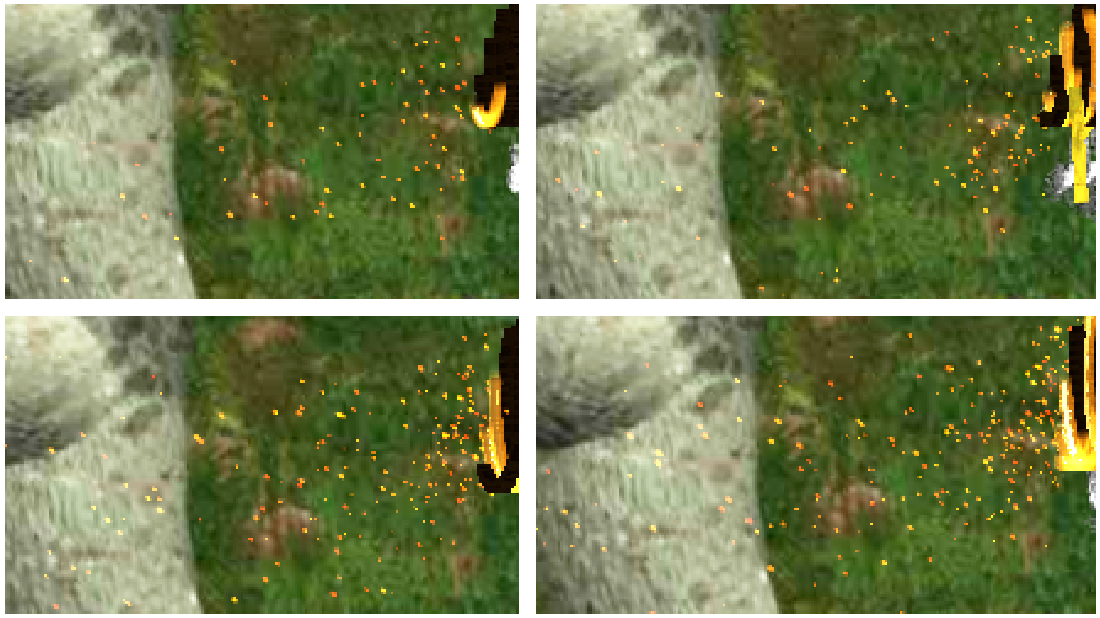

Figure 3.9: Spark Propagation in Proposed Wood Model

3.3 Falling down of Wood under Combustion

In this section, we will explain how the wood falls down depending on the physical and thermal changes during the decomposition phase of wood combustion. As our simulation is based on physics, we have modeled falling behavior of wood under combustion. In order to simulate falling behavior, we have used momentum.

In our implementation, wood stands on two non-conductive legs. Wood model has been affected by three forces that are F_K, F_L and G which stands for "Center of Mass" of the model, as illustrated in Figure 3.10 with their directions.

While pyrolysis phase has been entered, wood particles begin to form char and release volatiles to propagate fire. In this transformation process, as wood burns, total shape and volume of the wood shrinks due to dying out of each combusted wood particle. While burning process has reached to a certain level, the model begins to fall down. According to "Law of Momentum Conservation", the equilibrium state of wood is given in Eq. 3.11, where F_K stands for the reaction force from left side of the wood, F_L stands for the reaction force from right side of the wood, G stands for center of mass of the wood.

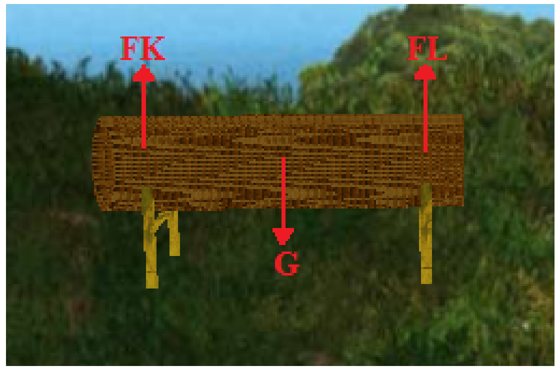

Figure 3.10: Forces acted to Wood Model

$$F_K + F_L = G \tag{3.11}$$

When wood particles begin to burn and as a result of this, there is no more equilibrium on the non-conductive legs, the wood will start falling down according to the conservation of momentum. In Eq. 3.12, the momentum of wood has been calculated according to force K (F_K).

$$F_L * D_L = G * D_G \tag{3.12}$$

By the modification of Eq. 3.11, in Eq. 3.12, D_L stands for the distance of force L (F_L) to force K (F_K) and D_G stands for the distance of center of mass (G) to force K (F_K). In every time step, for decomposition reaction of each wood particle, Eq. 3.12 is calculated recursively and depending on its value, the wood object starts falling down. Our approach is generalized in Algorithm 5.

Algorithm 5 Procedure for falling down of wood under combustion

```
1. For each P_ijk,
   1.1 If Decomposition starts as defined in section ~3.1.3.2
     1.1.1 Calculate ''Momentum Conservation'' according to Eq.3.12.
       1.1.2 Set new Position of P_ijk to process falling down
             behavior.
2. Pass to each radial,x and y neighbor particles of P_ijk
```

In Figure 3.11, falling behavior of wood has been shown and to emphasize falling behavior, we have not displayed fire propagation.

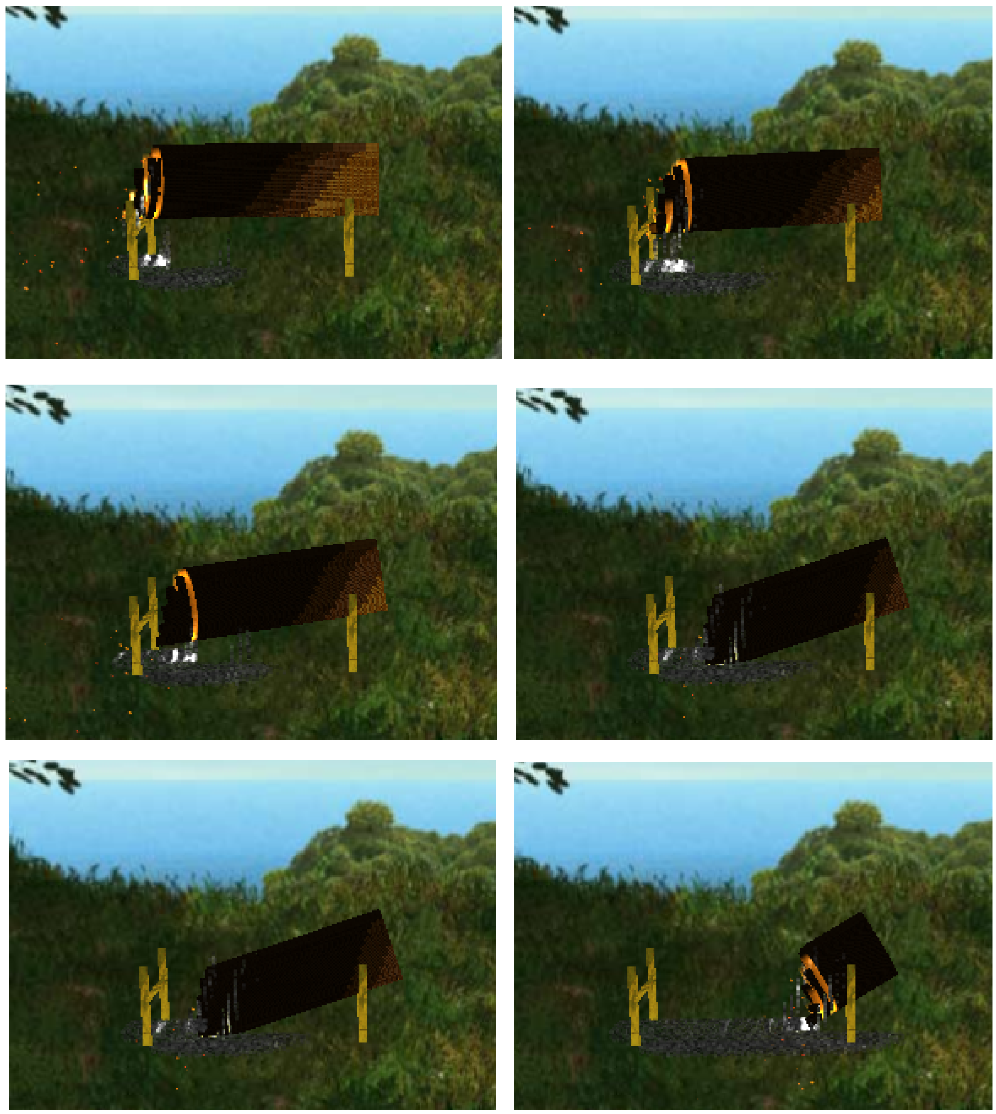

Figure 3.11: Falling Down Of Wood

Chapter 4

Simulation Results

We have run our proposed simulation on a 2.40 GHz Intel Core2 Duo[1] with a Ati Mobil Radeon^{TM} HD3430[2] graphics card and 4 GB RAM. This simulation includes the simulation of burning and decomposition of wood, fire construction and propagation, and falling behavior of wood under combustion process. Our implementation is done using C++.

There are no similar simulations that analyze and visualize the physical and thermal effects of combustion of wood based on real combustion reactions. Therefore, in order to evaluate the success of the proposed physical simulation of wood combustion by using a particle system, we have performed an experimental study and will discuss the results in detail.

In our proposed simulation, as it is mentioned in section 3.1.1, there are 7 layers, 43 rings and 360 particles for each ring. Thus, there are a total of 108360 particles for the wood.

For each wood combustion type - *Left-Side Combustion*, *Middle Combustion* and *Multiple Combustion*, we have measured the *Combustion Duration* for several wood models in which each has different number of wood particles in their

[1] Intel Core2 Duo is a registered trademark of Intel Co.

[2] Ati Mobil Radeon^{TM} HD3430 is a registered trademark of Advanced Micro Devices (AMD), Inc.

representations. *Combustion Duration* is defined as the duration that starts by the drying of the 1^{st} wood particle till the end of decomposition of the last wood particle. Note that combustion process includes all physical and thermal sub-processes - drying, pyrolysis and charring. However, in this experiment we have only considered the wood particles, not the fire and the char particles. Therefore, we have ignored char particles produced during charring phase and fire particles produced during fire propagation phase. By multiplication of number of layers, number of rings and the particle number in each ring, total number of wood particles have been calculated. We have used five different wood models. In each model, we have fixed the number of rings as 43 and number of particles found in each ring as 360, as same in our proposed system Figure 4.6. In order to increase or decrease the total number of wood particles, we have only changed the layer numbers. Wood models according to newly assigned layer numbers are shown in Figure 4.1.

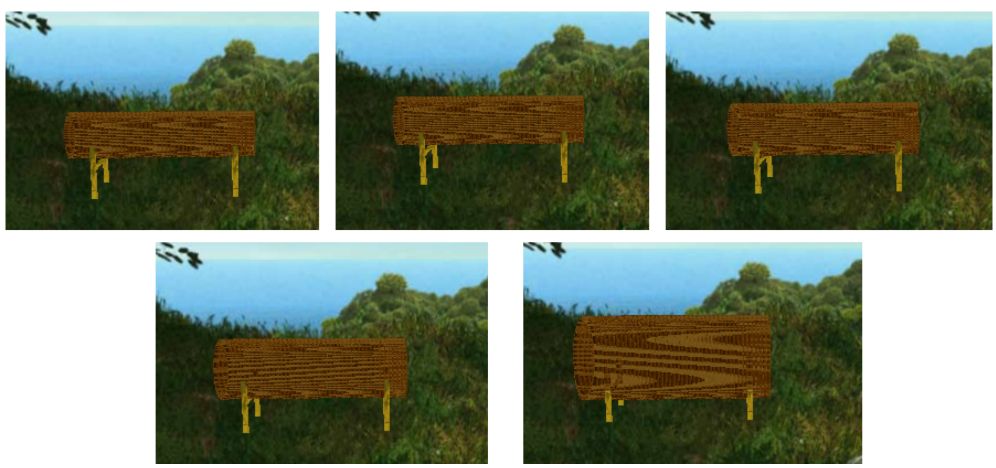

Figure 4.1: Wood Models as 3-Layered, 7-Layered, 14-Layered, 28-Layered, 70-Layered

Width of the wood model increases depending on the layer number as seen in Figure 4.1. In Table 4.1, for *Left-Side Combustion* type, total number of wood particles for each wood model and their *Combustion Duration*s are shown.

According to Table 4.1, for each wood model, rate of number of total wood particles with respect to their *Combustion Duration* are illustrated in Figure 4.2.

Table 4.1: Data of Five Wood Models in Left-Side Combustion

	Layer × Circle × Particle	**Number of Wood Particles**	**Combustion Duration (msec)**
≈Our System / 2	3 × 43 × 360	46440	198790
Our System	7 × 43 × 360	108360	225530
Our System x 2	14 × 43 × 360	216720	336010
Our System x 4	28 × 43 × 360	443440	567440
Our System x 10	70 × 43 × 360	1083600	1265000

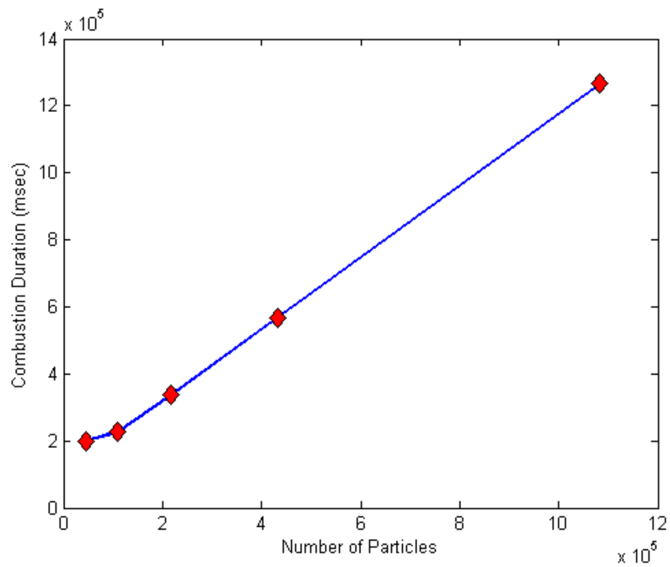

Figure 4.2: Rate of Total Number of Wood Particles with respect to Combustion Duration For Left-Side Combustion

The second bullet represents the rate of our proposed system simulation. When the total number of wood particles is approximately half of our proposed system, the difference of total number of wood particles is greater than the change in *Combustion Duration*. This means that even though the total number of wood particles is less, all wood models have to reach threshold temperature value $T_{threshold}$ to start combustion process. In third, fourth and fifth bullets, the total number of wood particles are twice, four times and ten times of the total number of wood particles found in our proposed system respectively. As it is seen, there is a linear increase in the rate of *Combustion Duration* after wood has begun to combust from left most particle.

In Table 4.2, for *Middle Combustion* type, total number of wood particles for each wood model and their *Combustion Duration*s are displayed.

Table 4.2: Data of Five Wood Models in Middle Combustion

	Layer × Circle × Particle	**Number of Wood Particles**	**Combustion Duration (msec)**
≈Our System / 2	3 × 43 × 360	46440	99770
Our System	7 × 43 × 360	108360	149590
Our System x 2	14 × 43 × 360	216720	242020
Our System x 4	28 × 43 × 360	443440	426690
Our System x 10	70 × 43 × 360	1083600	999770

According to Table 4.2, for each wood model, rate of number of total wood particles with respect to their *Combustion Duration* are illustrated in Figure 4.3.

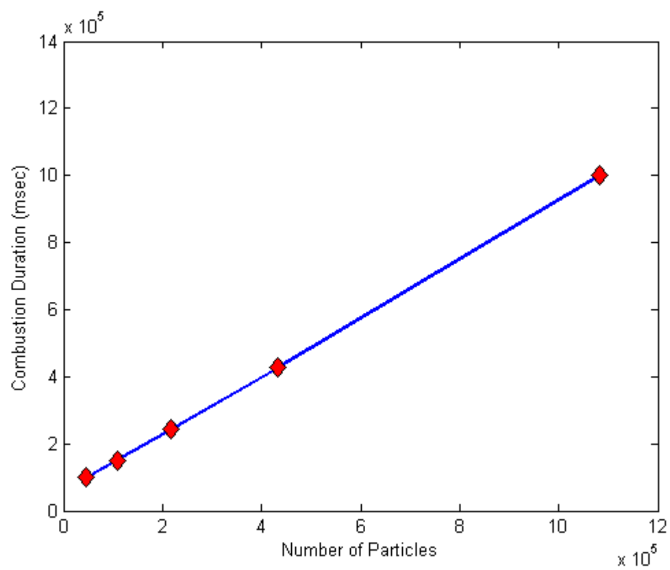

Figure 4.3: Rate of Total Number of Wood Particles with respect to Combustion Duration for Middle Combustion

Same as in Left-Side Combustion case, while wood has begun to combust from its middle particle, the rate of total number of wood particles with respect to *Combustion Duration* linearly increases (Figure 4.3).

In Table 4.3, for *Multiple Combustion* type, total number of wood particles for each wood model and their *Combustion Duration*s are displayed.

Table 4.3: Data of Five Wood Models in Multiple Combustion

	Layer × Circle × Particle	Number of Wood Particles	Combustion Duration (msec)
≈Our System / 2	3 × 43 × 360	46440	63230
Our System	7 × 43 × 360	108360	128550
Our System x 2	14 × 43 × 360	216720	228250
Our System x 4	28 × 43 × 360	443440	407330
Our System x 10	70 × 43 × 360	1083600	913090

According to Table 4.3, for each wood model, rate of number of total wood particles with respect to their *Combustion Duration* are shown in Figure 4.4.

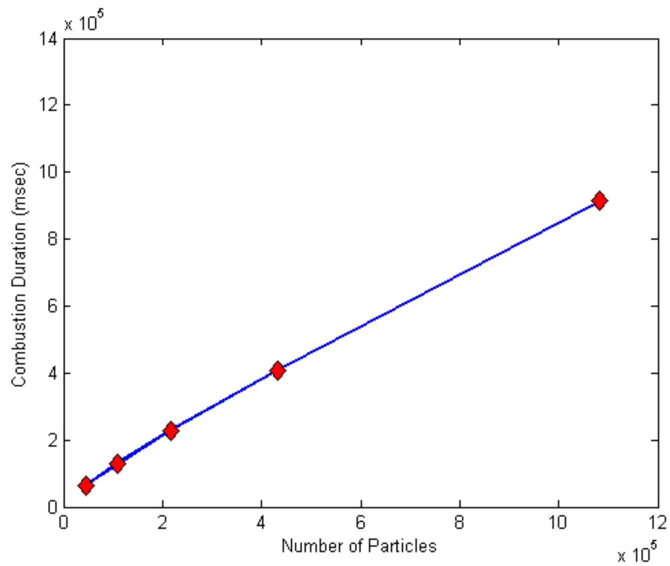

Figure 4.4: Rate of Total Number of Wood Particles with respect to Combustion Duration for Multiple Combustion

As it is seen in Figure 4.4, the rate of number of total wood particles with respect to their *Combustion Duration* distinguishes *Multiple Combustion* type from *Left-Side Combustion* and *Middle Combustion* types. In *Multiple Combustion*, simultaneously two combustion processes have been applied to five different wood models. Therefore, compared to *Left-Side Combustion* and *Middle Combustion* types, a parabolic behavior has been observed in rate of number of total wood particles with respect to their *Combustion Duration*.

In order to perform a generalized analysis, we have measured the frame rate for each of the five different wood models for *Multiple Combustion* type. In this final experiment, in addition to real wood combustion reactions, fire and smoke propagation, char production, spark propagation and falling behavior of the burning wood model are also included. In Table 4.4, number of wood particles found in each of the five wood models and corresponding frame rates (FPS) are shown. As it is displayed in Figure 4.5, frame rate is inversely proportional to the number of wood particles. While the number of wood particles has been increased, the frame rate for each wood model is decreased.

Table 4.4: Frame Rate of Five Wood Models

	Number of Wood Particles	**Frame Per Second(FPS) (Hz)**
≈Our System / 2	46440	27
Our System	108360	24
Our System x 2	216720	22
Our System x 4	443440	19
Our System x 10	1083600	17

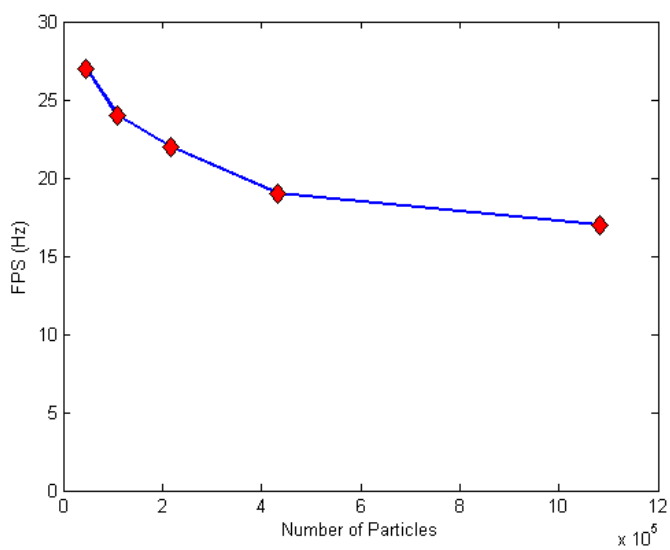

Figure 4.5: Frame Rate of Five Wood Model with respect to Combustion Duration for Multiple Combustion

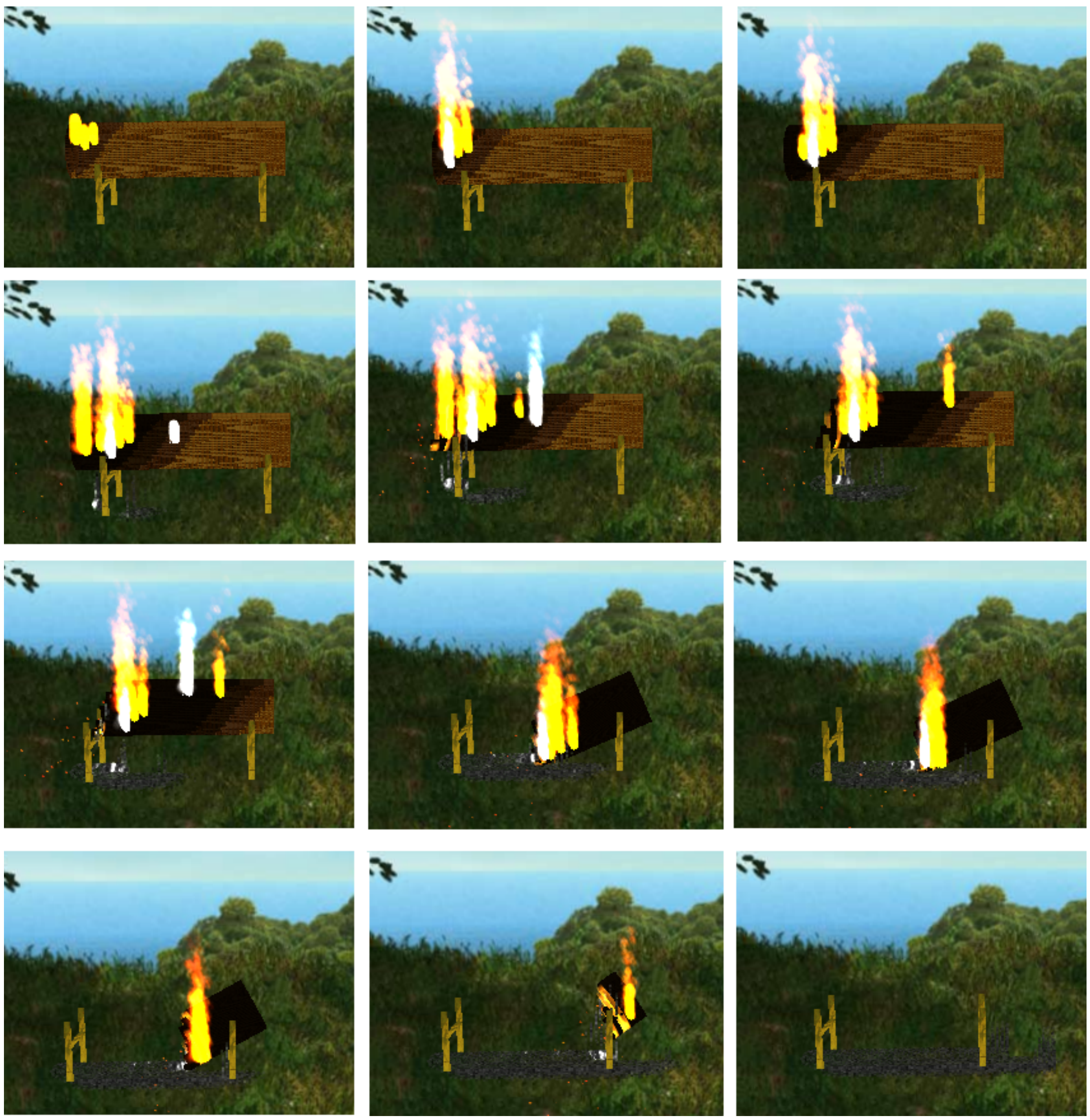

Figure 4.6: Our Proposed System

Chapter 5

Conclusion and Future Work

Modeling natural phenomena is one of the most challenging problems of computer graphics. The reason behind this challenge is the structural complexity, as the simulation of natural phenomena depends on some physical equations that are difficult to implement and model.

In our thesis, we have represented a physically based simulation of a particle based method for decomposition of burning wood and combustion process. We have implemented algorithms for drying, pyrolysis and charring subprocesses of combustion process. Thermal and physical reactions used in our algorithms are actual reactions defined in [24]. Therefore net reaction rates which have determined the amount of drying, pyrolyzing and charring are actual data values. This means that we have implemented our physical simulation depending on actual combustion reactions. Note that each wood particle has similar property values which means in our wood modeling approach, there is no any shell structure. Therefore, internal and external wood particles do not have different combustion thresholds.

Interpolation operations have been used for fire propagation and each fire particle position depends on the particle temperature value calculated during pyrolysis phase of combustion reactions.

Additionally, we have a simple algorithm for the falling behavior of wood under combustion process. Depending on decomposition of each wood particle, we have calculated momentum of wood object recursively and located the falling wood particles to their new coordinate positions successfully.

While implementing our proposed system, we have applied “Surface Modeling with Oriented Particle System” approach [39]. Although we have obtained satisfactory results for decomposition of the wood object, we have not attained similar results for deformation of the wood object. During heat transfer in drying and pyrolysis phases, depending on changes in temperature of each wood particle, its shape should also be shrinked. However, we have not observed such deformation process in our simulation. We have rendered each particle with tiny textures, so we could not achieve a realistic wood model as we have assumed.

We have an experimental work on our simulation in order to measure timing performance of our proposed system. At first, we have modelled five different wood models having different layer numbers. Then, we have measured each wood model's combustion duration. According to the results, we have observed that the increase in total number of wood particle has a linear relation with the increase in combustion duration. Additionally, we have measured the total system frame rate for five different wood models. In this experiment, we have observed that the increase in the number of wood particles is inversely proportional to the frame rate of each wood model.

Additionally, our simulation have some limitations. One of the conspicuous restriction is randomness of our physical based system. Due to the real combustion reactions specified in [24], the flow of particle property has been calculated according to the value of neighbor particle properties. The property values such as heat transfer, color darkening, decomposition of each particle have been applied to their neighbors in a sequential manner. Therefore, randomness could not be applied to combustion process in our approach. Also, height of wood model has been specified with respect to the number of ordered rings and width of wood model has been determined by the number of nested layers. The width and height sizes are statically determined in our system as stated in Section 3.1.1. Width and height of wood model has not been altered conveniently.

As future work, deformation of wood object will be improved. Additionally, rendering of wood object will be enhanced to make more realistic visualization. One another work that can be done in future is the addition of shell structure to the wood. Thus, the variation between the external layer and the internal layers can be analyzed. Lastly, real sound effects can be added to the simulation in order to make wood combustion more natural.

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