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Tesla's Fountain – Modeling and Simulation in Ceramics Technology

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Abstract **-**In this paper, we present Tesla's Fountain in ceramics technology reconstruction from basic 3D model, simulation of the engine, light and fluids till the real materialization. As the one of the most important model purposes, we enrich this solution by additional multicolor lights. All of this elements are designed based on Tesla's original patent no. 1,113,716, US patent office, granted Oct,13. In this model we applied ceramics technology based on ceramic materials casting and sintering. At the time when the patent was granted, the metal materials science and technologies were more advanced than the ceramics technology and applications. We performed all materials characteristics analyses and preparation steps based on the one author's patent no. 46121, Serbia patent office, granted 21.12.1991. This is one original two patents solution with complete new over-bridging by the state-of-the-art computer modeling and simulation technology.

Keywords - 3d modeling, computer simulation, ceramics, casting, sintering.

1. Introduction

The world famous inventor Nikola Tesla, besides his mainstream inventions in the field of electro techniques, also created Fountain in original design solution and materials[1]. The project "Computer Simulation and 3-D Modelling of the Original Patents of Nikola Tesla" in cooperation with "Nikola Tesla Museum" of Belgrade, which represents an institution of national importance, has started in 2009 [2].. Basically, the main purpose of the project is to digitalize, visualize and reconstruct (in real models) the original legacy of the Museum. The part of this paper is based on research within the project entitled "Computer Simulation and Modelling of the Original Patents of Nikola Tesla" and approved by the Ministry of Education, Science and Technological Development of the Republic of Serbia.The first Tesla's patent that was under our attention was Tesla's Fountain patented as *Tesla's Fountain*, no. 1,113,716, US patent office, granted Oct,13,1914 (Fig. 1).

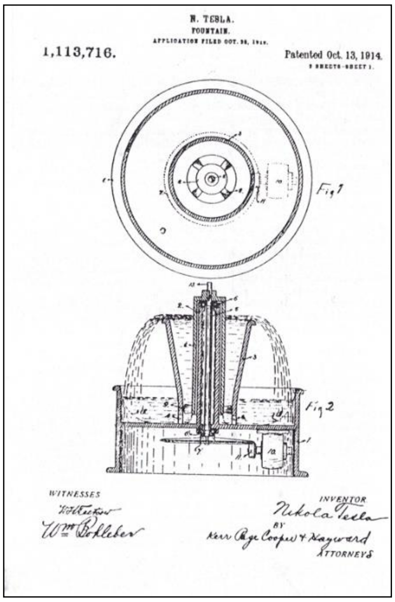

Fig. 1. Original Tesla’s Fountain patent.

We were working intensively to produce 300.000 particle 3D model of Tesla’s Fountain (Fig 3.) [1]. The application that were used are *3ds Max, Adobe Photoshop*, *RealFlow*, *V-Ray*, *Microsoft Visual Studio C++*. Then, we used different tools to generate digital model of Tesla's fountain in various configurations and environments. To comply this complex plan, there has been cooperation among the authors and professional experts from Museum. We used original construction schema from Museum (Fig 2.) to generate first 3D model of Tesla’s Fountain.

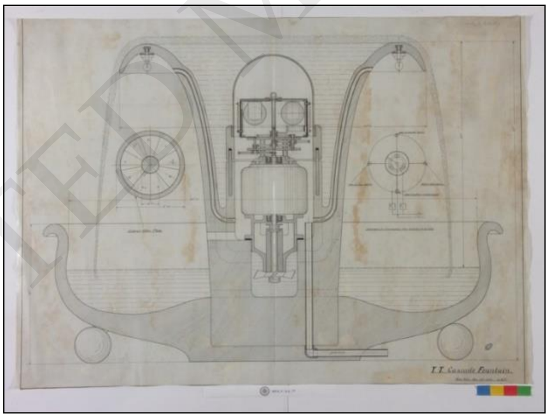

Fig. 2. Tesla-Tiffani original Fountain construction (Museum of Nikola Tesla Heritage).

The original construction predicts the solid materials for basic structure (metal). The main idea in patent is to use just one induction motor to generate water flow (from down to up) and to run the complex light control mechanism using the mechanical redactors (Fig. 2).

The Tesla Fountain in ceramics has many benefits for research of the inner structure as well as artistic and visual ones. After the initial structure modelling we concentrate on a problem of light control. In his original patent (Fig. 1) Tesla used multi color filters to generate interesting color effects in Fountain water flow. We implemented this original idea in our model (Fig. 3):

Fig. 3. Color filters at tho top of Tesla's fountain (detail).

To run this color filter system on the top on the Fountain, Tesla predicted complex mechanical system with differentials, similar to clock mechanism. This unit reduces the high rotational speed of main induction motor which also runs the water pump on the same axis (Fig. 1). Our model follows this part of the original construction also (Fig 4.).

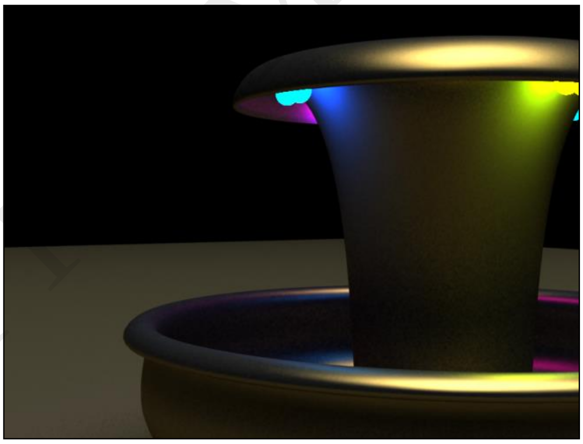

Fig. 4. The complete model of Tesla fountain in solid material.

As to the authors known the first Tesla's experiments have been done in materials like metal, bronze-metal and also in some phases. This is the first time, that the authors applied ceramic materials technologies in combination of casting and sintering. The basic knowledge and results in this technology are very well known but also here is presented quite new application.

When the Tesla as an inventor, used basic metal materials science for his patent, the ceramic materials properties had still been developing. If ceramics solution was implemented, It would be easier to consolidate the samples, and they would be much lighter, very firm and stable in construction, with possible controlled porosity, than in the case of the metal technology implementation. Regarding atmospheric corrosion, and other environmental conditions, ceramics have advantages in comparison with metal applications. Also, ceramics have much better thermal characteristics than metal considering the outdoor physical- chemical impacts on the fountain. Also the ceramics materials described in the patent feature one very important characteristic such as the surface layer, which allows the material to be resistant to environmental effects. It is very flexible for modeling, especially using contemporary software technologies. Eventually, the ceramics technology is much cheaper than the metal technology. The ceramic designing is more flexible and more likely to result in a more attractive final shape.

2. Theoretical basis of the fluid simulation

This section offers a definition of the types of computational fluid dynamics methods which define the fluid flows, as well as detailed theoretical foundation of the Smoothed-Particle Hydrodynamics (SPH) numerical method used for simulation of the Tesla fountain [3],[4].

2.1. Computational fluid dynamics methods

As previously mentioned, all existing methods have certain drawbacks regarding the physical correctness or computational complexity. In order to minimize the effects of these drawbacks, the primary goal is to achieve sufficiently good trade-off between these two aspects. All methods can be divided into mesh-based and particle-based methods. Taking the mathematical representation of fluid flows into consideration, this classification corresponds to Eulerian and Lagrangian view, respectively, although the Lagrangian view can be defined either as particle-based or mesh-based [5]-[7]. In the case of Eulerian view, the simulation domain is discretized by using a fixed mesh. This implies that fluid's properties, also known as field variables, such as pressure, velocity, acceleration, etc., which control the dynamics of fluids, can be calculated only at discrete points of the mesh. These properties are defined as functions of space and time, which means that values of the properties of each fluid that occupies a particular position at a particular time will be the same as the values of defined properties in the flow domain. In order to connect the Lagrangian and Eulerian models, the position of a particle at time *t* needs to be determined (Mei, 2001) [16]. If the position of a particle at time t is known, any physical property of a particle can be interpreted as a property at the spatial coordinates of that particle. Furthermore, the following can be stated:

$$\vec{q} = \vec{q}(\vec{x}, t) \tag{1}$$

which gives the velocity field at all fixed points. Also, Lagrangian pressure can be used to obtain the Eulerian pressure:

$$p(\vec{a}(\vec{x}, t), t) = p(\vec{x}, t) \tag{2}$$

Unlike the Eulerian view of fluid flows where fluids exist only at defined domain locations, in the Lagrangian view fluids exist at any domain location. This view describes the fluid as a discrete number of particles which are able to move freely through the domain depending on the acting forces. In fact, this means that flow domain is not discrete but continuous and this property allows the simulation of more complex fluid flows.

Initial position of the particle in Lagrangian view at time t_0 can be represented as:

$$\vec{x}_0 = (x_0, y_0, z_0) \tag{3}$$

The position of the particle at the later time t can be defined in the following way:

$$\vec{x} = \vec{x}(\vec{x}_0, t) \tag{4}$$

For initial time t_0 Eq. (4) becomes:

$$\vec{x}_0 = \vec{x}(\vec{x}_0, t_0) \tag{5}$$

If any three quantities a, b, and c are used instead of the initial position $\vec{x}_0$ in order to identify the particle, can be written that

$$\vec{x}_0 = \vec{x}_0(\vec{a}) \tag{6}$$

The path of a particle identified by $\vec{a}$ is given by:

$$\vec{x} = \vec{x}(\vec{a}, t) \tag{7}$$

It should be noted that $\vec{a}, t$ are the independent variables, while $\vec{x} = (x, y, z)$ are dependent variables.

After this, the particle velocity can be calculated using the particle position as:

$$\vec{q} = \frac{\partial \vec{x}}{\partial t}\bigg|_{\vec{a}} \tag{8}$$

Similarly, the particle acceleration can be calculated as follows:

$$\frac{\partial \vec{q}}{\partial t}\bigg|_{\vec{a}} = \frac{\partial^2 \vec{x}}{\partial t^2}\bigg|_{\vec{a}} \tag{9}$$

Other quantities such as density and pressure can be expressed in terms of $\vec{a}$ and t as follows:

$$\rho = \rho(\vec{a}, t), \quad p = p(\vec{a}, t) \tag{10}$$

In the case of Eulerian view, the physical correctness is better, but flows are unrealistic and constrained at discrete locations. It is possible to try to solve the problem of unrealistic flows by making meshes be larger, but it would make the memory usage much higher, as well as raise the computational cost and make a real-time application be impossible. On the other side, the performance of the particle-based fluid flows is dependent on the number of particles and optimization algorithms. In overall, Lagrangian view of fluid flows has better performances for practical applications, including the real-time applications.

2.2. Smoothed-particle hydrodynamics (SPH)

Smoothed-particle hydrodynamics (SPH) is a particle-based Lagrangian numerical method used for simulating the dynamics of continuum media, among others, for simulating the flow of fluids. The method was developed by Gingold and Monaghan (1977) [8] and Lucy (1977) initially for compressible flow problems (Monaghan, 1992) [13] , and since then has been used in astrophysics, ballistics, volcanology, and oceanography [9], [10] . The method's name comes from the term fluid dynamics, also known as hydrodynamics. The SPH method works by dividing the fluid into a set of discrete elements known as particles. These smoothed particles are represented as point masses in the simulation domain *Ω* and carry information about fluid's properties which describe a fluid motion. Particles have a spatial distance known as smoothing length, over which their properties are smoothed by a kernel function. This means that the physical quantity of any particle can be obtained by summing the relevant properties of all the particles which lie within the range of the kernel. For example, using Monaghan's popular cubic spline kernel the temperature at position *r* depends on the temperatures of all the particles within a radial distance *2h* of *r*. The integral interpolant of any continuous field quantity *A* can be defined as follows:

$$A_I(r) = \int_{\Omega} A(r')W(r-r',h)dr' \tag{11}$$

Integration is applied over the whole domain *Ω*, where *r* is a position vector in the domain *Ω*, while *W* is a smoothing or interpolating kernel function having *h* as smoothing length. Interpolating kernel function has a role to smooth particle's contribution to an arbitrary SPH quantity field. Kernel function's characteristics define the performance of the final results, but among optional characteristics, this kernel function must satisfy the following properties:

$$\int_{\Omega} W(r-r',h)dr' = 1 \tag{12}$$

$$\lim_{h\to 0} W(r-r',h) = \delta(r-r') \tag{13}$$

where *δ* is a Dirac delta function. Other properties of a kernel function are the following:

$$W(r,h) \geq 0 \tag{14}$$

$$W(r,h) = W(-r,h) \tag{15}$$

Previous equations show that a suitable kernel function has to be normalized (Eq. (12)), non-negative (Eq. (14)), and axial symmetric (Eq. (15)). In order to control the physical correctness and computational complexity, a smoothing length *h* should be chosen in a suitable way. The smoothing length represents the largest distance from a given particle at which all particles interacting with that particle should be located. In other words, all particles that interact with a given particle are enclosed in a circle defined by a radius which equals *h*. This implies that value *W(r, h)* equals zero if distance between a given particle and any other particle is larger than smoothing length *h*, i.e. if $r > h$. Actually, the smoothing length *h* defines the number of particles which interact with a given particle, and its value should ensure a suitable number of interacting particles, as well as to prevent a possible high computational cost by keeping the number of interacting particles below the allowed limit.

The integral interpolant from Eq. (11) can be approximated with summation interpolant as follows:

$$A_S(r) = \sum_j V_j A_j W(r - r_j, h) \tag{16}$$

where V_j is a theoretical volume of a neighboring particle j of a given particle. Since $V_j = m_j / \rho_j$, Eq. (16) can be rewritten as:

$$A_S(r) = \sum_j \frac{m_j}{\rho_j} A_j W(r - r_j, h) \tag{17}$$

where m_j and ρ_j are mass and mass density of particle j, respectively. For example, the density of particle i can be defined in the following way:

$$\rho_i = \rho(r_i) = \sum_j m_j \frac{\rho_j}{\rho_j} W(r_i - r_j, h) = \sum_j m_j W(r_i - r_j, h) \tag{18}$$

where the summation over j includes all particles in the simulation. Taking into account that $m_j A_j / \rho_j$ is not dependent on r, the gradient and the Laplacian will be dependent only on kernel function W. The gradient of Eq. (17) can be represented as follows:

$$\nabla A_S(r) = \sum_j m_j \frac{A_j}{\rho_j} \nabla W(r - r_j, h) \tag{19}$$

There is another version of the gradient (Kelager, 2006) which proved to give more accurate results and is defined as:

$$\nabla A(r) = \rho \sum_j \left(\frac{A_j}{\rho_j^{\,2}} + \frac{A}{\rho^2} \right) m_j \nabla W(r - r_j, h) \tag{20}$$

Finally, the Laplacian of Eq. (17) is defined as:

$$\nabla^2 A_S(r) = \sum_j m_j \frac{A_j}{\rho_j} \nabla^2 W(r - r_j, h) \tag{21}$$

Although the value of the smoothing length can be fixed in both space and time, this does not take advantage of the full power of SPH. By assigning each particle its own smoothing length and allowing it to vary with time, the resolution of a simulation can be made to automatically adapt itself depending on local conditions. For example, in a very dense region where many particles are close to each other, the smoothing length can be made relatively small, yielding high spatial resolution. Conversely, in low-density regions where individual particles are far apart and the resolution is low, the smoothing length can be increased, optimizing the computation for the regions of interest. Combined with an equation of state and an integrator, SPH can simulate hydrodynamic flows efficiently [14]-[16].. However, the traditional artificial viscosity formulation used in SPH tends to smear out shocks and contact discontinuities to a much greater extent than state-of-the-art mesh-based schemes [11],[12]. .

3. Usage of SPH in the simulation

The Fountain fluid flow simulation has many steps, and most of them are performed continuously (throughout the whole duration of the simulation). The steps can be presented adequately using a flow chart to describe the algorithm. The flow chart for an SPH simulation that has been used for Fountain looks like in Fig. 5:

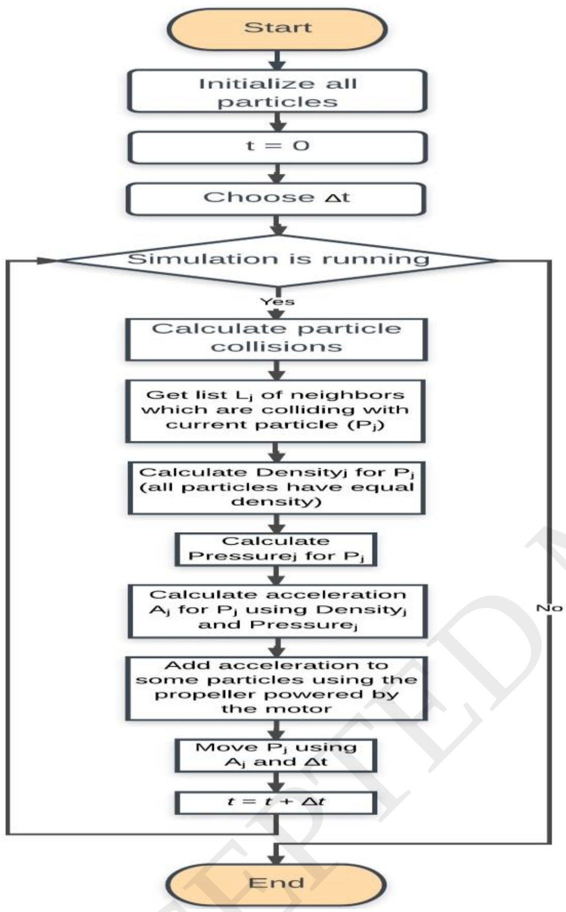

Fig. 5: Flow chart of the Fountain simulation

The key structure used in our simulation is Quaternion. It is a structure that holds the information about objects, in this case the particle's rotation. Quaternions are also used to represent rotations. They are compact, do not suffer from gimbal lock and can easily be interpolated. *Unity* environment internally uses Quaternions to represent all rotations. They are based on complex numbers. The individual Quaternion components (x, y, z, w) are almost never accessed or modified directly; most often the existing rotations are used (e.g. from the Transform) and from them the new rotations are constructed.

Another important structure *Unity3D* employed is *RigidBody*. This structure contains data about velocity and acceleration, and has methods to calculate the forces that affect one object (including gravity). A new vector is created and its force is added by using the previously described method.

3.1. Force distribution in simulation

The forces that are active in the simulation are pushing the particles in several directions. First of all, the propeller is actively pushing the particles of water towards the upper part of the fountain. It's adding force to the particles located in the lower middle part of the fountain so they are moving in an upward direction. Particles that are colliding with the other ones are also adding velocity to them.

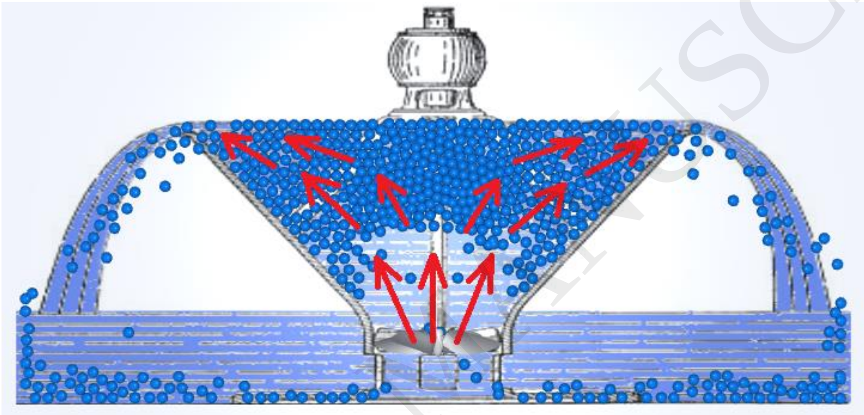

Fig. 6: Force of the propeller

There is also the effect of gravity on the water particles (Fig. 6). The water is affected by it all the time, but the effect can be clearly noticed in two places: near the side walls of the fountain, and on the edges of the fountain. That's where other forces are the weakest, so the force of gravity can be clearly seen.

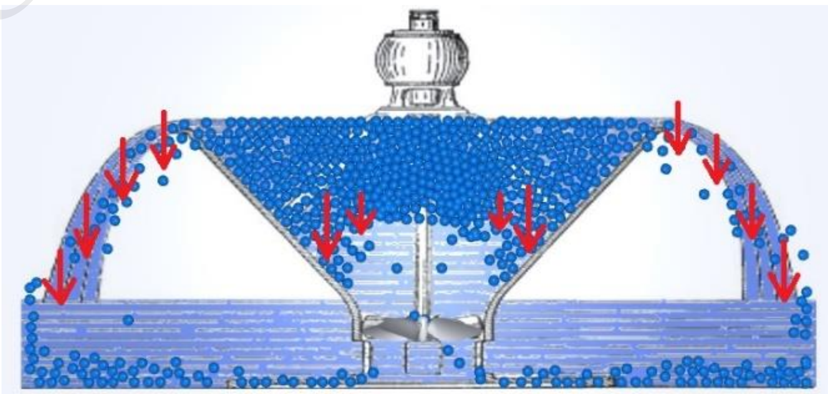

Fig. 7: Force of gravity near the side walls and on the edges

At the bottom of the fountain, there is a natural flow of water, so that when the particles drop from the edge of the fountain, they are moving towards the propeller again, so that the process can keep going indefinitely (Fig. 7).

There are 2 active forces in the simulation. The first one is the force of the propeller, which is actively pushing the particles of water up and away from the center of the fountain during the simulation. The second one is the force of gravity, which is actively pushing the particles of water down, in every point of the fountain. These forces form vectors of the water movement.

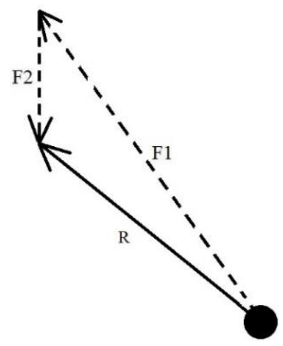

Fig. 8: Forces affecting particles near the motor

Forces that are affecting the particles on figure 8 are the following: F_1 represents the force of the propeller. It is a strong force that gives the most velocity to the particles. F_2 represents the force of gravity. Gravity slows the particles down, and pushes them to the bottom of the fountain. R represents the resulting force, and it's calculated by adding the two vectors that affect the particle.

Vector addition is the operation of adding two or more vectors together into a vector sum. The so-called parallelogram law gives the rule for vector addition of two or more vectors. For two vectors A and B, the vector sum A+B is obtained by placing them head to tail and drawing the vector from the free tail to the free head. In Cartesian coordinates, vector addition can be performed simply by adding the corresponding components of the vectors, so if $A=(a_1,a_2,...,a_n)$ and $B=(b_1,b_2,...,b_n)$,

$$A+B=(a_1+b_1,a_2+b_2,...,a_n+b_n).$$

This rule can be simplified by placing the second vector on the ending point of the first one, and drawing a parallelogram diagonal (connecting the starting point of the first vector and the end point of the second vector). When two particles collide, the first one adds force to the second one, thus pushing it out faster.

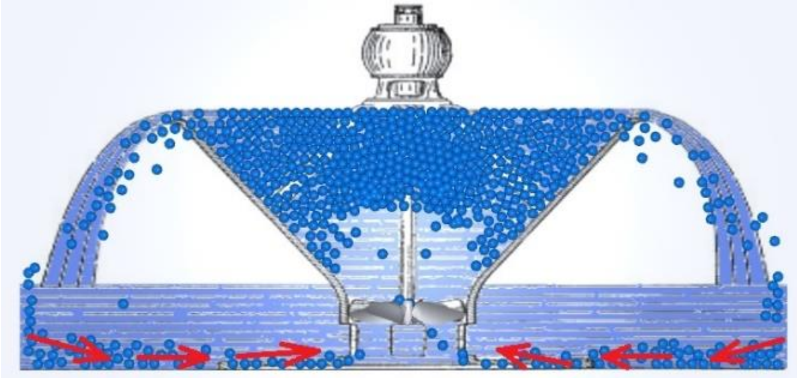

Fig. 9: Flow of water at the bottom of the fountain

Forces that are affecting the particles on figure 9 are the following: R_1 and R_2 are the forces of the particles created by the propeller. Force R represents the resulting force, gained by their addition. On the edge of the fountain, the force of the propeller gets much weaker than at the center of the fountain. This is where the force of gravity takes over the particles, and they start falling from the edge of the fountain to the pool on the bottom.

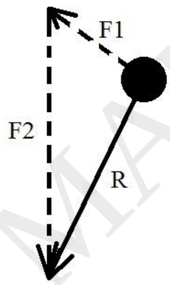

Fig. 10: Forces on the edge of the fountain

Forces that are affecting the particles on figure 10 are the following: F_1 represents the weaker force of the propeller affecting the particle, F_2 represents the force of gravity, and R represents the resulting force (the behavior of the particle on the edge of the fountain). On the bottom of the fountain the water particles are flowing towards the propeller, where they will be accelerated again, to continue circulating in the fountain.

4. Model realization pipeline

Realization of Tesla Fountain is complex. We used different hardware and software [2], [17].

Software: 4.14.3+ Unreal engine, Nvidia codeworks for Android, Oculus Rift Tools, Maya 2017 LT.

Hardware: WINDOWS 10 64 OS, PC Athlon FX 4200, 8GB RAM, 2GB VRAM 6870, VR GEAR SAMSUNG, SAMSUNG GALAXY E7, Intel i7 16GB RAM, GeForce GTX 1050.

The modeling was done in Maya software based on original photos of fountains Nikola Tesla who are from the Nikola Tesla Museum. The same software is made and optimization models for SamsungGearVR. This is a crucial step because of the limitations of the phone. After this model was transferred to a format suitable for .fbx * 3D Engine and imported into Unreal Engine 4. On the basis of this created a scene suitable for implementation in a VR environment.

The model consists of several elements:

1. Fontana of Nikola Tesla with all the details (the engine and the environment)

2. Landscape

The next step is to develop wire model of the Fountain. Our first model is described in Fig. 11.

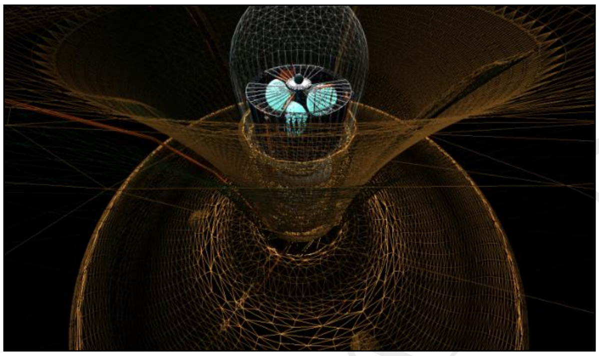

Fig. 11. Complex model, about 300.000 points in Fountain definition.

Next step is to create inner structure of the fountain including motor case. Landscape is then added to model (Fig. 12).

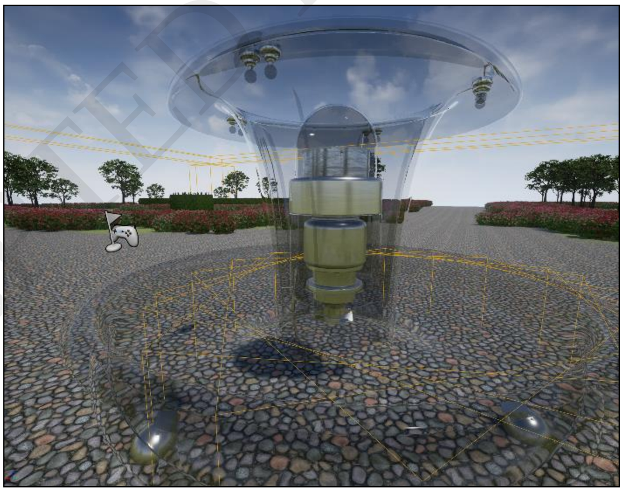

Fig. 12. Inner structure of Fountain definition.

Based on that model, we developed standard solid model of the Tesla's Fountain. Then, all details of the model are extended (Fig. 13).

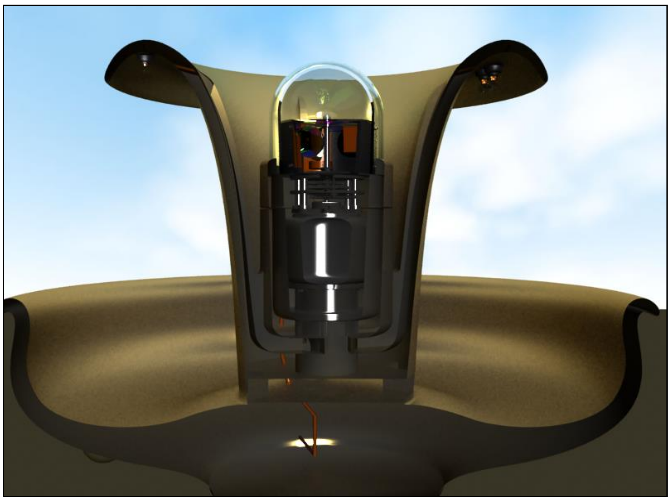

Fig.13. Tesla's fountain structure. There are many electric and mechanical components inside the Fountain.

The next step is to develop and to render standard bronze model of the Fountain (Fig. 14):

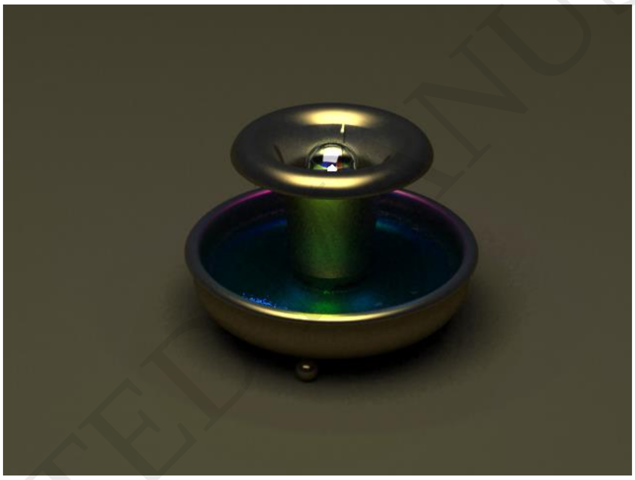

Fig. 14. Tesla's fountain, water is in reservoir.

And next step is to render water (Fig.15).

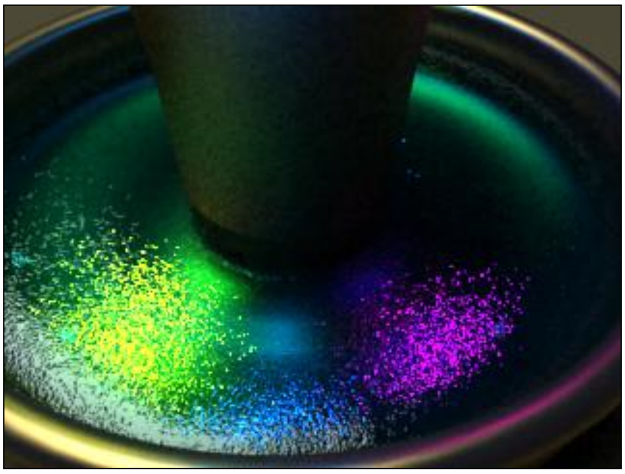

Fig. 15. Water rendering, detailed.

Finally, we added light mechanism (Fig. 16).

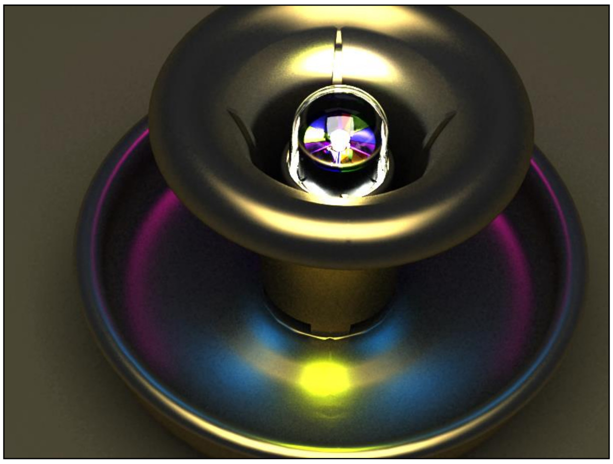

Fig.16. Fountain in bronze with lights on.

Finally, we transferred materials from metal to ceramic (Fig.17).

Fig. 17. Tesla fountain in ceramic.

Finally, we complete all details and realized fountain in full scale ceramic. It is integrated with color filter (Fig 18.)

Fig. 18. Tesla's Fountain complete realization.

5. Production in ceramics

After the animation of the model, the main inventor idea is presented visually – one induction motor works like a water pump and at the same time it is connected via mechanical differentials to run the color filter which speed is proportional to the water flow in that way. The next steps are to develop new ceramic material as the basic structure for Tesla's Fountain [18]-[20].

The invention belongs to the field of ceramics technology, and it is classified by International Classification of the patents in Class C 04B 35/20.

The invention **primarily** refers to the process of making laboratory glassware based on self-glazed cordierite by casting, pouring into plaster molds. Unlike the procedure of making it based on porcelain, previous firing and glazing of the thin walls products is eliminated. Depending on the melter composition, molded products are fired on temperatures between 1 550 and 1650K and during that process continual glazed layer appears.

Realization is focused at one question: how to approach technological process which will allow obtaining glazed material for Fountain with thin walls only by firing, and improve hardness during its usage?

Tesla's Fountain glassware with thin walls (thickness 1-3mm) is made based on hard porcelain by casting in plaster forms. As glazing of raw products with such thin walls is not practically possible, they have to be fired first ("biscuit baking"), usually at 1200- 1300K; after that they are glazed inside as well outside and fired at higher temperature – usually 1550 to 1650K.

Production of the Tesla's Fountain glassware based on the self-glazed cordierite would have following advantages:

- Investment and production costs would decrease up to 50%
- Better resistance to thermal shocks because of the lower coefficient of the thermal dilatation would be achieved
- Better composition of the glaze and tiles could be expected, since the glaze pushes itself out of the mass during the firing process.

If we start with the need to achieve the production of the Tesla's Fountain glassware in only one firing, we have elaborated the process for obtaining cordierite materials which can give satisfactory self-glazing and small deformation on the firing temperature.

The composition of these materials is within following limits:

• Talc. Raw or fired	25-35 mas.%
• Clay. Matter	25-35 mas.%
• Alpha-small clay	10-25 mas.%
• Feldspar	10-25 mas%
• Pyrophyllite	0-20 mas.%

In order to achieve better esthetic image of the product, natural raw materials used in this kind of production should contain as little as possible iron, free or in the coupling condition. Clayish matters in those compositions allow obtaining suspension available for casting in plaster molds by introducing electrolytes, as water glass and sodium carbonate are, in quantities up to 0.2 mas% and water. Besides that, they increase hardness of the drip moldings in raw state.

Talc with the rest of the mass components forms mineral cordierite, during the firing process on temperatures above 1530K, and cordierite is characterized by a small coefficient of the thermal dilatation.

Depending on the melter composition (feldspar and pyrophyllite), firing temperature is within the limit of 1650K.Chemical composition of the mass and the elevation of the temperature affect forming of the continual glazed layer. As self-glazing can appear from any side, it is necessary to hone the surface which was in touch with the firing pad. Beside Tesla’s Fountain materials, other products for different fields and usage can be made this way: nor guides or kitchen dishes, as many others, too.

5.1 Performing Procedure Example

Already measured quantity of the material – 28 mas.% of talc, 22 mas% of alpha –small clay, 26 mas.% of kaolin, 14 mas.% of feldspar, and 10 mas% of pyrophyllite with addition of 0.2 mas% of water glass and 35 mas% of water is grinded in the bead mill for 16 hours. The suspension obtained that way is used for casting the other products. Wall thickness of the casting is determined by the retention time in the plaster mold. After taking the product out of the mold, castings are drying, cleaning and firing on 1550K. After firing, by honing, eventually **glued** pad is removed.

Tesla’s Fountain glassware obtained this way is characterized by good weight stability and does not glue during the accidental touch in the furnace.

Fig.19. Tesla's 3D Fountain model with water simulation.

After the modelling and simulation, the next step is to materialise model into the real construction (Fig 19). In today's state of technology, it is easy to manufacture basic structure in classic way or to use 3D printers for that purpose. The main problem is to produce mechanical part and moving part of the Tesla's fountain. That is the point that we decide to innovate the original construction and to substitute the whole mechanical part with the static color lamps supplied controlled by the microprocessor devices.

6. CONCLUSION

In this paper theoretical and practical realization of the Tesla's Fountain model is proposed. Tesla Fountain model is realized through the project with Museum of Nikola Tesla. The main intention of this paper is to develop ceramic model of Tesla's Fountain beginning from Tesla's original patent pending schemes through the all necessary steps of modeling. Introduction represents starting point in a view of Tesla original patent. Section 1 provides a mathematical foundation and theoretical basis of the fluid simulation including computation fluid dynamics methods. Also, smoothed-particle hydrodynamics (SPH) method is presented in detail. Section 3 shows details about the usage of SPH in the simulation including basic algorithm and details fluid moving parts simulation physics and environment. Section 4 provides Model realization pipeline with details about hardware and software requirements. All necessary steps in modeling are represented. Section 5 shows the possibilities and technology for realization of the Tesla fountain in ceramics, using state-of-the-art innovative production process. Authors' intention is to develop further applications and modifications starting from the basic concept described in this paper, with possible industrial application (producing of the Tesla's Fountain).

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