Applied Finite Element Method Simulation in 3D Printing

M. Iliescu, E. Nuțu, B. Comănescu

Abstract**—** 3D printing, as part of Rapid Prototyping Technology, is a modern and efficient way of reducing product's design and manufacture cycle. Its benefits in designing and manufacturing elements of a laser medical device are presented by this paper. Simulation involving computational fluid dynamics (CFD) and heat transfer phenomena, carried out with finite element method, has been applied in order to improve one of device's elements shape, so as to get optimum laser device's functional characteristics.

Keywords**—** finite element method, model, simulation, 3D printing.

I. INTRODUCTION

THERE are new challenges in designing and manufacturing products with various special characteristics, complicated configuration, short production time, better understanding and communicating of their design [8].

So, in the late 80's, there has been developed, *additive fabrication*, that refers to a group of technologies used for building physical models, prototypes, tooling components, and even finished series production parts—all from 3D computer-aided design (CAD) data, medical scans, or data from 3D scanning systems. [7]. An important advantage for additive fabrication is its ability to create almost any shape or geometric feature.

One basic application of additive fabrication is rapid manufacturing (RM), that means manufacturing solid objects by the sequential delivery of energy and/or material to specified points in space to produce that part. Current practice is to control the manufacturing process by computer using a mathematical model created with the aid of a computer [6]. It refers to obtaining finished production parts by "just-in-time" manufacturing.

The two main aspects of rapid manufacturing can be considered as *rapid tooling* (RT) – the technologies enabling to produce tools quickly and *rapid prototyping* (RP).

Rapid prototyping is the automatic construction of physical objects using solid freeform fabrication. It takes virtual designs from computer aided design (CAD) or animation modeling software, transforms them into thin, virtual, horizontal cross-sections and then creates each cross-section in physical space, one after the next until the model is finished. So, the virtual model and the physical model correspond almost identically [6].

By Rapid Prototyping, objects can be formed with any geometric complexity or intricacy without the need for elaborate machine setup or final assembly. They can be made from multiple materials as composites, or materials can even be varied in a controlled fashion at any location in the object. So, the construction of complex parts can be reduced to a manageable, straightforward, and relatively fast process [9].

There are many rapid prototyping technologies, differing by the way layers are built to create the part, and by the base material. It can be mentioned*: Selective Laser Sintering* (SLS) – for thermoplastics and metal powders; *Stereolithography* (SLA) – for photopolymers; *Electron Beam Melting* (EBM) – for titanium alloys; *3D Printing* (3DP) – for various composites powder.

Ink jet printing comes from the printer and plotter industry where the technique involves shooting tiny droplets of ink on paper to produce graphic images. RP ink jet techniques utilize ink jet technology to shoot droplets of liquid-to-solid compound and form a layer of an RP mod Three-Dimensional Printing is based on the inkjet printing process, where binder is printed on a powder layer to selectively bind powder together for each layer [5]. So, relatively quick and not too expensive models can be obtained – in the early design process of a product or, for testing products characteristics, by prototyping.

A schematic representation of ink jet 3D printing process is represented in figure 1 [10].

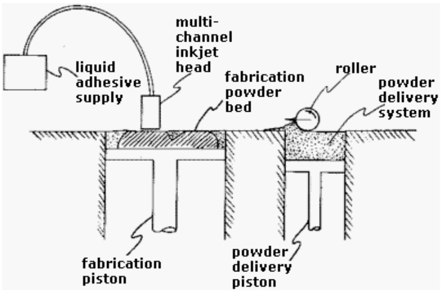

Fig. 1 [10] Schematic representation of 3D printing process.

Manuscript received January 8, 2009: Revised version received ***..

Mihaiela Iliescu is PhD. Eng., Associated Professor in Manufacturing Department of "POLITEHNICA" University in Bucharest, ROMANIA (corresponding author to provide phone: 004-0722-619805; e-mail: iomi@clicknet.ro).

Emil Nuțu in MSc. Eng., Assistant in Strength of Materials Department of "POLITEHNICA" University in Bucharest, ROMANIA (e-mail: numil2003@yahoo.com).

Brînduş Comănescu is a physician, MSc., working in Optoelctronica S.A. Institute, related to Atomics Physics Institute, Măgurele, ROMANIA (e-mail: brindus@optoel.ro).

This paper presents the application of 3D printing rapid prototyping technology in a laser device components fabrication. This device is used in urology - for splitting kidney stones and in surgery - for fixing damaged bones.

As it is *an innovative laser device*, Rapid Prototyping is very efficient, mainly, because of the fact that the real components' materials are very expensive ones and the least designing and/or manufacturing mistake costs a lot – effort, material, time, all of the meaning time and money.

For the same reason, as stated above, finite element method simulation has been applied in studying one of the most important device's characteristics – exit cooling fluid's temperature [12], [13]. Optimum laser device's characteristics are obtained only if the mentioned temperature does not exceed a certain value, suppose it should be about 37°C (Celsius degrees).

II. EXPERIMENTAL RESEARCH

There have been obtained real prototypes, by 3D printing, for all laser device's components. For two of them, called *side cap* and *connecting piece*, detailed rapid prototyping process aspects are going to be presented.

A. Experimental System

The studied laser device is schematically presented in figure 2. The components to be prototyped are the ones indicated by arrows while and their drawings are shown in figure 3 (a. – for side cap, b. – for connecting piece).

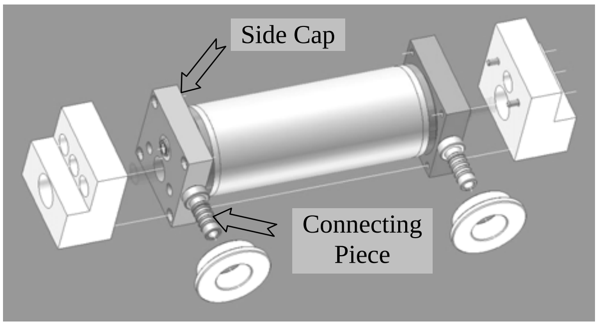

Fig. 2. Scheme of the laser device.

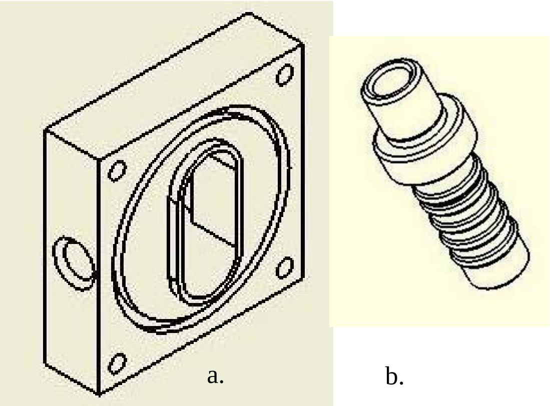
a. b.

Fig. 3. Drawings of the “Side Cap” and “Connecting Piece”.

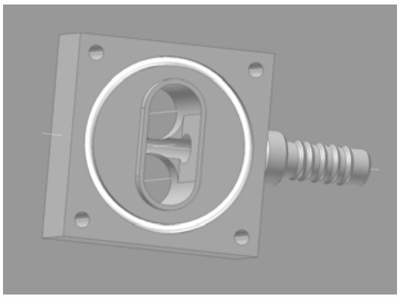

Fig. 4 Assembly of “Side Cap” and “Connecting

Detailed assembly of the two special studied parts is evidenced in figure 4.

The laser involved is solid state holmium one, with a THC:YAG rod emitting at 2100 nanometer, of 20 watts power and 250÷350 microseconds pulse duration.

The *technological system* used was made of:

-printing machine ZPrinter 310 Plus (Z Corporation);

- materials used for rapid prototyping: zp®131 *powder* (high performance composites for tough parts and very good resolution); zb60 *binder solution* and z-max *high strength epoxy* [3].

- compressed air cleaning enclosure;

- electric oven.

B. Experiments

There were necessary some “steps” to be carried on while experimenting, meaning:

→ Computer aided designing of the part to be prototyped.

→ “Recognizing” the design by printing machine software, ZPrint; so, an automatic calculus of the required volume / mass amount of powder is performed;

→ Setting machining parameters, such as 0.01 mm layer thickness so, the time for prototype printing is indicated - for the studied prototypes, was about 21 minutes.

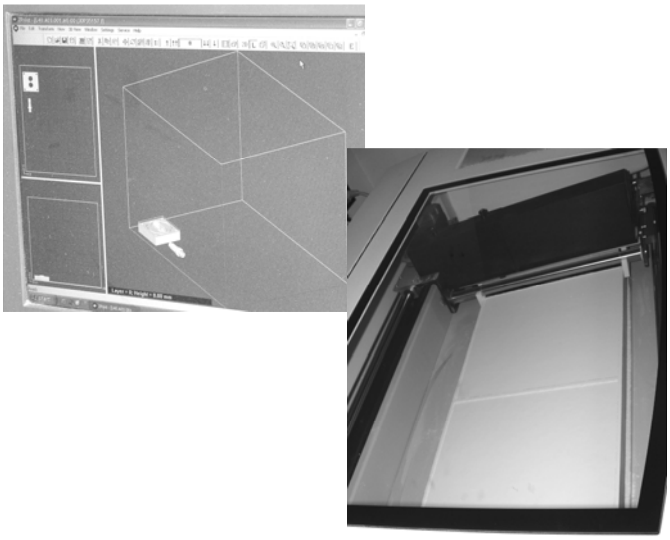

Fig. 5 Initial 3D printing process phase

An image of the computer screen, and of the ZPrinter machine, in the early stages of ink jet printing process is presented in figure 5.

→ 3D printing process – meaning, successively layer by layer obtaining the prototype

Images taken while the process is on are shown in figure 6 – when referring to computer screen image and in figure 7 – when referring to real, prototyping process.

→ Once the process over and the powder prototype hardened a little, the prototype is carefully extracted - see figure 8.

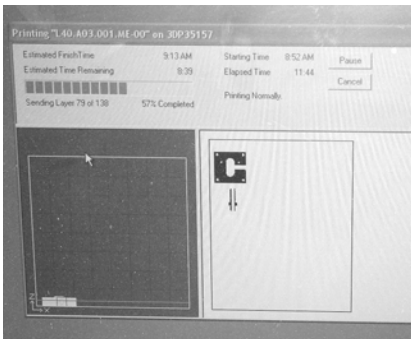
Printing "L40.A03.001.ME-00" on 3DP35157
Estimated FinishTime 9:13 AM
Estimated Time Remaining 8:39
Sending Layer 79 of 138 57% Completed
Starting Time 8:52 AM
Elapsed Time 11:44
Printing Normally.

Fig. 6 Ink jet printing process - computer screen image

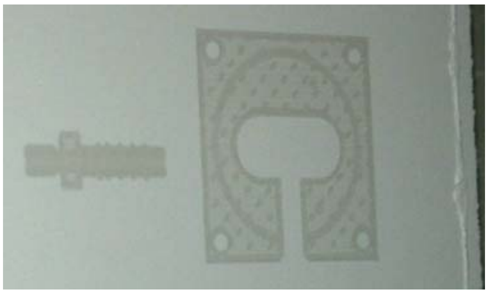

Fig. 7 Ink jet printing process – Zprinter machine image

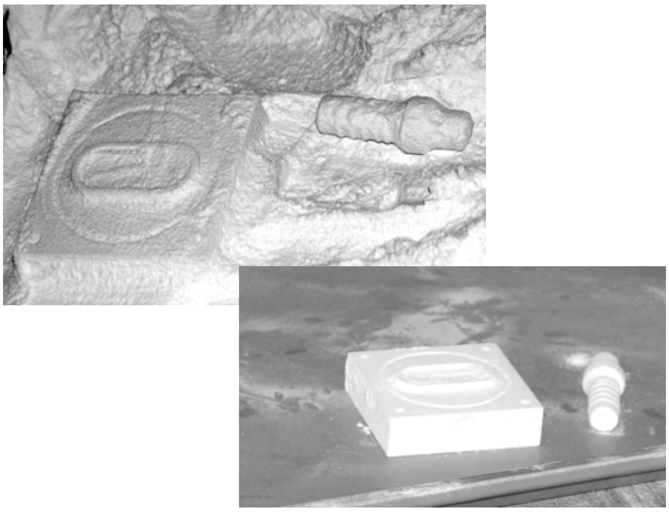

Fig. 8 Extracted prototypes

→ Cleaning out of the remaining powder, into the special vacuuming enclosure and “adjusting” it – as presented in figure 9.

→ Drying into an electric oven and, then, impregnating by a mixture of special binder and high strength epoxy are further steps required to obtain a hard, and ready to use prototype part – see figure 10 and figure 11

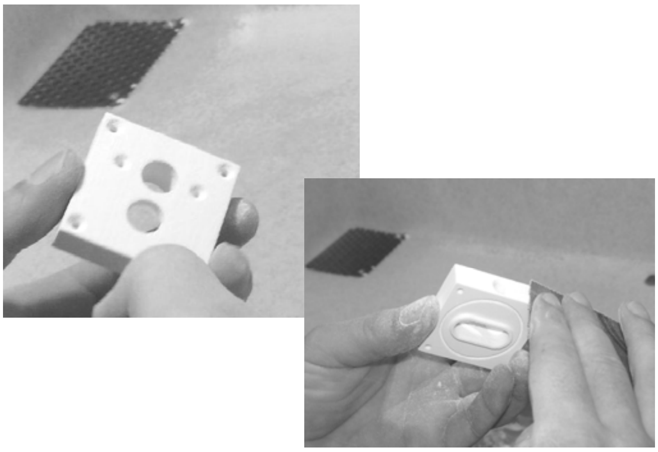

Fig. 9 Compressed air cleaning and adjusting of the prototype

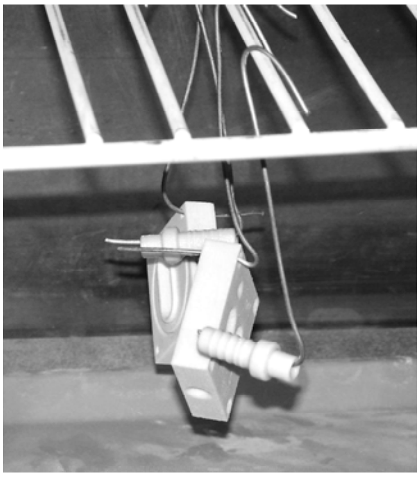

Fig. 10 Electric oven drying of prototypes

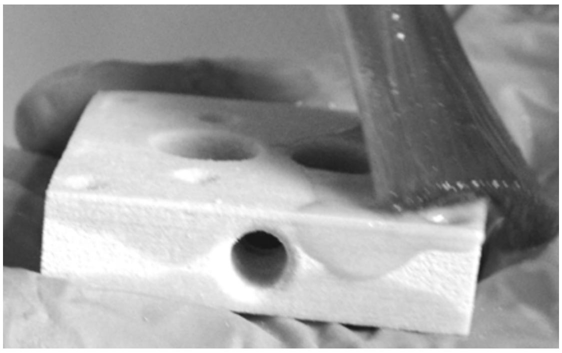

Fig. 11 Resin impregnating the prototype

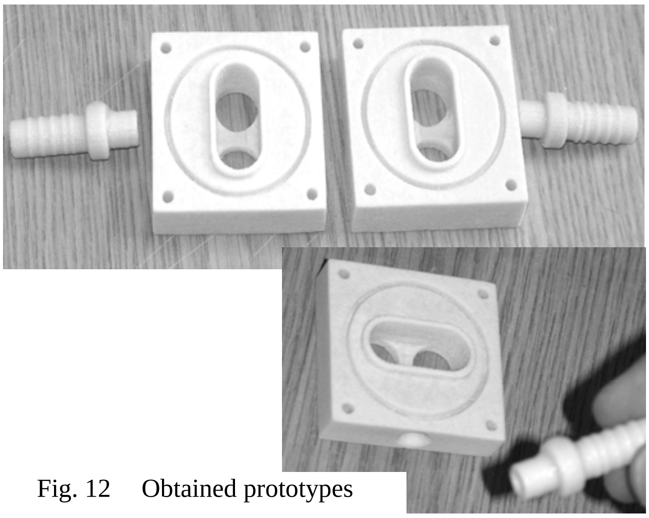

Fig. 12 Obtained prototypes

Obtained prototypes are presented in figure 12.

It should be mentioned that the parts (side cap and connecting piece) must join together by a threaded assembly type but, the thread could not be obtained by rapid prototyping (it was almost impossible to extract the models out of the powder without damaging the threaded part). Thus, threading operations were carried out after impregnating and drying, on a drilling machine

C. Experiments Results

Similarly, there were obtained all other components of the lased device [2]. When trying to fix them together, problems, dealing with parts geometry and dimensions, have been noticed.

One of them was about the cooling fluid, due to the fact that through each of side cap's main central holes there is special glass tube that isolates the laser flash and, respectively, active medium (Holmium) from the other components. The connecting pieces represent the entrance / exit of the cooling fluid, which is unionized water, for maintaining appropriate temperature of laser "body".

The major problem, while joining the prototyped parts, was that the cooling fluid could not correctly "get" into both of the glass tubes, as they were too long and their end restricted the fluid access. Another problem was that the shape of the parts "flushed" by the cooling water did not fit tight so, there was fluid spread away. That's why it was pointed out the need of using special insulating elements, such as O-rings

III. TEMPERATURE FIELD SIMULATION

Because of cooling fluid's temperature influence on appropriate laser device functioning, a simulation of temperature field has been done. It, involved computational fluid dynamics (CFD) and heat transfer phenomena within a finite element method [11]. The bases consisted in the need of upper limit for cooling fluid's temperature, meaning, at the exit (outlet) it should not exceed a specified value – depending on laser type active medium.

This simulation was done, considering the fact that it should be better to discover errors and miss-functioning of laser device, just before manufacturing its components from the special and very expensive required materials.

In fact, it has been conceived as an extension of rapid prototyping goal – economically obtaining prototypes for fit and function tests.

So, as *simulation problem*, there have been considered the following aspects:

- the laser device could appropriately work if its cooling fluid exit temperature does not exceed 35^{o}C;
– the cooling fluid was un-ionized water, and its temperature, when entering the laser device is about 20^{o}C;
- the two inside glass tubes – one flash and, the other, active medium, of the laser device are heated, each, up to 75 ^{o}C and, respectively, 80 ^{o}C (degree Celsius);
- the flow rate of the cooling fluid was considered within the range of 7 to 15 liters per minute;
- the length of cylindrical part (shield) inside which cooling fluid flows, is about 70 mm, while its inside diameter is about 37 mm. (millimeters).

D. Model Description

For modeling cooling fluid temperature field distribution, there has been used the finite element method (FEM) within a conjugate simulation approach - a 3D model involving computational fluid dynamics (CFD) and heat transfer phenomena was built. It was assumed that steady-state would be relevant.

The model was built and analyzed with ANSYS CFX software. Its geometry was defined by the liquid shape - generated within the inside volume of laser device's shield – as shown in figure 13.

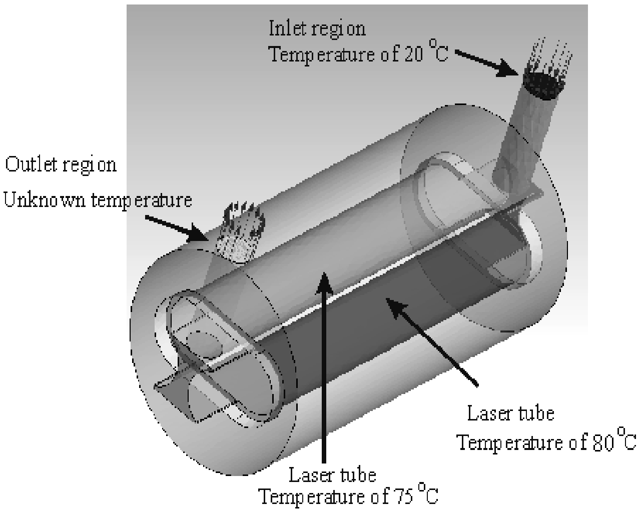

Fig. 13 Model geometry and boundary conditions

So, the above mentioned figure presents the 3D construction of model's geometry (shape) and the boundary conditions - meaning: the *inlet* and *outlet regions*, as well as the *laser tubes – liquid interfaces*. It can be noticed the inlet (entrance) cooling fluid's temperature about 20 ^{o}C (degree Celsius), the two laser tubes' temperatures, set at 75 ^{o}C and, respectively, 80 ^{o}C (degrees Celsius).

The unconstraint boundaries were associated with normal working conditions.

It should be mentioned that, in order to avoid the generation of bad shaped finite elements, all the sharp edges were chamfered, small-sized regions of material was removed (in comparison with the true geometry resulting from the device). However, this does not have a significant influence on simulation's results.

Using ANSYS capabilities, a 3D mesh was automatically generated, resulting, after refining, into a total of 202,151 elements (tetrahedral: 123,157, pyramids: 1,754 and wedges: 77,240).

As described in [1], a denser special meshing, inflation of triangular elements which can greatly improve accuracy, is needed near the model boundaries, where turbulence may be significant.

The creation of the inflated boundaries generates elements of prismatic shape in the surface vicinity. This approach allows obtaining a better approximation of the velocity field, near the walls, were its changes can be significant, by inserting flat prismatic wedge-shaped elements having a smaller length along the direction normal to the surface.

For the studied laser device, the velocity field of cooling fluid can significantly influence the temperature distribution, which is of interest. In figure 14 there are presented the global mesh image, as well as a detail view, in order to emphasize the mesh refinement near the boundaries.

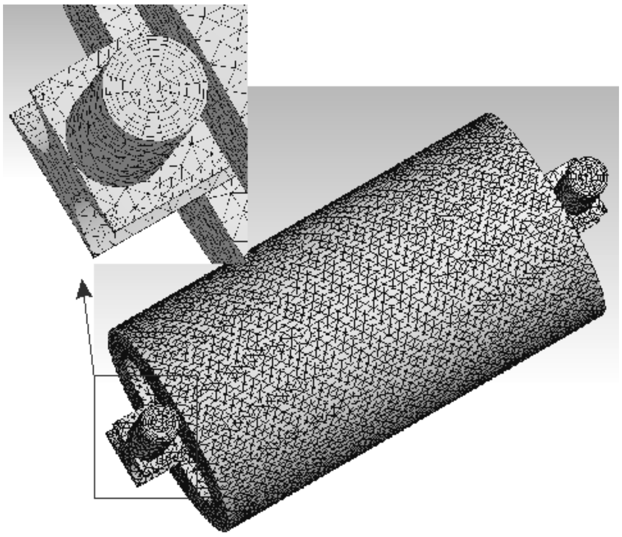

Fig. 14 Model mesh with a detailed view of the inflated surface

As for the real aspects, there have been stated:

- the fluid properties were "taken" directly from ANSYS CFX material database, which offers the commonly used fluid properties, including (un-ionized) water at 25^{o}C – as, the differences between 20^{o}C and 25^{o}C water corresponding properties are very small, so they can be neglected within this evaluation [4];
- the flow was specified as steady state with turbulence and heat transfer - turbulences was modeled using the k-ε turbulence model and heat transfer was modeled with thermal energy model, which is suitable for relatively low speed flow applications [1].

E. Simulation Results

As the simulation's goal is to establish the influence of water flow rate on the outlet temperature, there were performed four analysis, considering different values of flow rate within the range 7 to 15 liters per minute (l/min), meaning 7; 10; 12.5 and, respectively, 15 liters per minute.

All these simulations carried on, resulted in a variation of outlet water temperature within the interval [47; 50] ^{o}C degree Celsius, obviously, greater than 35^{o}C (as required).

It couldn't be noticed any significant influence of water flow rate, on cooling fluid's outlet temperature, despite of expectations.

In order to emphasize the flow field, streamlines were used for showing the path of zero mass particles from the inlet to the outlet region – see figure 15 (a. – front view; b. – back view).

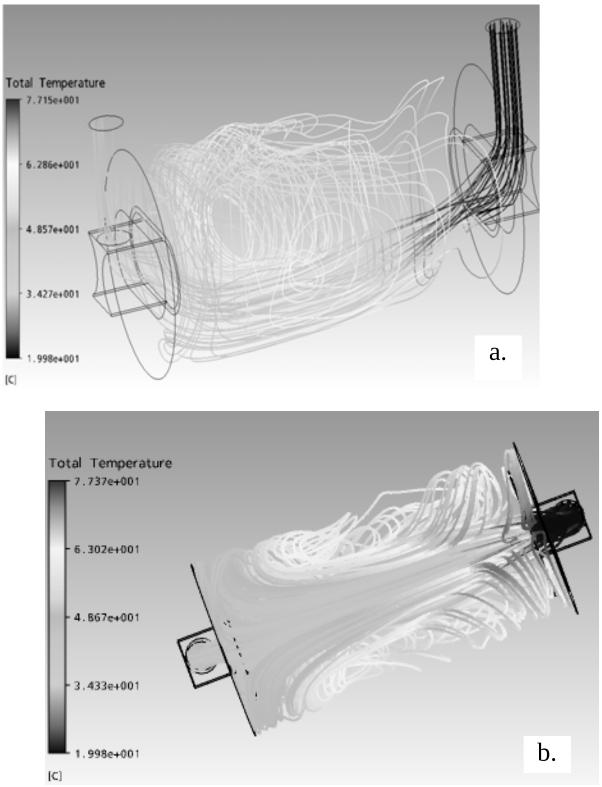

Fig. 15 Temperature distribution field – with streamlines

It can be seen that the temperature is initially low, with inlet value, but as the fluid mixes, part of it remains within the tube and its temperature grows up to 80^{o}C (the maximum applied temperature), slowing down the process of cooling and, making it inefficient.

A better view of cooling fluid temperature field is represented by figure 16 and figure 17– where it can be noticed temperature distribution into different relevant planes, for the analysis run out with a 7 liters per minute flow (mid-longitudinal section and, respectively, cross section).

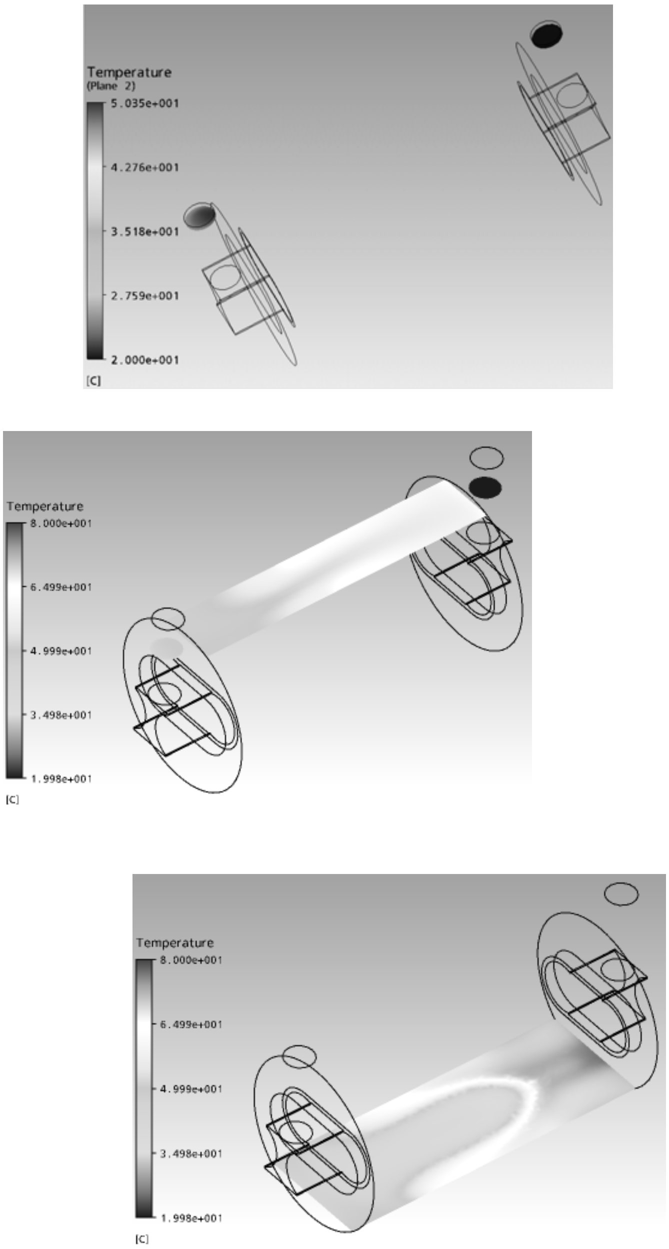

Fig. 16 Temperature distribution in different mid-longitudinal sections - 7 liters per minute flow rate

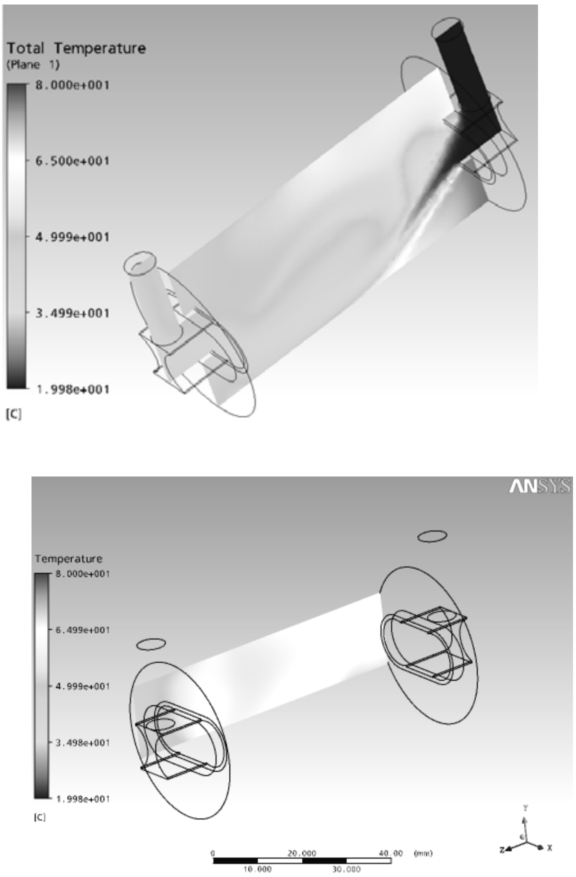

Fig. 17 Temperature distribution in cross section - 7 liters per minute flow rate

The reason for such result may be the geometry of volume flow, which does not offer a proper guidance to water flow and also the tube length, which is about 70 mm long. Using a longer tube may result in a better mixture of different water thermal regions inside it and, as a consequence, in a better cooling of laser device.

So, there has been the idea of optimizing cylindrical part's (shield) shape, in order to obtain a solution for a more efficient cooling fluid's flow. A sensibility analysis regarding the influence of the tube length and diameter upon the outlet water temperature, has also been done.

- *Influence of shield length on the outlet temperature*

The influence of water flow shield length on cooling fluid temperature distribution was simply observed by analyzing three other cases.

So, there were considered length of values: 105 mm, 140 mm and 175 mm respectively, obtained by multiplying the initial length value with 1.5, 2 and, respectively, 2.5.,

Figure 18 shows the cooling fluid temperature field, with streamlines, when the cylindrical part (shield) length is about 140 mm.

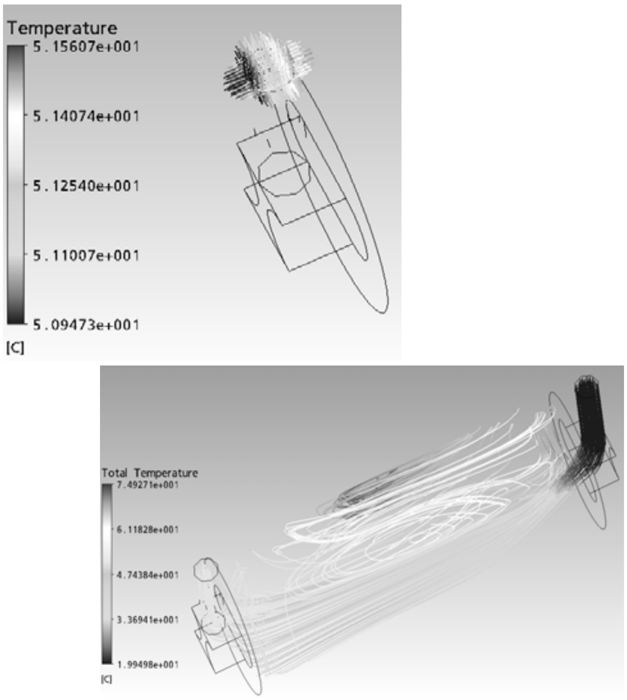

Fig. 18 Streamlines of cooling fluid temperature distribution – shield's length of 140 mm

The results showed that the grater the length is, the more heated the water becomes, fact partially expected, because of the fact that the longer the shield, the longer the heating surface of the laser tubes

- *Influence of shield diameter on the outlet temperature*

Simulations results obtained, induced the idea that diminishing the water flow tube diameter may improve the value of outlet cooling fluid temperature, by constraining it into the very vicinity of the heated tubes.

So, the water tube inner diameter was diminished to the value of 30 mm, which was the minimum value allowed by the device's construction. It was obtained an outlet temperature decreased to 41^{o}C (degree Celsius) but, it was not enough

Results of the simulation, using equally spaced dimensionless points positioned on the outlet region are presented by figure 19.

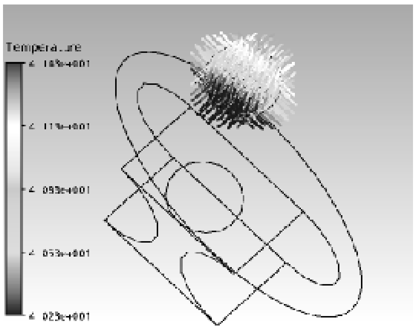

Fig. 19 Temperature field in the outlet region – shield's length of 140 mm

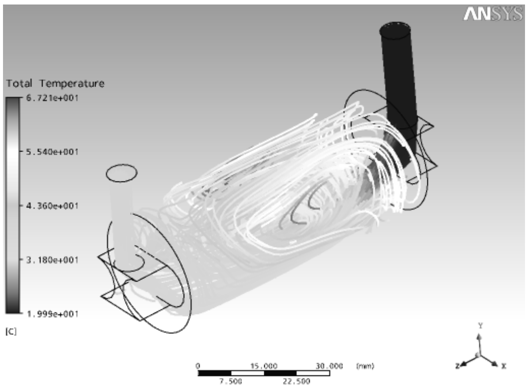

Fig. 19 Temperature field in the outlet region - shield's length of 140 mm (continuing)

- *Shape quasi-optimization of the shield*

There have been studied three shape types of the shield, as shown in figure 20.

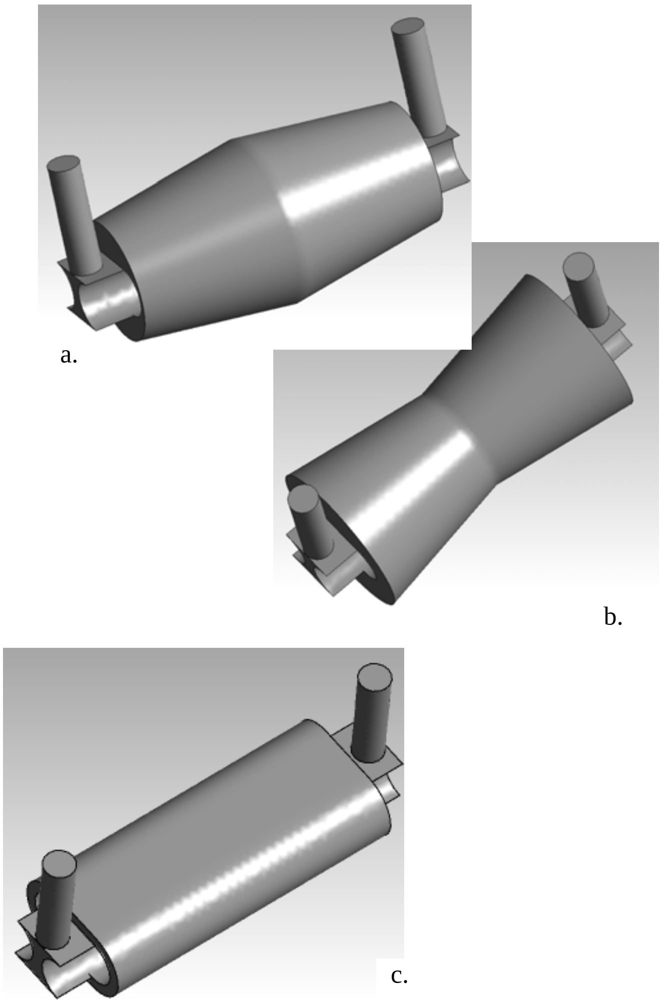

Fig. 20 Various shield's shape types studied

The presented shapes are not unique, their choice has been done intuitively, based on by streamlines flow field distribution. It has, also, been considered the minimum shield's inner diameter, The goal was to obtain a simple configuration, without modifying the geometry and/or sizes of other device components.

Simulation results indicated that the best configuration of all three is the third one (c variant), when the outlet cooling fluid temperature is, of almost, 35 ^{o}C (degree Celsius), as needed.

Figure 21 points out field temperature distribution, for the three cases (a., b. and c.), mentioned above.

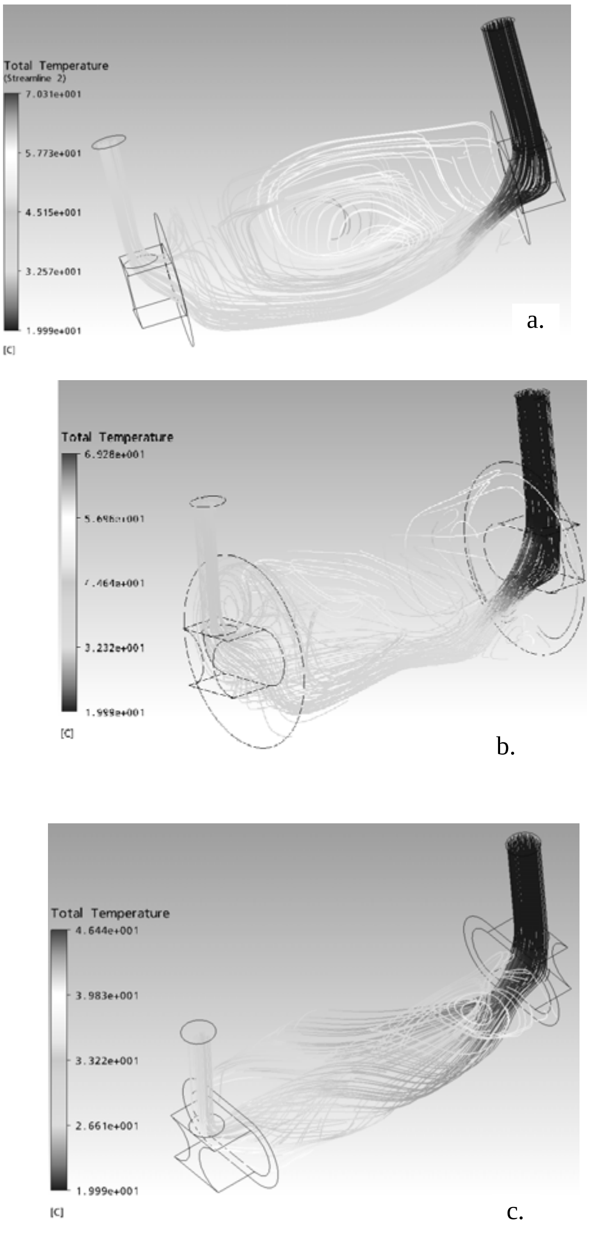

Fig. 21 Streamlines of cooling fluid temperature distribution – various shield shape

IV. CONCLUSION

Additive fabrication represents a group of new technologies which enables obtaining parts with, almost, any shape or geometric feature. By rapid prototyping, as part of additive fabrication, the physical, real, model and the virtual one are, most of all, identically. 3D printing represents one RP technology, where, relatively quick and not too expensive models can be obtained.

There has been studied the component elements of an innovative laser device and, with 3D printing technology it was possible to discover some errors in their design. So, it was possible to save time (about one month) and money but, more important, not to waste very expensive special materials.

The simulation of cooling fluid's temperature distribution field proved that some changes should be done, so that the functioning of laser device to be appropriate.

There have been studied shields of different length and diameter values but, no important improvement of outlet temperature has been determined.

Different shield shapes have, also, been considered and, fortunately, one of them proved to be optimum for obtaining and outlet temperature of cooling fluid, about the value of 35 ^{o}C (degree Celsius

Further research and use of other (than ink-jet printing) Rapid Prototyping technique, could be done if several changes in component parts would be required. Thus, Rapid prototyping should be used for reducing product development cycle.

REFERENCES

[1] *Ansys CFX* Help, Release 11

[2] Iliescu M., Comănescu B., Nuțu E., "*Rapid Prototyping Use in Manufacturing components of a Medical Laser device*", 2nd WSEAS International Conference on Additive Technologies ICAT 2008, DAAAM Specialized Conference, ISBN 3-901509–72-0, Ptuj, Slovenia, September, 2008

[3] Z CORPORATION, *Available from:* http://www.zcorp.com/Products/3D-Printers, *Accessed:* 2008-10.

[4] http://webbook.nist.gov/chemistry/fluid, *Accessed:* 2008-10.

[5] Ink Jet Printing, *Available from:* http://www. Rapid Prototyping Inkjet.html, *Accessed:* 2008-10.

[6] Rapid Prototyping, Available from: http://en.wikipedia.org/wiki/Rapid_prototyping, *Accessed: 2008-10*.

[7] http://wohlersassociates.com/additive-fabrication.html, *Accessed:* 2008-10.

[8] http://www.designnews.com/article/7233Rapid_ Manufacturing_s_Role_in_the_Factory_of_the_Future.php, *Accessed: 2009-01*

[9] http://www. Rapid Manufacturing\Rapid Prototyping and Solid Freeform Fabrication - The Worldwide Guide.htm, Accessed: 2009-01

[10] http://www Rapid Manufacturing\Rapid Prototyping Ink Jet.htm, Accessed: 2009-01

[11] Hluoic N., Basch D., Fertlaj K., Computational Issues of Signal Analysis in Time Domain, WSEAS Transactions on Computers, Issue 1, volume 6, January 2008, ISSN 1109-2750, pag. 1-8,

[12] Chen R., An Iteration Method for Finite-Element Solutions of the Nonlinear Poisson-Boltzamann Equations, WSEAS Transactions on Computers, Issue 4, volume 7, April 2008, ISSN 1109-2750, pag. 165-173

[13] Ugail H., Kirman S., Shape reconstruction Using Partial Differential Equations, WSEAS Transactions on Computers, Issue 10, volume 5, October 2006, ISSN 1109-2750, pag. 2156-2161