LIQUID LIGTH GUIDE

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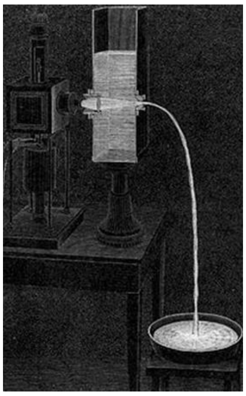
1. Introduction

Light guide is a fiber-optic cable which is used to transfer signal (light pulses). This is one of basic ways of information transfer. It is wide spread in computer networks, telecommunications, medicine, fiberoptic ect. Usually is made from glass, quartz or plastic. In this paper, research of the properties of water which enable water jet to serve as a light guide is presented. Colladons' apparatus for so called "light fountain" or "light pipe" from 1840 was constructed. The main goal was to determine how intensity of transferred light and length of jet capable to transfer light depend on the shape of the jet. Experimental results are described and compared with a computer model.

2. Apparatus



The apparatus was very similar to Colladons' apparatus [Figure 1] but with few extra improvements so the measurements could be done. [Figure 4] A large transparent vessel with a horizontal nozzle and a laser (He-Ne laser, 630nm) was set. The nozzle and laser were in the same horizontal level and laser was pointed into the nozzle so it could enter a water jet leaving the nozzle. Nozzle had to have perfectly smooth walls and narrow toward the end so it could prevent turbulences to appear. The plastic end of pens turned better of any other glass of metal tubes.

Figure 1: Colladons' apparatus [4]

3. Materials and methods

In the beginning in vessel was 10 liters of water and the jet was almost horizontal. As water seeped, because of the reducing height of water in the vessel and hydrostatic pressure, the output velocity also reduced so the curvature of water jet became steeper. Every few seconds the intensity of light in jet, always in the same vertical distance form nozzle, was measured. A photo resistor was set so that it could be moved horizontally. It had larger sensor surface than the cross section of jet so that when it was placed inside of jet all light came onto the sensor. At the same time the jet was photographed so measurements could be taken and curvature could be determined mathematically (the coefficient of parabola).

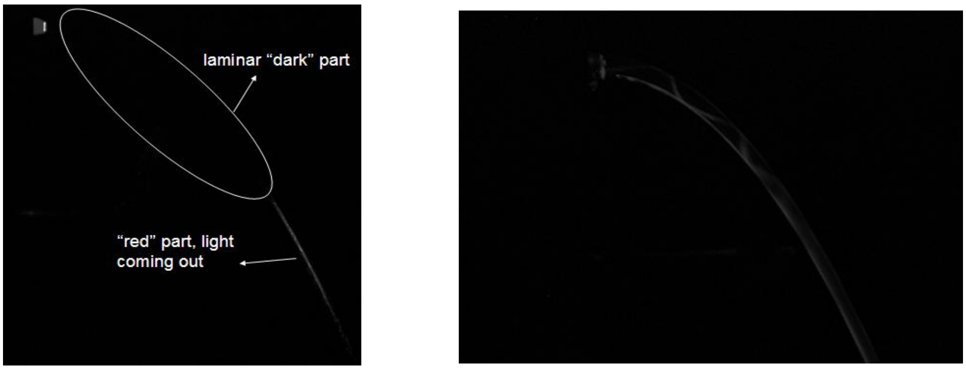


Figure 2: a) the effect („dark“ and red part) b) reflections inside a jet (in opaque water)

3.1. Measuring the length of laminar part of the jet

There were two phases in the jet; “black” and red part (since the laser was red). First part where jet was “dark” and smooth was part where the light was completely inside of the jet and wasn’t coming out (in our eye) so it couldn’t be seen (in the dark). After some length, the jet wasn’t consistent (smooth) any more and started to turn into drops. This part of the jet was always bright and red because light started to come out of the jet. Here it couldn’t serve any more as a light guide. Goal was to determine how the length of laminar part of the jet depends on the shape of the jet. Laminar part is important because only this part of jet can conduct the light. It was photographed and pictures were processed with program “ImageJ”. The coefficient of parabola which jet described was calculated and the length of the curve of “dark” part of jet was measured. As a reference for dimensions there was a ruler photographed in the picture.

3.2. Measuring the intensity of light

As the shape of jet and parabola coefficient changed; due to the geometry optics, the intensity of light that stays inside of the jet also changed. Also, intensity which came to the place of measurement changed. It was measured always on the same vertical level (about 5 cm below the output level) in “black” part of jet. At this place a photo resistor was put and the resistance was measured since it depends on intensity of light. The dependence of intensity on electrical resistance (of photo resistor) is not linear and it was necessary to calibrate it.

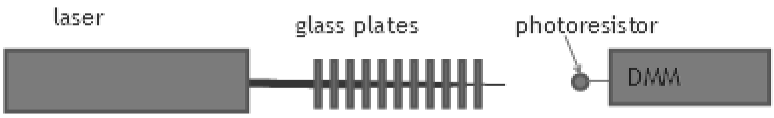
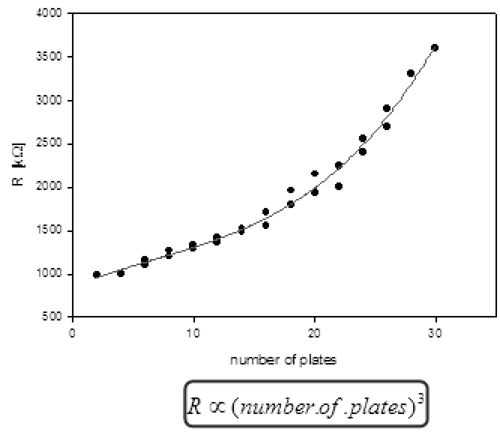
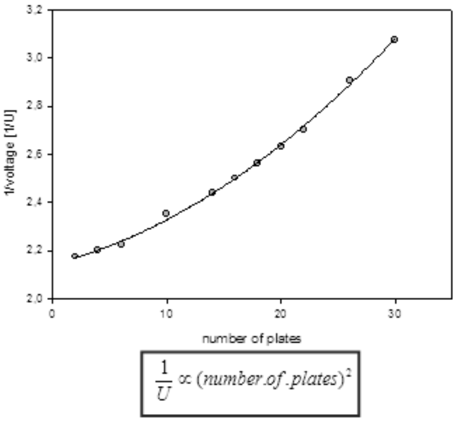


Figure 3: Calibration of the photo resistor

Some materials (e.g. glass plates) absorb the light that passes through them. Changing the number of glass plates the total absorption was changed so the intensity of light on resistor too. The light absorption is proportional to the number of plates. Different number of them was put between laser and photo resistor. [Figure 3] The dependence of resistance on number of glass plate was determined. [Graph 1]



Graph 1: Calibration of the photo resistor



Graph 2: Calibration of the photo diode

The same procedure was repeated with photo diode instead of resistor and voltage was measured. It was known that the dependence of voltage on light intensity was linear. This way the dependence of voltage on the number of plates N was determined. [Graph 2] Since for the photo diode is $I \propto U$ (I as light intensity) and the previous calibrations gave these relations; $R \propto (N)^3$ and $\frac{1}{U} \propto (N)^2$ it followed that the dependence of intensity on electrical resistance of photo resistor is: $I \propto \left(\frac{1}{R}\right)^{\frac{2}{3}}$.

The area of photo resistor was larger then the area of cross section of jet for all diameters of nozzle. This way all light inside of the jet was absorbed by the resistor.

Now when it was known how to get the intensity from resistance and when the apparatus was constructed [Figure 4] and the method were developed the measurements could be done.

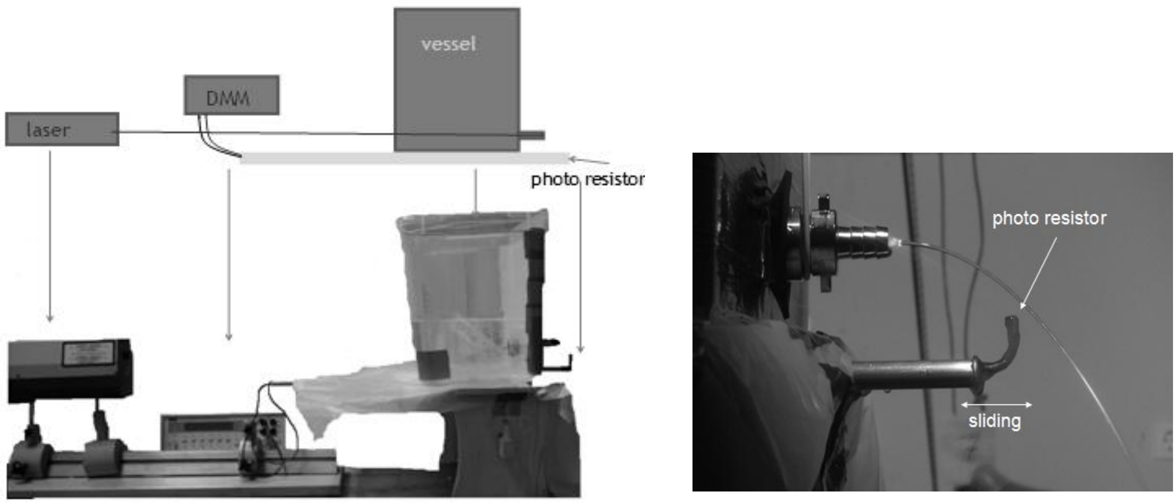


Figure 4: The apparatus

4. Theory

There are two main reasons for the loss of the light: hydrodynamic and optical. Hydrodynamic reason is the decomposition of the jet. Because of the gravity the velocity of water increased and since the flow rate has to be constant, the diameter of the jet decreased. On the surface of the jet there are always small fluctuations called Plateau-Rayleigh fluctuations, no matter how laminar the jet is. If the perturbations are decomposed into sinusoidal components, it can be seen that some components grow with time while others decay with time. Among those that grow with time and increase of velocity, some grow at faster rates than the others. In addition, the jet narrows over the path due to continuity equation, so jet turns into drops. These turbulences are unpredictable and it's very hard to theoretically determine the place at the jet where they will cause leakage of light from the jet. That's why it was photographed.

Second reason is optical. In different mediums light spreads with different velocity and has a different wavelength and that's why it refracts or reflects when it comes to the border between two different mediums. What will happen with light when it comes to border depends on the input angle and refractive index. If input angle is smaller than the boundary angle (for water it is 48.6°) the light passes in second medium but with different output angle. This angle is determined by the Snell's law. If the input angle is greater than boundary angle, the total internal reflection happens and it means that the light stays in the previous medium, and the 100% of initial intensity is preserved. It is important not to forget that even if the most of the light refracts still some percent of the initial light and it's intensity stays in initial medium. This percentage is determined with the formula:

$$K = \left(\frac{n_1 \cos\alpha - n_2 \cos\alpha}{n_1 \cos\alpha + n_2 \cos\alpha} \right)^2$$

Formula 1: Percentage of light that stays inside of jet in dependance of the input angle

5. Computer simulation

This math model was made to calculate the intensity of the light at the end of the "dark" jet. Simulation required some approximations. Considering jet as a projectile motion of water particles it's shape could be written in perfect conditions as $y = \frac{-g}{2v^2} x^2$. In program, jet was presented with two parabolas. They had same formulas but one was translated above another for the value of the diameter of the nozzle. [Figure 5] It was assumed that the first reflection has the lowest angle of incidence, so if the ray gets reflected first time, it will reflect later as well and the intensity will stay unchanged after first interaction. That's why in the program only the place where laser ray strikes the edge of the jet first time was observed. [Figure 6]

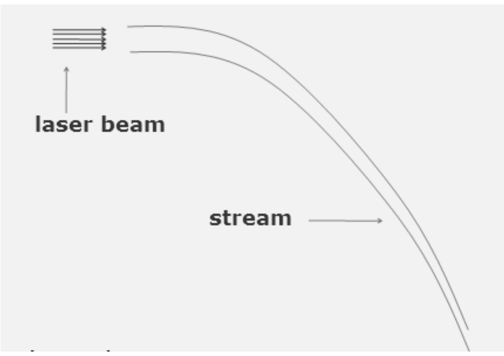


Figure 5: Jet and laser represented in program

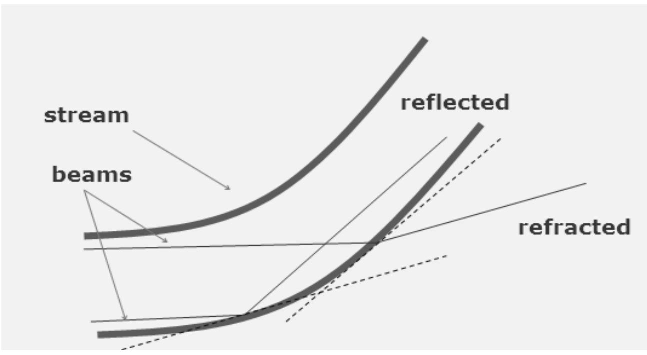


Figure 6: First intersection of laser ray and jet parabola

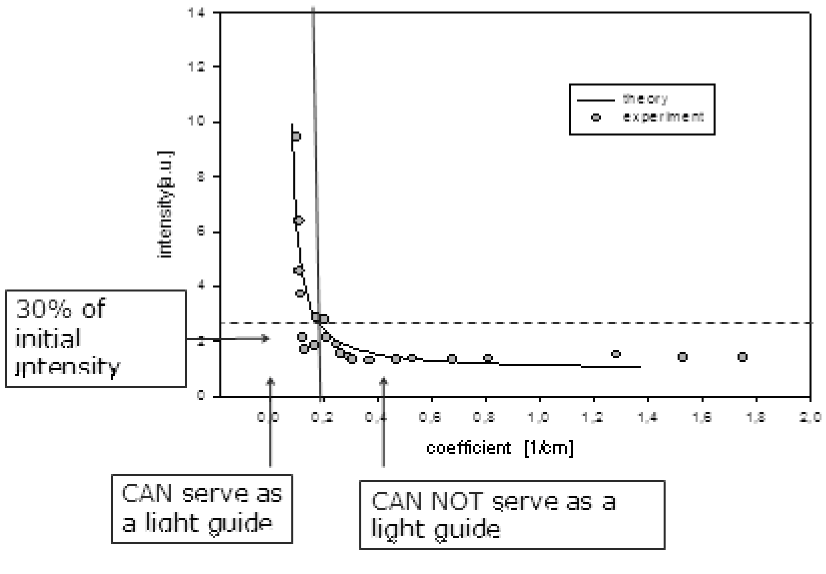
The laser beams were simulated as a set of parallel lines. [Figure 5] This is how the program worked: 1. for each line the intersection with beam parabola is found 2. angle between laser ray and straight line perpendicular to the parabola is found 3. if the angle is greater than the boundary one the percentage of intensity stays 100, if the angle is smaller the percentage is calculated by the formula [Formula 1] 4. intensities are multiplied with 1/n if there is n observed rays and than summed 5. this procedure is repeated for different parabola coefficients so the measurement with different output velocities are simulated.

6. Results and discussion

6.1. Dependence: Intensity of light - coefficient

The intensity of light that stays in jet after first refraction (until the beginning of the dissipation of the jet) decreases steeply as the coefficient of the parabola starts to increase. Later it becomes almost a constant. [Graph 3] As criteria of a good light guide it was taken a number of 30% of initial intensity that has to be preserved. This number was an arbitrary number that was chosen on basis of measurements. From graph it can be seen that the maximal coefficient of parabola for jet to still be “good” light guide is 0.2.

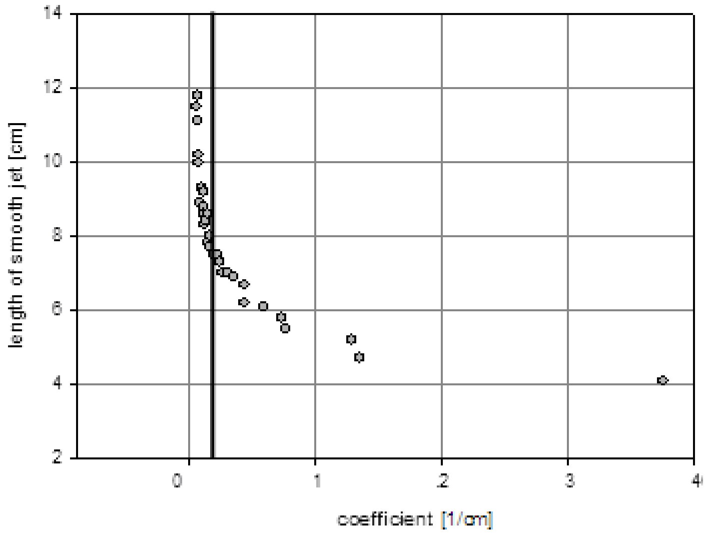
In graph the line represents the computer model and dots measurements. Theory and measurements agree very well. It confirms theory that only the first intersection is important and that it is satisfactorily to present the jet as two identical parabolas.



Graph 3: Intensity dependence of parabola coefficient

6.2. Dependence: Length of the laminar part of the jet – coefficient

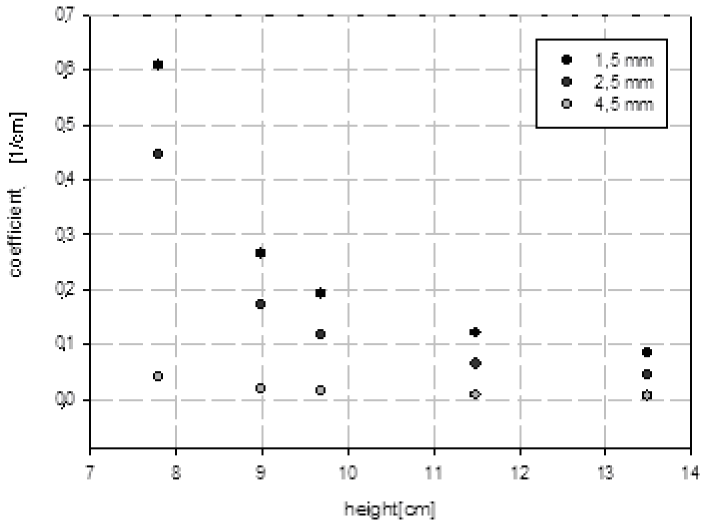
The length of the laminar part of the jet wasn’t possible to predict theoretically because the turbulences appear after only few centimeters from the nozzle, but the question is when they significantly influence on the refraction and reflection. In [Graph 4] the measurements of the length of curve of “black” part of the jet from taken pictures are shown.



Graph 4: Dependence of length of laminar part of jet on coefficient of parabola

6.3 Influence of the diameter of the nozzle

The diameter affects the coefficient of the parabola. The thicker the jet is for the same height of the water in the vessel, coefficient is smaller which means that the jet is more horizontal. [Graph 5] It may seem contradictory but it's because of the friction with nozzles which can't be neglected. In case of greater diameter the friction with nozzles smaller effect on the outcome velocity. That's also why the velocity couldn't be determined from the height. The diameter was from 1.5mm to 4.5 mm.



Graph 5: Influence of diameter of the nozzle on the coefficient of parabola

7. Conclusion

The goal of research was accomplished. Conditions under which the jet operates as a light guide were determined. If it has a coefficient of parabola which describes its shape smaller than 0.2, then it preserves more than 30% of initial light. This 30% of intensity that was declared as a boundary for water jet to be a “good” light guide because no matter how steep the curvature of jet is, it always leads some amount of light till the end (where it turns into drops), but after this 30% the intensity decreases really slowly with tendency of becoming a constant as the coefficient is increased. Moreover, for smaller coefficients the length on which this intensity of light can be transported (length of “black” jet) is longer. Diameter of the jet affects the outcome velocity and the coefficient for the same height of water in vessel. The best light guide possible to achieve is with big diameter of the nozzle, and a lot of water in vessel so the coefficient is smaller.

This solution gives intensity dependence on water path parabola coefficient which is not very practical. A more useful solution would be dependence on initial jet velocity. However, it wasn’t practically feasible to measure jet velocity for different coefficients. Also it wasn’t possible to determine velocity neither theoretically because of the unknown friction with nozzles.

In comparison with industrial light guides composed of glass or plastic this light guide made of water stream guides light at shorter distance due to greater absorption of light and disintegration of water stream.

8. Literature

[1] Halliday, Resnick, Walker (2000): Fundamentals of Physics: Wiley

[2] A.Llor (2005): Statistical hydrodynamic models for developed mixing instability flows: Springer Berlin

[3] S.M. Čantrak (2005): Hydrodinamics: Beograd

[4] http://en.wikipedia.org/wiki/Optical_fiber

[5] http://en.wikipedia.org/wiki/Plateau%E2%80%93Rayleigh_instability