AIR FLOW AND ENVIRONMENTAL WIND VISUALIZATION USING A CW DIODE PUMPED FREQUENCY DOUBLED Nd:YAG Laser

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Abstract
Preliminary results obtained in developing a visualisation technique for non-invasive analysis of air flow inside INCAS subsonic wind tunnel and its appendages are presented. The visualisation technique is based on using a green light sheet generated by a continuous wave (cw) longitudinally diode pumped and frequency doubled Nd:YAG laser. The output laser beam is expanded on one direction and collimated on rectangular direction. The system is tailored to the requirements of qualitative analysis and vortex tracking requirements inside the INCAS 2.5m x 2.0m subsonic wind tunnel test section, for measurements performed on aircraft models. Also the developed laser techniques is used for non-invasive air flow field analysis into environmental facilities settling room (air flow calming area). Quantitative analysis is enabled using special image processing tools upon movies and pictures obtained during the experiments. The basic experimental layout in the wind tunnel takes advantage of information obtained from the investigation of various aircraft models using the developed visualisation technique. These results are further developed using a Particle Imaging Velocimetry (PIV) experimental technique.The focus is on visualisation techniques to be used for wind flow characterization at different altitudes in industrial and civil buildings areas using a light sheet generated by a Nd:YAG cw pumped and doubled laser at 532 nm wavelength. The results are important for prevention of biological/chemical disasters such as spreading of extremely toxic pollutants due to wind. Numerical simulations of wind flow and experimental visualisation results are compared. A good agreement between these results is observed.

Keywords: air flow, visualization, laser light sheet, light frequency doubling, diode pumped Nd:YAG laser, wind engineering, building aerodynamics

1. Introduction

Results obtained in developing a visualization technique for the experimental investigation of air flow in the proximity of the studied aircraft model are presented. The developed visualization technique is dedicated to be used in wind tunnels [1 - 4].

One major feature of the developed visualization technique consists in the fact that it is non-invasive regarding the air flow, in contrast with traditional methods based on use of Pitot tube or small cloth ribbons mounted on the studied aircraft model. The developed visualization technique means no intrusion into the air flow, especially into the boundary layer of the aircraft model. This is important in studying air flow at low speeds versus the aircraft model, simulating two basic operations of an airplane: take off and landing [2].

The visualisation technique relays on using a green light sheet generated by a continuous wave diode pumped frequency doubled Nd:YAG laser.

The system is tailored to the requirements of qualitative and further quantitative analysis and vortex tracking requirements inside the National Institute for Aerospace Research “Elie Carafoli” (INCAS) 2.5mx2.0m subsonic wind tunnel.

The results obtained in developing a project oriented towards a new field of interdisciplinary applicative research in Romania, namely environmental aerodynamics are presented. The presented results are obtained by creating an applied research setup based on computer simulation of atmospheric pollution and its experimental validation in wind tunnel by using a laser light sheet visualization technique. Cases of possible urban and industrial pollution accidents are investigated.

The developed experimental setup system and the presented results are aiming to meet the micro meteorology modeling requirements imposed by the European project **COST C14 “The Impact of Wind and Storm on City Life and Built Environment”** as well as the ongoing European project **COST 732 “Quality Assurance and Improvement of Micro-Scale Meteorological Models”.**

2.1. Theory - Principle of Operation

One major requirement to be fulfilled in developing the experimental setup consists in its simplicity and reliability. The principle of operation is based on the following steps:

- using a small volume frequency doubled Nd:YAG emitter a light sheet is generated, an observation plane for the air flow being defined in this way;
- using a simple technique, small particles (seeds) are injected into the air flow in order to enhance the optical effects, making thus the visualization more reliable;
- by positioning the green laser light sheet longitudinally or transversally versus the aircraft model, various effects appearing in the air flow can be visualized and investigated.

2.2. Theory - Environmental Aerodynamics

The theoretical support of the performed experiments is included into a type of interdisciplinary scientific activity relatively newly appeared in Romania, namely Wind Engineering and Building Aerodynamics. It has been developed for the last three decades as a field of structural engineering. This science analyzes wind effects on the natural and built environment. It studies strong winds which may cause pedestrian discomfort as well as extreme winds such as tornadoes, hurricanes and storms which may cause widespread destruction. The knowledge of Wind Engineering is used to analyze and design all high altitude buildings, cable suspension and cable stayed bridges, electricity transmission towers and telecommunication towers and all other types of towers and chimneys. The wind load is the dominant load in the analysis of many tall buildings, dominant load which has to be considered when designing such buildings.

Wind Engineering and Building Aerodynamics studies also how possible pollution catastrophic events, such as explosions of containers of toxic volatile chemicals, could propagate into industrial and civilian buildings area. The atmospheric air flow (wind) is considered as one main propagation agent of such disasters.

Wind Engineering and Build Aerodynamics tries to improve the urban area quality by improving the safety, efficiency and comfort of the building environment and reducing storm induced damages and pollution catastrophic events.

Wind Engineering and Building Aerodynamics draw upon meteorology, aerodynamics, Geographic Information System, Wind Energy, Air Pollution and a number of specialist engineering disciplines. The tools used include climate models, atmospheric boundary layer wind tunnels and numerical models. It involves, among other topics, how wind impacting buildings must be accounted for in engineering.

Wind Engineering and Building Aerodynamics has some particular tasks, some main sub domains of research related to its core:

- **Wind effects in urban areas** – This includes data about how wind speed and turbulence characteristics differs according to the shape of the buildings.
- **Wind effects on pedestrians** - This is a particularization on ground level winds, buildings air ventilation assessment and effects on transportation.
- **Transfer of gas and pollutants in urban areas** – This refers to how wind influences on rain falls and snow-bound buildings and their cumulated effects on environment.
- **Wind effects on building and urban structures** – includes fundamental problems on buildings response at high velocity winds.

Two main activities are to be considered in the frame of Wind Engineering and Building Aerodynamics:

1. CFD - Computational Fluid Dynamics - A system of computer codes developed for applied to the prediction of surface pressure and local wind influence on buildings. Wind loads studies are a very important aspect as the number of tall buildings is increasing. Buildings and their components are to be designed to withstand the code-specified wind loads. One main result of apply-

ing these numerical codes consists in defining air flow lines and the speed of air flow.

2. Experimental confirmation of CFD - It represents a combination of several experimental techniques dedicated to characterization of air flow upon building models. These techniques are preferably non-invasive, meaning that they do not imply insertion of some measuring device into the air flow. Among these experimental techniques visualization of air flow using laser beams are of interest because they are non-invasive and able to get many accurate insights concerning the studied phenomena.

Using the experimental confirmation as feedback, the computer design codes for building construction are generated and the effective design technical drawings are obtained.

3. Experimental setup

The experimental setup used for is composed of three major parts:

A - LASER EMITTER;
B - WIND TUNNEL;
C - SEED GENERATOR.

A - LASER EMITTER

Two versions of a homemade cw longitudinally pumped Nd:YAG laser emitter were used: one generating 30 mW at 532 nm (green) and the other with 100 mW at the same wavelength.

For manufacturing the laser emitter a cylindrical Nd:YAG active medium is used. The Nd:YAG active medium has a multilayered thin film deposited mirror with ~99% reflectivity at 1.06 μm (lasing wavelength) and transparent at 808 nm (pumping wavelength) on one end face. The extraction mirror is deposited on the other end face. The Nd:YAG active medium is longitudinally continuous wave pumped with a 2W (30 mW green wavelength output power) or 4W (100mW output power) laser diode.

For both versions, KTP crystals were used as laser frequency doublers.

The green laser light sheet is obtained by using a simple cylindrical lens with ~ 12.5 mm focal length. The cylindrical lens is mounted such as its focal line is positioned very close to the laser output mirror.

The laser beam has a Gaussian transverse intensity distribution. The laser beam diameter is ~ 2 mm measured in the near field, at the frequency doubling crystal. The Gaussian transverse intensity distribution still remains after passing through frequency doubling crystal. The green laser light sheet has ~4 mm thickness measured at approximately 8 m from the cylindrical lens. The angular spread of the green laser light sheet is of ~70°.

In Fig. 1, the schematic of the laser emitter is presented.

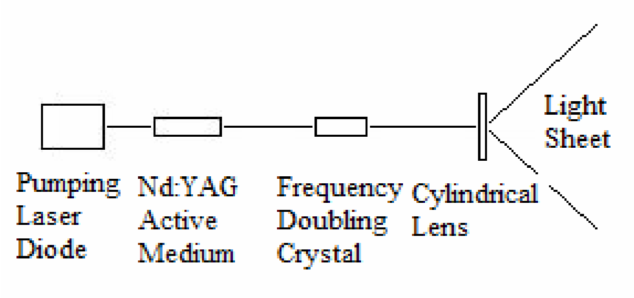

Fig. 1 – The laser emitter setup schematic representation. The positions of the pumping laser diode, laser active medium, frequency doubling crystal and cylindrical lens are indicated. The position of the green laser light sheet is also indicated.

A standard, commercial digital 10 Mega pixels camera was used for recording the picture shots relevant for air flow around the aircraft model surface.

B - WIND TUNNEL

The experiments were performed into the INCAS subsonic wind tunnel. The size of the transverse testing section is 2m×2.5m. The aircraft model is mounted on three supports on a rotating platform, which is the top platform of an aerodynamic balance. The measurement of various forces acting upon the aircraft model as a result of air pressure is performed by using this aerodynamic balance.

In Figure 2 a schematic of the INCAS subsonic wind tunnel is presented. The INCAS subsonic wind tunnel has a continuous air flow with variable speeds. The controlled air flow is obtained with a continuous wave (cw) electric motor with 2 MW power output powered by a hex phased thyristor rectifier bridge. The cw 2 MW electric motor is cooled with a 20 kW ventilator. The variation of air flow speed is controlled by revolution frequency of the cw 2 MW electric motor.

During visualization experiments air flow speed was low (10 ÷ 20 m/s), in order to simulate take off or landing procedures.

The visualization experiments were performed in normal temperature and pressure conditions.

As can be observed in Figure 2, the air flow has a closed circuit in the frame of the INCAS subsonic wind tunnel. In each of the four corners of air flow closed circuit semicircular deflectors are used in order to assure a smooth air flow.

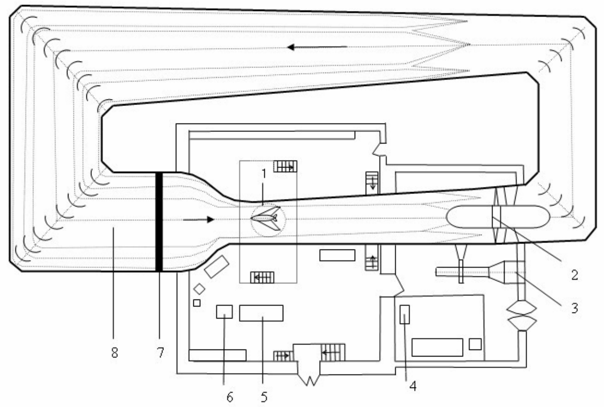

Fig. 2. Schematic of the INCAS subsonic wind tunnel. The place where the aircraft model is mounted is pointed symbolic draw of it. The air flow direction is indicated with an arrow.
1 - test section (the aircraft model is included in the schematic); 2 - motor fan; 3 - cooling fan; 4 - high voltage panel; 5 - data console (system of data acquisition coupled with aerodynamic balance and other detection sensors); 6 - motor control console; 7 - wire net (a system of variable diaphragms for air flow rate control); 8 - settling room (air flow calming area).

C - SEEDING GENERATOR

The seeding agent is smoke resulted from paraffin oil burning. The smoke generator has an oil pumping system, an arm with an oil nozzle, ended with a heating resistor which partially vaporizes the oil. The arm is used to manually adjust the origin of the smoke wake in the flow field. It is the single, appreciable small, unavoidable disturbance of the air flow. In Fig. 3 some details of the seeding generator experimental setup are presented.

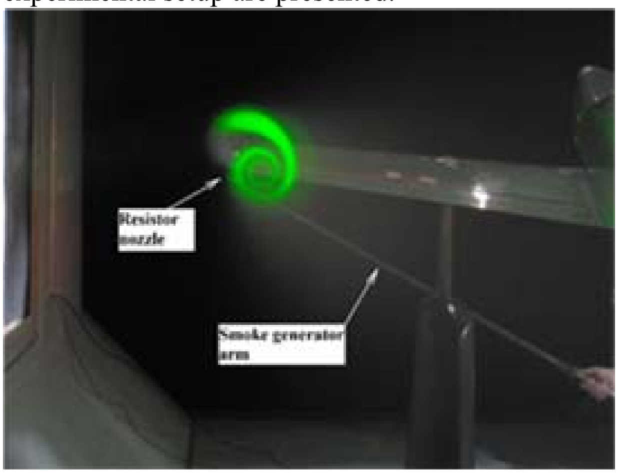

Fig. 3. Experimental setup. There are indicated the resistor nozzle and the arm (pipe) of the smoke generator. The aircraft model and air flow effects can be observed.

4.1 Results obtained on testing aircraft models

The purpose of the air flow visualization experiments is to investigate the phenomena produced at low speed, meaning two main airplane operations: take off and landing. The studied aircraft model was placed at different attack angles. The angle of attack is defined as the angle formed by the aircraft axis and the wind tunnel average flow direction.

Two types of visualizations were performed:
- Longitudinally - the green laser light sheet being placed parallel with air flow direction, along longitudinal sections of the studied aircraft model, mainly along the symmetry plane;
- Transverse - the green laser light sheet is perpendicular to air flow direction, along transverse sections of the studied aircraft model, at different positions relative to the wing tips.

The resistor nozzle of the smoke generator was placed in front of the aircraft model into the position of interest. The seeding smoke appears as a low level shinning hallow around the aircraft model surface. The boundary layer of the studied aircraft model appears relatively clearly defined as can be observed in the pictures presented in the followings.

LONGITUDINALLY VISUALIZATIONS

In Figures 4 and 5 visualizations performed with the green laser light sheet oriented along the air flow are presented. The green laser light sheet was fixed approximately into the middle plane (section) of the aircraft model. The visualizations were performed using two attack angle values, one corresponding to airplane taking off (Figure 4, attack angle of ~35°) and cruise (normal) flight, as presented in Figure 5, attack angle being of ~2°.

In both Figures 4 and 5, it can be observed that the air containing paraffin oil smoke flow near the aircraft model surface appears as clearly defined with a shape slightly dependent on attack angle.

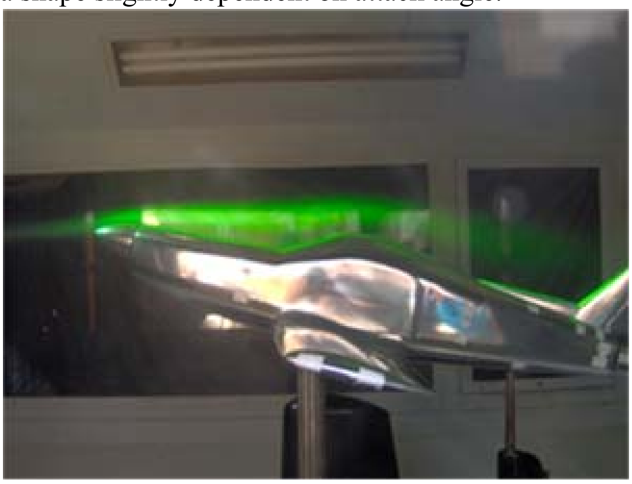

Fig. 4 - Visualization of air flow performed with longitudinally oriented laser light sheet. The air flow lines with seeding smoke near the aircraft model surface are indicated with an arrow. The attack angle of the aircraft model versus the airflow is of ~35°. The air flow speed is 15 m/s.

Fig. 5 - Visualization of air flow performed with longitudinally oriented laser light sheet. The air flow lines with seeding smoke near the aircraft model surface are indicated with an arrow. The attack angle of the aircraft model versus the airflow direction is ~2°. The air flow speed is 15 m/s.

TRANSVERSE VISUALIZATIONS

In Figures 6, 7 and 8 visualizations performed with the green laser light sheet oriented on a transverse direction versus the air flow are presented. The green laser light sheet was placed at different distances versus the wing tips of the aircraft model.

Fig. 6 - Visualization of air flow performed with transversally oriented laser light sheet. The air flow lines with seeding smoke are indicated with an arrow. The air flow vortex appearing at the end of aircraft model wing is indicated with an arrow. The attack angle of the aircraft model versus the airflow is of ~35°. The air flow speed is 15 m/s.

Fig. 7 - Visualization of air flow performed with transversally oriented laser light sheet. The air flow lines with seeding smoke are indicated with an arrow. The air flow vortex appearing at the end of aircraft model wing is indicated with an arrow. The attack angle of the aircraft model versus the airflow is of ~35°. The air flow speed is 15 m/s.

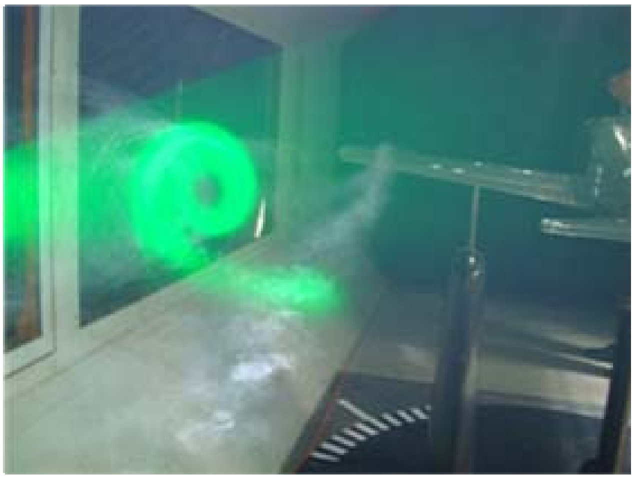

Fig. 8 - Visualization of air flow performed with transversally oriented laser light sheet. The air flow lines with seeding smoke are indicated with an arrow. The air flow vortex appearing at the end of aircraft model wing is indicated with an arrow. The attack angle of the aircraft model versus the airflow is of ~35°. The air flow speed is 15 m/s.

In Figures 3, 6, 7 and 8 how were placed the green laser light sheet, the smoke generator and aircraft model relatively versus each other can be observed.

In Figures 3, 6, 7 and 8 a major result obtained by using the developed laser visualizations techniques is observed. This result consists in visualization of air vortexes which appear at the wing tips of the studied aircraft model. These vortexes are of particular importance in two important aircraft operations, namely taking off and landing, whatever it is its type, subsonic or supersonic. The smoke generator is placed at or near the tip of the aircraft model wing. It is to be mentioned that the air vortex is formed in a plane which is oriented at approximately the attack angle value versus the horizontal plane of the studied aircraft model. The size of this air increases with the relative distance from the aircraft model wing tip, in the air flow direction, until becoming diffuse. The shape of the air flow lines at the wing tips, considering the observed air vortexes, can be described as enclosed into a conical envelope with a relatively clear defined top point and diffuse bases.

It has to be underlined that these air vortexes appearing at the aircraft wing tips were predicted using Computational Fluid Dynamics, but not computer numerically simulated. Such computer simulations are extremely complicated and time and hardware resource consuming. Also, experimental observation of such air vortexes is complicated being reported in literature only in few references [2].

4.2 -Results in environmental aerodynamics

The presented results refer to two main possible applications of Wind Engineering and Building Aerodynamics, namely:

- Wind effects upon urban civilian areas;
- Wind as possible pollution propagation agent in industrial areas.

For both types of presented results the same procedure was applied, by the following steps:

1. 3D electronic maps of areas under investigation were generated, details like building heights and shape being carefully considered;
2. CFD programs are generated considering the possible wind flow directions and speeds;
3. On scale models of investigated areas are manufactured and placed in convenient chosen zones of INCAS subsonic wind tunnel facility considering the possible natural wind directions and speeds;
4. Imposing an on scale air flow speed upon building models, in the range 1 ÷ 5 m/s, the green laser sheet visualization technique is used for obtaining details on wind possible evolutions into investigated areas.

The results obtained in investigating two building areas are presented:

A. A residential urban area situated in centre of Bucharest, namely around the Armenian Street and Armenian Church Episcopal Office;

B. An industrial area, namely that of ROMAG PROD factory (the main Romanian manufacturer of heavy water for nuclear industry applications), an area situated near Drobeta Turnu-Severin city.

The Armenian Street and Armenian Church Episcopal Office is investigated mainly regarding wind possible effects. One main issue of these investigations is related on the possible future problems appeared as a high building is under construction in the middle of the investigated area.

The area of ROMAG PROD factory is investigated mainly regarding the possible role played by wind as a pollution propagation agent. To be more specific: possible contamination of the nearby city with hydrogenated sulphur (H_2S) is investigated.

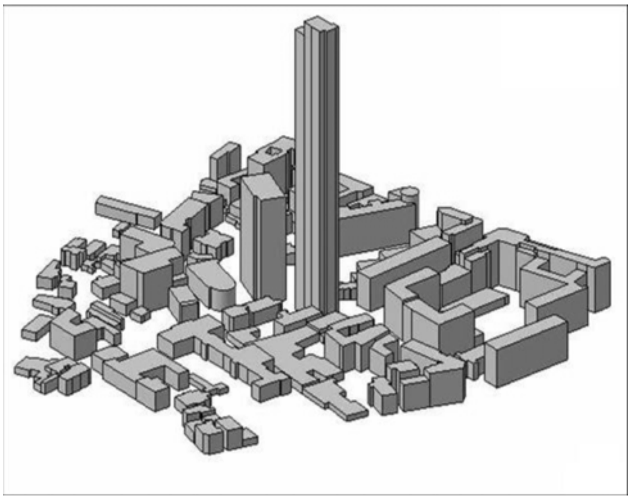

Fig. 9. Computer generated 3D layout of a central Bucharest urban area. Used for EVICVA urban comfort research project. The central high building under construction is evident

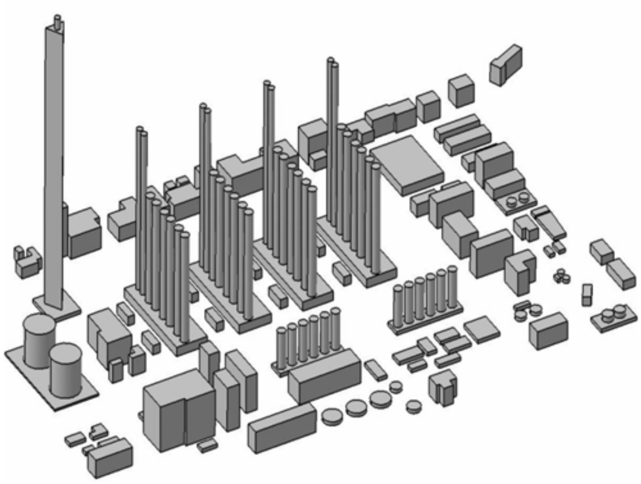

Fig. 10. Computer generated 3D layout of ROMAG PROD industrial area (Drobeta Turnu-Severin). Used for SCAI environmental research project.

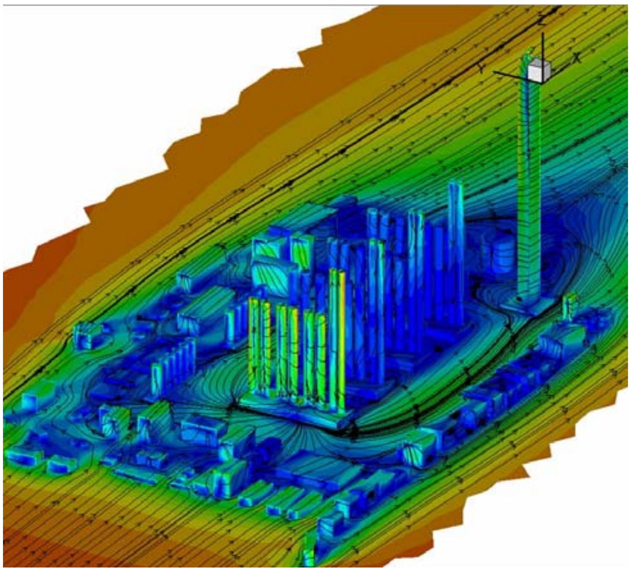

Figure 11. Simulation of air flow over ROMAG PROD industrial area. TECPLOT visualization of Mach stream traces.

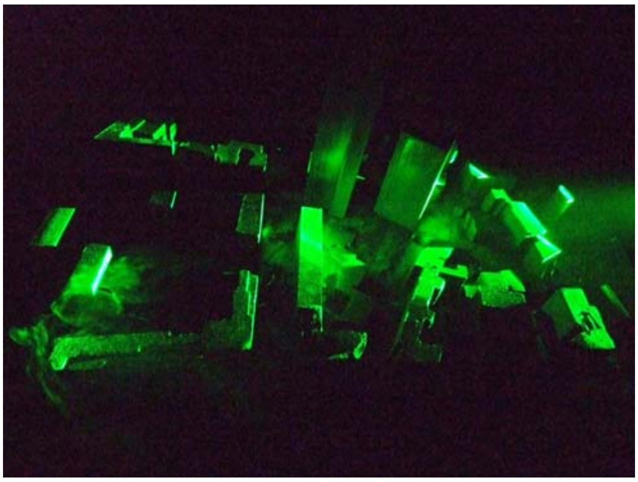

Fig. 12. Experimental visualization performed in the frame of EVICVA project. Visualization was realized with a single laser beam.

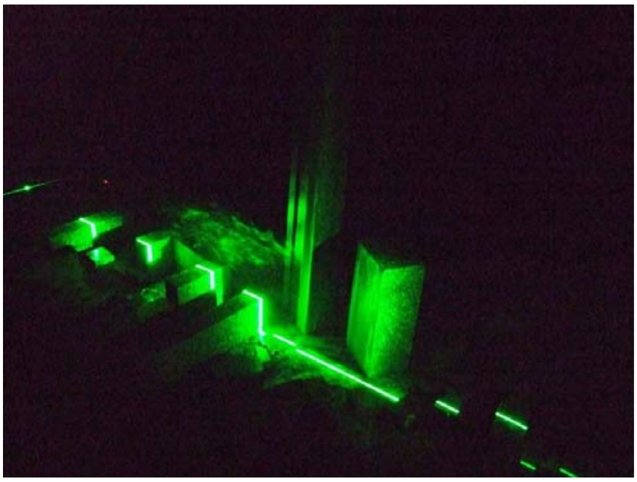

Fig. 13. Experimental visualization performed in the frame of EVICVA project. Visualization was realized with a single laser beam.

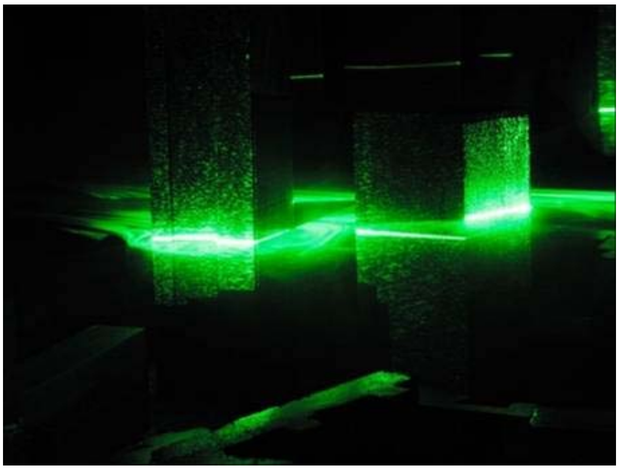

Fig. 14. Experimental visualization performed in the frame of EVICVA project. Visualization was realized with two laser beams.

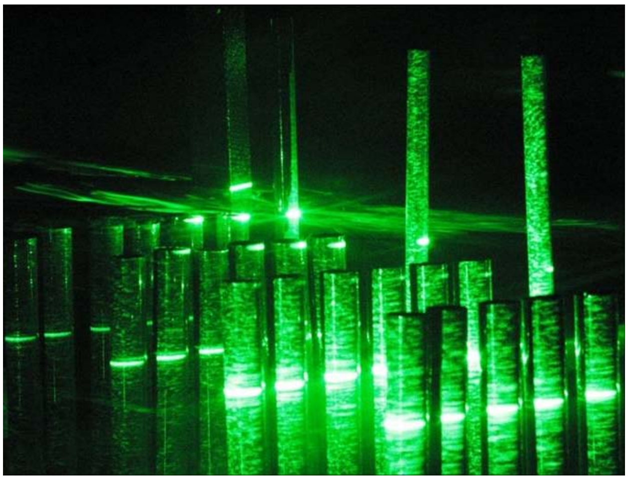

Fig. 15. Experimental visualization performed in the frame of SCAI project. Visualization was realized with two laser beams. (Step 3).

5. Conclusions

Preliminary results obtained in air flow visualization by using laser green light sheet are presented. The presented results are obtained for the first time in Romania. The presented results and the used visualization techniques will be further improved.

Experimental results obtained for the first time in Romania in the field of Wind Engineering and Building Aerodynamics by using green laser light sheet visua-lization techniques are presented.

The obtained experimental and computer simulation results are in good agreement.

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