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# Education Program on Physics and Chemistry for Non-Equilibrium Processes at the Interfaces between Solid-Liquid-Gaseous Media

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**Abstract**

The training on Non-equilibrium processes in allocated areas in physics was primarily developed by Anton Antonov (1934–2021) from 1984–2011. During this time, physics students at the South-West University "Neofit Rilski" in Blagoevgrad were trained.

Oleg Mosin (1966–2016) at Moscow State University of Applied Biotechnology performed the education with a nonequilibrium process in physics and chemistry.

The authors participated in a program for laboratory experiments on non-equilibrium processes. The processes are at the interfaces between solid-liquid-gaseous media. They also participated in scientific research and analysis of non-equilibrium processes under various natural and laboratory conditions. In the laboratory, conditions were created models near to natural environmental conditions.

There are two main directions of study. The first direction involves the analysis of laboratory effects in corona gas discharge at the interfaces of air-solid surface and air-liquid medium-solid surface. The photographic registration method used is called electrophotography. Antonov and co-authors obtained electrophotographic images using a polymerized methacrylate film on a metal substrate rather than a photographic film.

In the second direction, the analysis focuses on the discrete evaporation of water droplets placed on a solid surface inside a hermetic air chamber. The restructuring of hydrogen bonds between water molecules is analyzed.

The obtained spectra are called the Non-equilibrium Energy Spectrum (NES) and the Differential Non-equilibrium Energy Spectrum (DNES).

In the second direction, analyses are conducted using test samples and control samples.

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During the training, students acquire skills in analyzing non-equilibrium media in air-liquid medium-solid surface systems using methods such as infrared spectroscopic analysis, statistical analysis, measurement of electrical parameters of liquids, pH, and oxidation-reduction potential (ORP). Electrochemical studies are conducted on various types of water in accordance with Ordinance No. 9/2001, Official State Gazette, issue 30, and decree No. 178/23.07.2004 of Council of Ministers, Bulgaria, about the quality of water, intended for drinking and household purposes.

**Keywords:** education, physics, Bulgaria, electrical processes, water, electric parameters.

## 1. Introduction

In nature, there are ongoing non-equilibrium processes at the boundaries between solid-liquid-gaseous media (Holzbecher, 2016; Heinze, Bloecher, 2019; Ignatov et al., 2023). Many of these processes involve reactions with polar molecules (Roduner, Radhakrishnan, 2016). In the physics and biophysics training program, the study of effects in non-equilibrium systems is achieved by examining samples and control samples.

Particularly valuable are the studies and analyses related to processes at boundary media concerning carbon emissions and global warming. Calcium carbonate ($CaCO_3$) undergoes processes influenced by natural factors such as temperature, humidity, and phase transitions. The possible process for the origin of life was described for water with calcium carbonate, Rupite, Bulgaria (Ignatov, 1999).

The Differential Non-equilibrium Energy Spectrum (DNES) is a method with studies in carbon emissions and global warming used to assess the structural changes in water resulting from environmental influences. This method assumes that factors other than the one under examination have an identical combined influence on the control and the analyzed sample. The NES and DNES spectral studies cover a range of wavelengths ($\lambda$) from 8 to 14 μm and wave numbers ($\tilde{\nu}$) from 1250 to 714 $cm^{-1}$. Within this range, the absorption and reflection of water exhibit the highest degree of polarization of infrared radiation, typically ranging from approximately 4 % to 10 % (Shaw, 1999).

To evaluate non-equilibrium conditions involving $CaCO_3$, several factors were analyzed, including the effects of cave water (Antonov, 1995), gas-solid heat exchange (Galvan, Hernandez, 2009), the development of $CO_2$ capture technologies, and the utilization of strategies to reduce anthropogenic emissions as part of solutions to combat climate change), and global dioxide emissions (Ozekmekci, Copur, 2021).

NES and DNES spectroscopy indicate changes in water structure resulting from an impact, assuming that the overall influence of all other factors except the examined impact is the same for the control and sample samples (Antonov, 1995).

NES and DNES methods are used for studies under dynamic natural conditions, such as water phase transitions (Todorov et al., 2010), solar eclipses (Ignatov et al., 2023), and mountain (Todorov et al., 2008; Boteva et al., 2013), glacier (Ignatov, Valcheva, 2023), mineral (Ignatov et al., 2021), and sea waters (Mehandjiev et al., 2023).

The Bulgarian scientist Nadjakov discovered sulfur photoconduction effects in 1937 and published a paper for photoelectrets. The practical application of photoelectrets is a photocopier. A few years later, Carlson developed electrophotographic copying called xerography.

In 1961 Antonov and Zadorozhniy researched with Nadjakov on the polarization effects of photoelectrets (Nadjakov et al., 1961).

In 1930, Carlson invented electrophotographic copying, which is called xerography.

Since 1960 Fridkin, Golovin, Antonov, and co-authors developed electrophotographic methods to register images (Golovin et al., 1960). Fridkin is recognized as the inventor of xerography in the former USSR.

Students are introduced to various image registration methods of coronal gas discharge laboratory conditions. The method was categorized as an electrophotographic method. There were calculations with a low of Schaffert (Schaffert et al., 1965)

The training methodology includes laboratory exercises, and the obtained experimental results are analyzed.

The training aims to enhance the student's creative process in developing working hypotheses, reference analyses, construction of laboratory experiments, analysis of results, and practical applications.

The authors educate the laboratory results and analyses in Bulgarian and English with methodology development (Ramankulov et al., 2019).

Q-methodology, a reliable method that takes individuals' unique perspectives, was employed to determine students' opinions and perceptions (Servet, 2016).

One of the co-authors, Ignatov, performed training with students in secondary schools in Teteven municipality, Bulgaria, with practices for the research of mountain water and digital methods (Soboleva, Karabaev, 2020; Soboleva et al., 2020).

In the modern world, the improvement of the methods for online education is necessary. The online learning environment by changing the students' behavior improves the quality of the education process (Delen, Liew, 2016).

Water processes in the environment are an object of education.

University students' education was applied to mobile phones (Valeeva et al., 2019).

The basic aim is to make connections for practical applications of the knowledge from physics and chemistry for the processes in the environment for clean water, global warming, and processes of the interfaces between solid-liquid-gaseous media. Especially the students have also qualifications for non-equilibrium processes with application in ecology.

## 2. Materials and methods

### 2.1. Educational practices and specializations

During the training, network modeling is also applied. Interdisciplinary dependencies are established between results and analyses in the natural sciences (Ignatov, 1989; Traxler, 2022).

The municipality of Teteven, Bulgaria, and Ignatov are co-organizers of the event with training "Days of Mountain Water". The event has been organized since 2010, each year on June 11th. (Athanasiadis et al., 2023)

Gramatikov is author of book Physics, South-West University "Neofit Rilski", Blagoevgrad.

Gramatikov participates in the project: Joint supervision of Ph.D. students in Physics.

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Funding organization: Karaganda State University "E.A. Buketov" (KSU), Kazakhstan.

Period: 2014–2019.

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### 2.2. Device for spectral analyses with methods NES and DNES

The energy (E) of hydrogen bonds among $H_2O$ molecules in water samples is measured in eV. The function f(E) is called the energy distribution spectrum. A non-equilibrium evaporation process of water droplets characterizes the energy spectrum of water. This non-equilibrium energy spectrum (NES) is measured in $eV^{-1}$. DNES is defined as the difference:

$$\Delta f(E)=f(\text{water sample}) - f(\text{control sample}) \quad (1)$$

DNES is measured in $eV^{-1}$ where f (*) denotes the evaluated energy.

The scheme of the device is shown in Figure 2.

The wetting angle θ was measured with a specially designed instrument which is described in detail (Antonov, 1995; Todorova, Antonov, 2000). Evaporation of water drops was performed in a sealed chamber with a stable temperature of 22°C and humidity of 65-70 % (Figure 1). The drops were placed on a 350 μm thick BoPET (biaxially-oriented polyethylene terephthalate) sheet.

The wetting angle θ is a function of a and $d_1$.

The device has the following technical features:

- Monochromatic filter with wavelength λ = 580 ± 7 nm;
- Water evaporation angle ranging from 72.3 deg to 0 deg.

Measured range of energy of hydrogen bonds among water molecules is λ = 8.9 ÷13.8 μm or E = (-0.08) ÷ (-0.1387) eV.

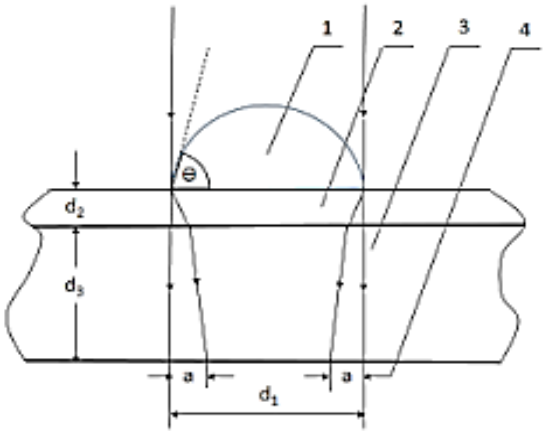


**Fig. 1.** Operating principle of the method for measuring the wetting angle of liquid drops on a hard surface: 1 – drop, 2 – thin Maylar sheet, 3 – glass plate, 4 – refraction ring width

### 2.3. Device for electrophotographic registration with device for coronal electric discharge

An extensive investigation was conducted on gas discharge emission for color coronal spectra within a controlled dark room environment. The emission was captured using photosensitive paper or color film, carefully positioned on a transparent Hostaphan electrode with a diameter of 87 mm. The electrode was filled with a conductive liquid comprising a 1 % NaCl solution in deionized water. Pulses with 12 kV voltage and a carrier frequency of 15 kHz were applied between the objects and the electrode copper coating.

Figure 2 shows the scheme of the device.

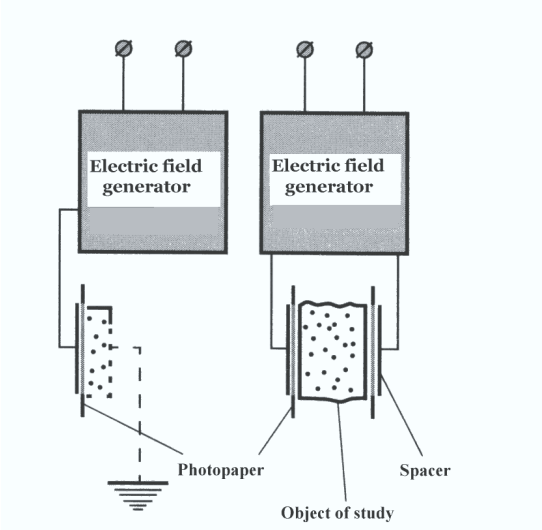


**Fig. 2.** Functional scheme of the gas corona discharge device

A corona gas discharge was produced within the gap between the investigated objects and the transparent electrode, resulting in a distinct glow surrounding the contact area. This discharge emitted electromagnetic waves within the wavelength ranges of 380–495 and 570–750±5 nm, which illuminated the respective photosensitive material based on the specific properties of the objects.

### 2.4. Statistical analyses

Statistical analyses are performed based on the working hypothesis and the available data. Student's t-test and Mann-Whitney U test are commonly applied. Students are trained to create computer programs for conducting t-tests.

## 3. Discussion

During the training on non-equilibrium processes between boundary media, air-water-solid or air-land, students acquire the following skills:

1. A complementary approach to scientific and applied physics, chemistry, biology, and medicine activities.
2. Knowledge of processes in non-equilibrium boundary media such as air-water-solid or air-land enables successful work in ecology.
3. Analyses of boundary media processes are particularly valuable for carbon emissions and global warming activities.
4. Spectral methods for studying water and its physicochemical composition are applicable in investigating acid rain and water filtration possibilities.
5. Conduct experiments and analyses of methods for alternative energy sources such as solar panels, osmosis diffusion, and batteries.
6. Experiments with electrophotography using corona discharge allow for image analysis skills. One of the collaborators, Iliev, works with a 3D printer to obtain images (Dankov et al., 2023).
7. Analyzing data from laboratory exercises enables work in scientific institutes and production companies.
8. Skills in structuring and implementing scientific-applied projects are acquired.
9. Skills in innovation, organization, and meeting deadlines for teamwork are developed.

## 4. Results

Training Program for Non-Equilibrium Processes

### 4.1. Measurement of IR Spectra of Water Using NES and DNES Methods

Measurements are conducted on samples and control samples of water and 1 % solutions of inorganic compounds and natural waters (Gramatikov et al., 1992, Todorov et al., 2008; Mehandjiev et al., 2023). The studies were made for medicinal plants (Ignatov et al., 2022). Students and doctoral students perform analyses as follows:

Using the NES method, analyses are conducted on various types of water-tap, mountain spring water, glacier water, mineral, and seawater.

The parameters after filtration with zeolite (Popova et al., 2022) and shungite (Ignatov et al., 2022) were studied.

The training shows the sizes of non-organic chemical particles. The size of the water molecule is 0.27 nm.

Analyses are performed based on the physicochemical composition of peaks in the NES spectra.

Calculations are made using Oxidation-Reduction Potential (ORP) and pH formulas to determine the presence of free electrons, positive ions, $H^+$ ions, and hydroxyl groups ($OH^-$).

A comprehensive analysis of the properties of the examined waters is conducted.

When studying with filtering systems, analyses are conducted using the DNES method on control samples before and after filtration. DNES is obtained by comparing the NES of samples and control samples. Statistical analysis demonstrates the reliability of the results.

The analysis is performed on the energy distribution between hydrogen bonds in water molecules.

Luck considers that in water, hydrogen bonds exist between one water molecule's hydrogen atom and another's (Luck, 1980). Most of them are bound by the energy of the connection (-E), and the remaining are free (E = 0). It is accepted that E has a negative value. This is known as Luck's two-state model.

A model was described with the Gaussian distribution of water molecules in clusters. This model corresponds with the results with NES and DNES spectrums (Mehandjiev et al., 2022).

The students have a task to make analyses with Gaussian distribution of the behavior of water molecules and estimation of the size of water clusters. The size of a dodecahedral cluster with 21 water molecules is 0.822 nm (Ignatov et al., 2021).

### 4.2. Electrophotographic Registration

The following directions are in the studies with electrophotographic registration.

1. Electrophotographic methods for image registration.
2. Fundamental schemes of xerography and the development of xerographic methods.
3. Antonov's experiments with electrophotography and electrographic copying of images.

4. Parameters of photographic films in corona discharge. Registration with black-and-white photographic films (Antonov, Yuskesselieva, 1968; Ignatov et al., 1998). Registration with color photographic films (Ignatov, 2007).

The coronal gas discharge effect (Pehek, 1976) is connected with dielectric permittivity, not electric conductivity (Antonov, 1995). The wavelength ranges for color coronal gas discharge effects are 380–495 and 570–750±5 nm (Ignatov et al., 2021; Ignatov et al., 2025)

**4.3. Comprehensive Application of Electrophotographic Methods and Spectral Analyses using NES and DNES, pH, ORP, and Conductivity in Water and Solution Studies**

During the training, investigations are conducted on water samples due to the applied treatment and control samples. The following calculations are performed for both samples: the wavelength λ in nm, the energy of the emitted photons E in eV, and the photon emission per cm2 from the water droplet base. The students are tasked with calculating the effective power of the electrical parameters for obtaining photon emission from the water droplet. The difference between the sample and the control sample provides information about the dielectric permeability. Electrical conductivity is measured in μS/cm, oxidation-reduction potential (ORP) in mV, and pH.

The statistical Mann-Whitney U test is applied for smaller measurements, while the t-test of Student is used for a more significant number.

One of the co-authors, Iliev, developed in the Faculty of Physics, Sofia University methods for the research of dialectical parameters (Iliev et al., 2012, Koduru et al., 2016).

**4.4. Training for the process with calcium carbonate of global warming**

The following reaction is valid:

$2HCO_3^- + Ca^{2+} \rightarrow CaCO_3 + CO_2 + H_2O$ (2)

The lime cycle is

$CaCO_3 \rightarrow CaO \rightarrow Ca(OH)_2 \rightarrow CaCO_3$ (3)

The chemical reaction (2) is a significant emitter of global dioxide emissions (Bian et al., 2022).

With the research of 713 and in the range 873 ÷ 879 $cm^{-1}$ is possible to estimate the influence on the environment and select the optimal value for the industry.

Developing $CO_2$ capture and using technologies to reduce anthropogenic emissions can be part of the solution against climate change (Ozekmekci, Copur, 2021).

**4.5. Visualization of the Gaussian distribution and mathematical modeling of hydrogen bonds between water molecules and structuring of clusters**

The authors create with spectral methods NES and DNES mathematical models of clusters of water molecules (Ignatov, Mosin, 2014; Ignatov et al., 2021). Also, the cluster calculation was performed with the model of the Gaussian distribution of water molecules (Mehandjiev et al., 2022).

The visualization of the structuring of water molecules makes education more attractive and visible for the students.

For the period 2013-2023, 82 students were tested. The main questions were:

1. Estimate the mathematical models of water molecules with tables.
2. Estimate the mathematical models with figures.

Table 1 illustrates the results with models of water molecules.

**Table 1.** Questions for the education with models of water molecules

| Which model is more understated for you? | | |
|---|---|---|
| With tables | 7 | 8.5 % |
| With figures | 75 | 91.5 % |

The results are similar to the results of the visualization method (Fuchova, Korenova, 2019) for the parts of the human brain.

The results with visualization are more extensive than 90 %.

The education with visualization is for the processes which are not directly visible with the human visual analyzer.

Table 2 shows the distribution of numbers of water molecules according to the energy of hydrogen bonds per each 100 water molecules in the bulk volume of water after the electrolysis process and control water (Ignatov et al., 2021)

**Table 2**. Distribution of numbers of water molecules according to the energy of hydrogen bonds per each 100 water molecules in the bulk volume of water after the electrolysis process and control water

| -E(eV) | Water sample | Control water sample | -E(eV) | Water sample | Control water sample |
|---|---|---|---|---|---|
| 0.0937 | 0 | 8 | 0.1187 | 0 | 5 |
| 0.0962 | 0 | 6 | 0.1212 | 9 | 2 |
| 0.0987 | 0 | 2 | 0.1237 | 0 | 7 |
| 0.1012 | 1 | 4 | 0.1262 | 9 | 2 |
| 0.1037 | 10 | 4 | 0.1287 | 11 | 5 |
| 0.1062 | 4 | 4 | 0.1312 | 11 | 7 |
| 0.1087 | 3 | 10 | 0.1337 | 0 | 8 |
| 0.1112 | 4 | 6 | 0.1362 | 10 | 1 |
| 0.1137 | 6 | 9 | 0.1387 | 20 | 2 |
| 0.1162 | 2 | 8 | – | – | – |

Figure 3 shows the dodecahedral cluster with 20 water molecules at E=-0.1387 eV; (λ = 8.95 μm); ($\tilde{\nu}$ = 1117 $cm^{-1}$) (Ignatov et al., 2021)

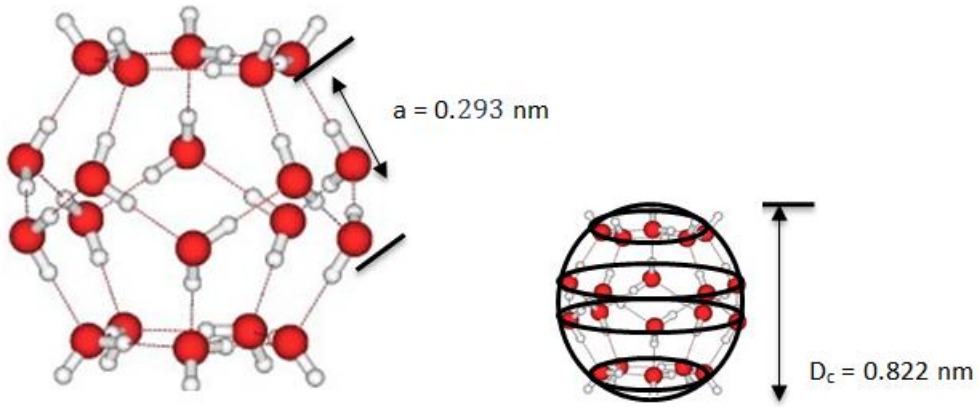


**Fig. 3.** Dodecahedral cluster with 20 water molecules at E=-0.1387 eV(λ = 8.95 μm)($\tilde{\nu}$ = 1117 $cm^{-1}$)

In 2013 Ignatov and Mosin published the life spans of water molecules and clusters. The achievement was cited in 2021 in the journal Scientific Reports (Nature Publishing Group) from (Gao, Fang, Ni, 2021). Water clusters are short-lived and flickering, with life spans estimated from $10^{-10}$ to $10^{-11}$ s and water molecules of $10^{-10}$ to $10^{-11}$ s.

The new calculations are connected with the Gaussian distribution of water molecules.

**4. 6. Visualization of corona gas discharge effects with electrography**

The research was done with electrophotographic registration of water drops from tap water in Sofia, Bulgaria (Ignatov, 2007). The results are connected with dielectric permittivity. Figure 4 illustrates the coronal electric effect or water drop from tap water.

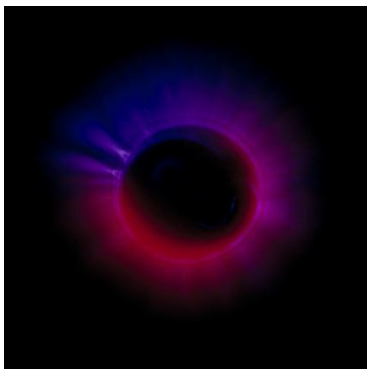

**Fig. 4**. Coronal electric effect or water drop from tap water

For the period 2013–2023, 82 students were tested.

The average results in the coronal electric discharge are – red (1.82), blue (2.64), and violet color (3.03) eV.

The main questions were:

1. Estimate the photon emission of corona electric effects of water drops from the tables with the values of the colors.
2. Estimate of photon emission of corona electric effects with results from water drops.

Table 3 illustrates the results.

**Table 3.** Questions for education with models of coronal electric emission

| Which model is more understated for you? | | |
|---|---|---|
| With tables | 3 | 3.7 % |
| With images | 79 | 96.3 % |

**4.7. Visualization of electrical parameters of water with osmosis diffusion between sea and river waters.**

The experiments were performed with a device for osmosis and diffusion. The patented ceramic element is with sea water or a solution of NaCl, and the Becher glass is with river water or deionized water (Mehandjiev et al., 2023) (Figure 5).

The direction of osmosis is from the Becher glass to the ceramic element. The direction of the diffusion is from the ceramic element.

The electric current results from the electrical charges – $Na^+$, $H^+$, $Cl^-$ ions.

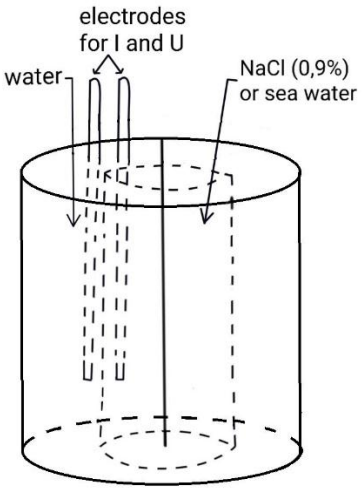


**Fig. 5.** Device for osmosis/diffusion

The main questions were:

1. Estimate the electrical process in osmosis/diffusion from the tables with the values of the colors.
2. Estimate of the electrical process in osmosis/diffusion from laboratory device.

Table 4 illustrates the results

**Table 4.** Questions for the education with process in osmosis/diffusion

| Which model is more understated for you? | | |
|---|---|---|
| With tables | 9 | 11.0 % |
| With images | 73 | 89.0 % |

Mann-Whitney U test was applied with the results from Tables 1, 3, and 4.

The results of group A are: 7, 3, 9.

The results of group B are: 75, 79, 73.

Based on the calculated U values:

$U_1 = 9$ for Group A.

$U_2 = 0$ for Group B.

Since U1 is more significant than U2 ($9 > 0$), it indicates that Group A has a higher rank sum than Group B. However, we need to know the critical U value or the significance level to determine whether this difference is statistically significant or due to random chance.

In summary, the Mann-Whitney U test results suggest that Group A has a higher rank sum than Group B.

The Mann-Whitney U test revealed a statistically significant difference between Group A and Group B ($p < 0.001$).

Education in physics and chemistry is complementary (Rodach et al., 2018; Gruzina et al., 2020) and has different applications and natural sciences, industry, sport, agriculture, and veterinary medicine. This education develops statistical methods for comparing different scientific results (Sidorov et al., 2018). One of the applications is modeling the water processes with acid rain (Popova et al., 2019).

## 5. Conclusion

Antonov created a training program on non-equilibrium processes in physics from 1984 to 2011. The program aimed to train physics students at the South-West University "Neofit Rilski" in Blagoevgrad. The program with students included laboratory experiments and scientific research on non-equilibrium processes at the interfaces of solid-liquid-gaseous media. Two main directions of study were pursued. The first involved the analysis of corona gas discharge effects at the interfaces of air-solid surface and air-liquid medium-solid surface using electrophotography. The second direction focused on the discrete evaporation of water droplets on a solid surface within a hermetic air chamber, analyzing the restructuring of hydrogen bonds between water molecules. Spectral studies used Non-equilibrium energy spectrum (NES) and Differential non-equilibrium energy spectrum (DNES) methods. The training also covered interdisciplinary dependencies in the natural sciences – physics, chemistry, biology, and medicine. They gained knowledge of processes in non-equilibrium boundary media, allowing for work in ecology. Analyses of boundary media processes were particularly valuable for carbon emissions and global warming studies. Various methods, such as infrared spectroscopic analysis, statistical analysis, and measurement of electrical parameters, pH, and oxidation-reduction potential (ORP), were used to analyze non-equilibrium media in air-liquid medium-solid surface systems. The training emphasized the importance of analyzing water's physicochemical composition for studies on acid rain, water filtration, and other applications. Students conducted experiments and analyses on alternative energy sources like solar panels, osmosis diffusion, and batteries. They also gained image analysis skills through electrophotography experiments using corona discharge and explored data analysis in laboratory exercises.

In conclusion, the training program on non-equilibrium processes fostered students' abilities in scientific analysis, interdisciplinary thinking, and practical applications. The comprehensive approach enabled them to understand and address complex phenomena related to non-equilibrium processes in various media. The acquired skills and knowledge are applied to scientific institutes, production companies, and environmental research. The training program provided a foundation for innovative

and collaborative work, encouraging students to contribute to scientific advancements and address contemporary challenges, including climate change and environmental sustainability.

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This research received no external funding.

**7. Competing interests**
The authors declare no competing interests.

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