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EXTENDED ABSTRACT
Ph. D. THESIS

Improved efficiency in corona condensation reactors with controlled field

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Chapter 1.Introduction

Water condensation is a natural phenomenon by which, under certain conditions, water molecules in the form of vapours in the air regroup and become the most widespread liquid on the globe: water.

The improvement of this thermodynamic phenomenon caught the attention of researchers for the following reasons:

1. The need to produce precipitation in arid areas.
2. Improving the yield of energy production processes with phase transformation.
3. Reducing the energy consumption of air drying installations.
4. Extraction of water from the atmosphere or desalination processes, both with the aim of obtaining drinking water.

On a large scale, condensing installations based on reducing the temperature of a mixture of gases and vapours use cooling systems with or without cold pumps. In general, the economic impact of such systems is less obvious if they are part of an energy production (electricity) assembly. However, in most applications, the reduction of humidity or the condensation of water, depending on the desired result, is implemented with the help of cold pumps. Sometimes hydrophobic filters are additionally used, which improve the efficiency of the systems to a certain extent. Increasing the efficiency of an installation of this type is certainly a desirable thing considering that the operation of heat pumps is generally electric and their energy consumption is high.

Regarding the physical mechanisms of water vapour condensation such as: increasing the vapour pressure towards the saturation value, reducing the temperature towards the "dew point", using hydrophobic filters or their combinations, there are other methods that can make this phase transformation more efficient.

1.1. Presentation of the doctoral thesis domain

Some of the studies carried out on the condensation process focused on influencing the thermodynamic process of water condensation with the help of electric fields, artificially created charge carriers or various types of ionizing radiation. The starting point of these studies is the Kelvin expression of saturated vapours pressure.

Substantial changes were made to the initial expression by adding additional parameters such as the presence of electric charges or electric field.

The study of the paper will use an oscillating electric field with variable frequency, but without changing the polarity. This special approach aims at the simultaneous application of a variable Colombian force in time and a force of the same nature but constant.

By composing these vectors is suspected that will be obtained an combination of the effects of the electric field types previously used in other works.

On the other hand, by using an electric field with variable frequency in search of a possible resonance of the specific phenomena within the condensation, it has not been studied. Most of the studies that use alternating electric field have the frequency of 50Hz, the industrial one. The use of a much higher and adjustable frequency can highlight possible particular behaviours, which once identified can create the basis for new studies in this scope.

1.2. Scope of the doctoral thesis

The general concern related to increasing the yield of thermodynamic processes is fuelled both by the new technologies available for research and by the current possibilities of an interdisciplinary approach to physics phenomena.

The purpose of this thesis is to refine some of the experimental methods that are the basis of studies of this type. The main sources that can generate measurement errors and can lead to wrong interpretations have been studied. Obtaining results that faithfully present the phase change phenomenon involves identifying the sources of uncertainty and eliminating them.

Carrying out a study using an electric field with oscillating intensity could be an element of novelty in the field. Also, the conditions under which the condensation phenomenon takes place must be monitored and stabilized as much as possible, considering that the transformation in question is of an exothermic nature and any change, no matter how small, can have unwanted effects on the results and their interpretation.

1.3. Content of the doctoral thesis

This work includes four chapters whose content is structured as follows:

The **first chapter** presents general aspects related to the condensation transformation and the applications in which this phenomenon is most often used.

Chapter 2 includes an overview of the thermodynamic process of condensation. The transformation will be analysed for the situation in which it takes place in the presence of some ion species and an intense electric field.

The experimental installation used will be presented in **Chapter 3** together with the explanations necessary to understand its operation. The two elements will be presented, the installation for the study of the condensation phenomenon and the high voltage source made for this study.

Chapter 4 will present the experimental results obtained with the previously presented installation and they will be analysed separately for each of the chosen conditions. Conclusions on the results will be presented for each of the particular situations studied. In the end, general conclusions related to the entire chain of experimental results will be expressed, as well as the contribution of the method used compared to the previous results studied.

Chapter 2. Theory of water molecules condensation process

The condensation process can be defined as a sequence of well-defined events whose order of development is always the same. The first step in the condensation process is nucleation. Nucleation is defined as the process by which at least two water molecules constitute a micro droplet of liquid water. This process takes place either in the presence of a foreign body or in the presence of another water molecule. If a foreign body is involved in the process, the element formed is called a nucleation bud. It will serve to continue the condensation process to form the micro drop of water by accumulating new molecules.

In the condensation process, considering that the vapours state represents a mixture of gases and water, it can be stated that for this phase the behaviour of the main state parameters obeys the typical gas equation. For the analytical expression of the phase change phenomenon, one of the most used methods for analysing the phenomenon is based on the Gibbs-Thomson equation [1 - 4].

2.1. Nucleation of water vapour

The vapours of a substance can condense through two distinct types of nucleation. Homogeneous nucleation implies the exclusion of any foreign elements that can constitute condensation buds so that the process takes place only through the contribution of the elements of the substance that changes its phase. In general, condensation by homogeneous nucleation takes place in the case of gas liquefaction and generally involves the use of an adiabatic thermodynamic transformation.

In particular, the condensation of water vapour presupposes, among other conditions, the coexistence of the two phases of water. Given that the state parameters are common to the two phases, the transformation takes place in one direction or the other depending on the vapor pressure. In the situation where the water vapour density exceeds the saturated vapour pressure limit, the phenomenon of nucleation and condensation occurs. For a micro droplet of radius r (considering it to be a sphere, the geometric shape with the minimum surface area for the given volume) the energy used for formation [5 - 7] will be:

$$\Delta G = 4\pi r^2 \sigma - \frac{4}{3}\pi r^3 nkT \ln \frac{p_v}{p_s}, \quad (1)$$

2.2. Heterogeneous nucleation in the presence of electrical charges

Considering that the nucleation phenomenon is part of a chain of vaporization-condensation processes that takes place permanently, the presence of micro-droplets formed around some ions will need a higher energy for vaporization than if they were neutral. This hypothesis created the premise that the presence of ions changes the vaporization-condensation process ratio in favour of condensation by changing the Gibbs energy of vaporization. Knowing the distance of the hydrogen bonds d_H = 1.88Å, the intensity of the electric field in the bond is $4.074 \cdot 10^{10}$ V/m, comparable to the intensity of the field exerted by a nearby nitrogen ion on a water molecule. As a result, a formation of an ion-dipole bond is plausible under these conditions.

The research carried out in this regard brings a new term, which explains the reduction of the vapour super saturation ratio at a certain temperature, in the presence of some ion species [8 - 9] and the proposed equation was called the "modified Kelvin-Thomson equation".

By increasing the total charge by an ion, Q_{ion}, or reducing the radius of the drop thus formed, the S_p ratio will be altered. Thus, the above relationship indicates that the presence of ions favour nucleation and reduces the rate of water vaporization.

To calculate the Gibbs free energy for a micro-droplet with n hydrogen bonds formed around an ion of radius r_0 the relationship of the modified Kelvin-Thomson equation is:

$$\Delta G_{0,n}^{dipol} = \Delta G_{0,n}^{dipol+Q} - \sum_{n=1}^{n} \Delta U = -nkT \cdot ln\left(\frac{p_v}{p_s}\right) + \sigma 4\pi(r_n^2 - r_0^2) - \frac{e^2}{8\pi\varepsilon_0}\left(1 - \frac{1}{\varepsilon_L}\right) \cdot \left(\frac{1}{r_0} - \frac{1}{r_n}\right) - \sum_{n=1}^{n} \left\{ \frac{1}{2}\alpha {E_{ion}}_{n-1}^{2} - kT \cdot ln\left[\frac{exp\left(\frac{pE_{ion_{n-1}}}{kT}\right) - exp\left(-\frac{pE_{ion_{n-1}}}{kT}\right)}{2\frac{pE_{ion_{n-1}}}{kT}} \right] \right\}. \quad (2)$$

In the right-hand side of the equation, the first term expresses the free energy variation due to vapour super saturation, the next term is the mechanical work required to change the area of the micro-droplet, the third term represents the change in the potential energy of the ion involved in the process, change due to the appearance of a dielectric film.

The last term of the equation shows the energy change associated with the interaction between the ion and the dipole molecules.

According to the studies carried out on an experimental basis on the veracity of the modified Kelvin-Thomson equation, results were found and documented regarding the behaviour of several types of molecules that present a dipole moment. Structures such as H2O, NH3, CH3OH and C5H5N were studied experimentally and differences were found

between the measured enthalpy and entropy values and those calculated according to the classic Kelvin-Thomson equation (abbreviated name CKT) [8].

In conclusion, considering the above, the nucleation mechanism will have a modified condensation-vaporization ratio. In the presence of charge carriers, the molecules will form micro droplets more easily and at the same time they will vaporize more difficult, than in their absence.

2.3. The effect of dielectrophoretic force on water molecules

An electric field of considerable intensity applied in an environment such as that formed by a mixture of air and water vapour can generate effects in the form of displacement or rotation of particles.

If the electric field is uniform with parallel field lines, only the particles charged with electric charge will move according to the sign of the charge they have and this under the action of a Colombian force.

If the electric field is non-uniform, each particle in the area of the field lines will have its surface exposed differently, corresponding to the electrodes.

Respectively, the surface facing the negative potential will be larger compared to the surface exposed to the positive potential. There will thus be an imbalance in the application of the Columbian force on the particle. The effect is commonly called dielectrophoresis and is widely used in the separation of particles with different dielectric properties than the medium in which they are found [10].

Needle-plane or wire-cylinder electrode systems generate such a divergent electric field.

The direction of the resulting dielectrophoretic force is dependent on the relative polarizability of the particle relative to that of the medium in which it is found as follows: if the polarizability of the particle is greater than that of the medium, the force is applied to the particle and directed towards the positive field-generating electrode (positive dielectrophoresis), if the polarizability of the medium is greater than that of the particle, the force will be applied to the medium and push the particle towards the electrode.

The resulting force is easily observable as an effect in the case of very small particles with a diameter of 1-1000μm because in their case gravity as well as Brownian forces have a negligible influence compared to the influence of the electric field [5 – 7, 11].

For a polarizable particle of radius r and dielectric permittivity ε_p in a medium with dielectric permittivity ε_m, the force applied to the particle can be expressed as:

$$\vec{F}_{\text{dep}} = 2\pi r^3 \varepsilon_{\text{m}} R_e \left\{\frac{\varepsilon_{\text{p}} - \varepsilon_{\text{m}}}{\varepsilon_{\text{p}} + 2\varepsilon_{\text{m}}}\right\} \nabla \left|\vec{E}\right| , \tag{3}$$

where R_e is the Reynolds number.

If the polarizability of the particle is greater than that of the environment, then the force applied to the particle will push the particle to the area with higher charge density and therefore with a more intense field, and this will happen in the case of water.

Chapter 3. Experimental setup

The present work studies the effect of the electric field in moist air on the rate of nucleation and condensation in the liquid phase of water vapour and is investigated both theoretically and experimentally by implementing a steam condenser with an improved phase change rate as well as by using an electric field with variable intensity over time.

A first objective of the conducted study aims at the most accurate quantitative assessment of how the intense electric field and corona discharges influence the condensation phenomenon. In order to achieve this objective, it was necessary to implement an evaluation system that consists in measuring the humidity of an air stream at ambient temperature before and after condensation.

Thus, an installation was made that produces and directs a flow of humid air to a condensation system at a constant speed. Carrying out experiments with the help of the created installation is a complex process, involving variables that depend on the environment in which the experiments are carried out. In order to control the parameters that can influence the experimental study, a working procedure was established, aiming to establish the parameters of relative humidity and ambient temperature with the help of an air conditioning system (air conditioning).

The preliminary tests carried out during the construction of the installation focused on the influence of the paths through which the humidified air is conducted, the size of the tubes, the shape and the materials used, following their influence on the humidity inside the condensation system [12 – 14]. The study on the condensation process highlighted the fact that "parasitic" condensation processes can appear in some segments of the installation and become sources of uncertainty in the determinations.

Starting from the thermodynamic aspects of the condensation phenomenon and taking into account the materials of other research in this field, a study method was identified that includes originality, construction elements and methods different from those used previously.

Thus, for experimentation, a source of water vapour generation by atomization was used, which allows obtaining a mixture of air, micro droplets and water vapour at ambient temperature in favour of obtaining them by boiling.

This approach excluded any parasitic condensation that could have developed along the path of the humid air flow management system caused by large temperature differences. These could have given rise to errors in the measurement or interpretation of the result.

On the other hand, in order to obtain the most faithful results on the studied phenomenon, an experiment and measurement method adapted to the used installation was developed.

The experimental installation was tested in several conditions, the efficiency of using such a condensation principle being also observed by reducing the humidity of a humidified air mixture at saturation (thick fog) to normal humidity values.

3.1. Condensation reactor

Being the central element of the experimental installation, the proposed condensation reactor presents distinct technical-functional characteristics compared to other methods used in previous studies.

From the electrical point of view, a simplified construction was approached, namely a wire-cylinder system that allows the use of an intense electric field, presents a minimum electrical capacity and allows a laminar flow of the moist air mixture.

The condensation reactor is sketched and described in figure 4, together with its main elements.

The main element of the condensing system is the cold cylinder, made of good thermally and electrically conductive stainless material (figure 4, detail "A", figure 5, detail "A") with a length of 214 mm and an inner diameter of 48 mm. Its role in the experimental installation is twofold: both as an electrode with zero potential in creating the electric field and as an element to retain and condense the vapors that come into contact with it.

In order to collect the condensation formed in this cylinder and for the phenomenon to occur in the first instance, the temperature of the cylinder must be lower (or at least equal) than the dew point temperature for the conditions in which the experiment is carried out. Obtaining this cylinder temperature was possible by implementing a cooling system figure 4, detail "C" that uses a liquid thermal agent (figure 4, detail "G") circulating on the outer surface of the cylinder.

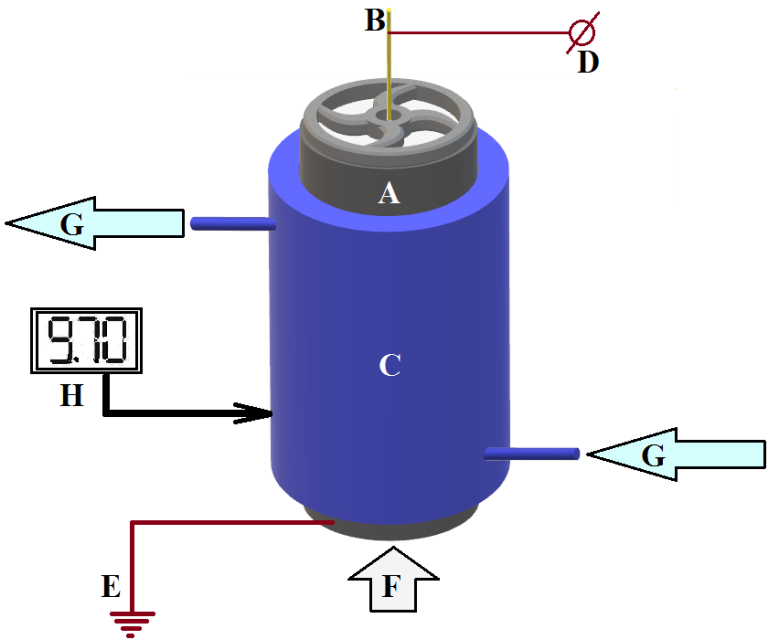


Figure 4. Scheme of the condensation reactor. A – metallic cylinder, B – corona discharge electrode; C – cooling system; D – high voltage connection; E – earth connection; F – humidified air inlet; G – thermal cooling agent.

The corona discharge wire (figure 4, detail "B") made of conductor with a diameter of 75 µm, fixed on insulating supports is arranged centrally and along the entire height of the

cylinder. In the upper part of the cylinder by means of an externally accessible electric terminal (figure 4, detail "D" and figure 8, detail "I"), an electric potential can be applied to the corona discharge wire. To create the desired electric field the cylinder is connected with a conductor (figure 4, detail "E") at zero potential by means of a metal sleeve with the connecting terminal.

Through the interior of the cylinder, in an upward direction, the humidified air mixture subjected to the experiment is led (figure 4, detail "F").

The electrical scheme used to feed the condensation reactor is shown in figure 5. Also in this figure, the layout of the electric field lines is sketched considering a sectional view of the condensation reactor.

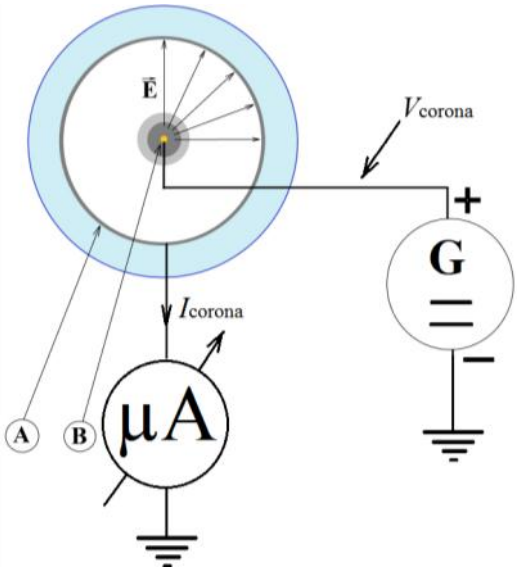


Figure 5. Electrical diagram of the condensing reactor cylinder, the cylinder is seen in section.

The discharge electrode "B" is positioned at a distance of 10mm in relation to the edges of the cylinder "A" so that the electric field formed inside the cylinder does not exceed the temperature controlled zone.

In order to draw the I-V characteristic of the corona discharge that takes place in the condensation reactor, the electrical diagram in figure 5 was used. Using three values of the relative humidity of the air, the graphs in figures 6 and 7 were drawn, separately for negative and positive corona discharge respectively.

From the presented characteristics, it can be observed that, in the case of negative corona discharge, the established currents are higher than in the case of positive corona. It is also obvious the similar characteristic in both cases as well as the fact that the dispersion of values in relation to air humidity is reduced, the family of characteristics obtained are roughly overlapping. The thermal power dissipated by the joule effect appeared under the action of the discharge current in the two cases falls between 4W-5.5W.

As such, the cooling system that will be used will have to be able to extract at least this thermal power so that the temperature of the condensation reactor remains constant.

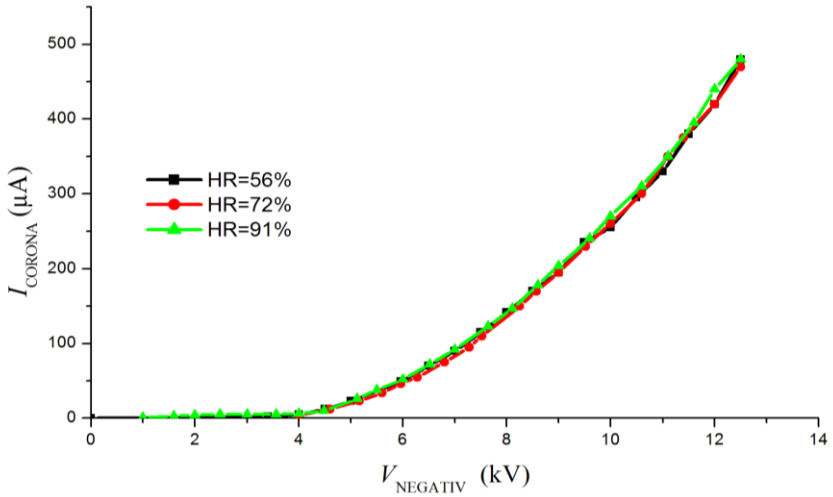


Figure 6. Electric characteristics of the condensation reactor for three values of relative humidity inside and for applied negative potentials.

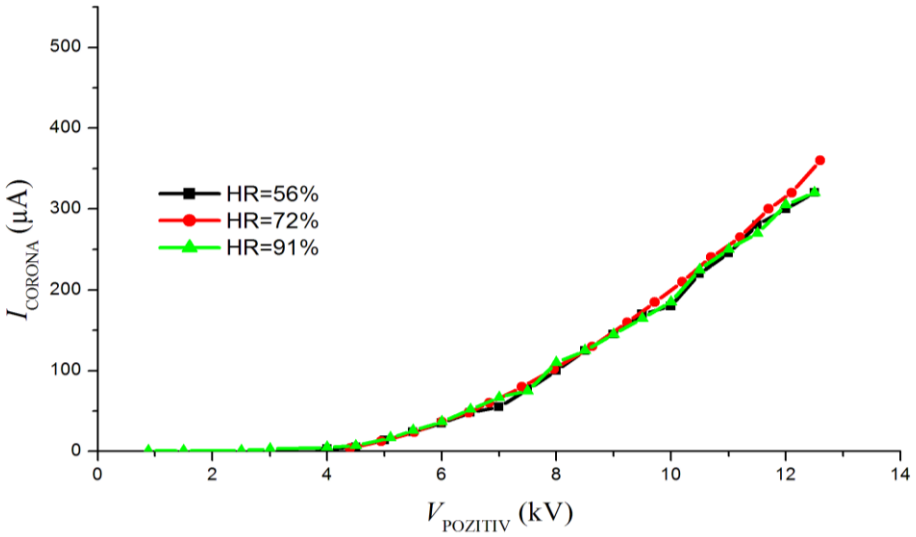


Figure 7. Electric characteristics of the condensation reactor for three values of relative humidity inside for applied negative potentials.

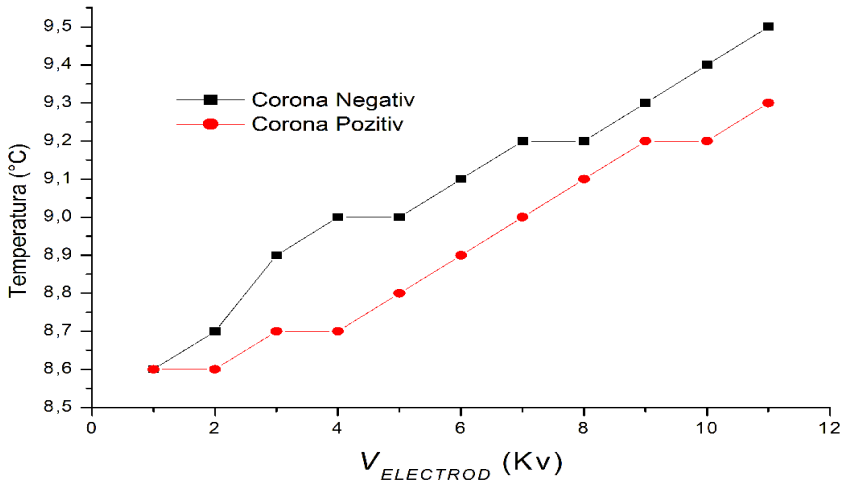


Figure 8. Temperature of the condensing cylinder regarding to the corona discharge intensity.

Figure 8 graphically shows the thermal effect of the corona discharge on the cylinder of the condensation reactor. The heat input brought by the joule effect is thus highlighted. The evaluation of a condensation in the presence of a corona discharge by calorimetric measurement would require the elimination of this amount of heat, which has no connection with the phase transformation but only with the thermal effect of the electric current.

3.2. Experimental setup blocks

In order to achieve the necessary conditions for the experiment, the condensation reactor is part of a complex installation. The elements of hydrodynamics, thermodynamics, electricity and measurement that are part of this installation will be described individually along the way.

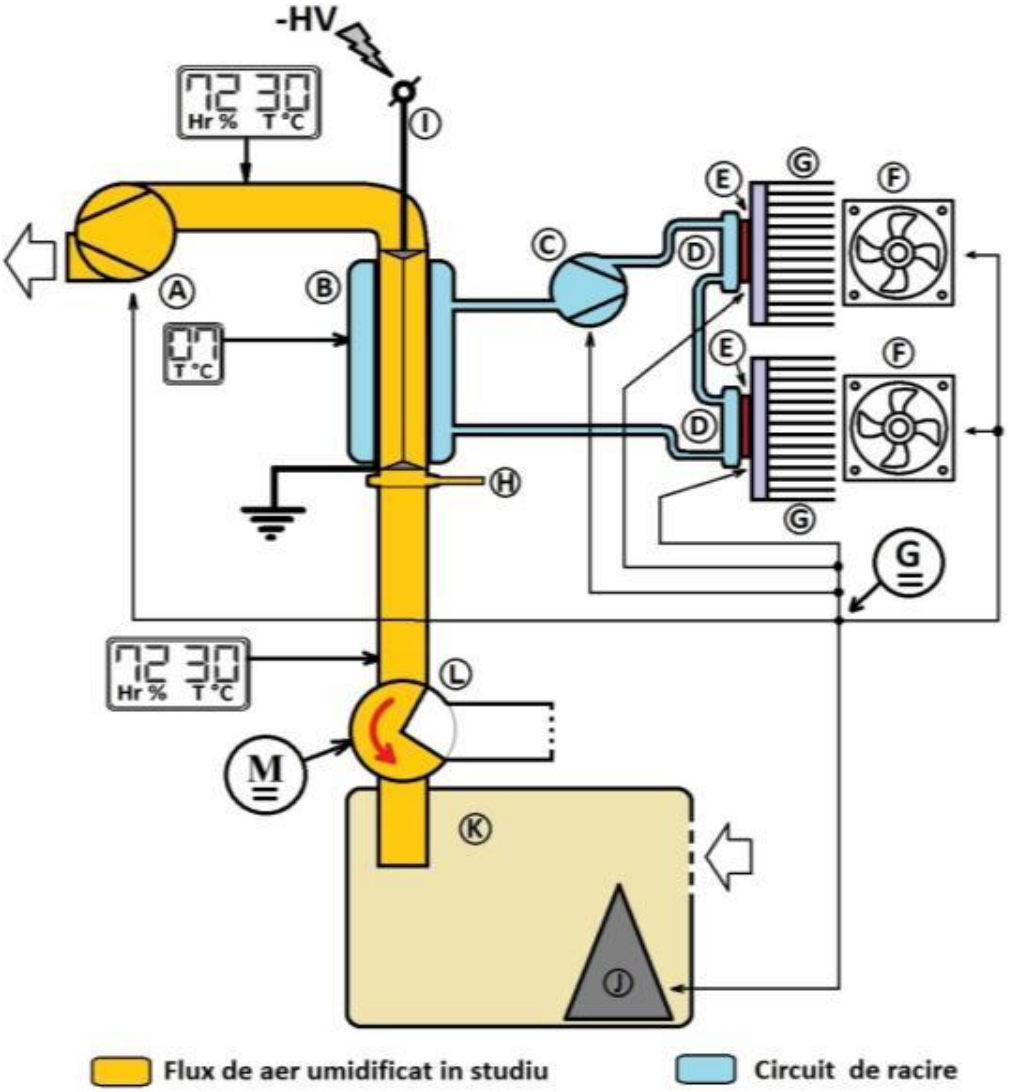


Figure 9. Diagram of the experimental setup.

The principle diagram of the experimental installation is presented in figure 9. The distinctive elements are:

A. Exhaust turbine used to move the moist air mixture at a known speed.

B. Condensation reactor. The condensation process takes place inside it.

C. Cooling circuit pump

D. Cooling system heat exchanger

E. Peltier element used in the cooling circuit

F. Cooling fan;

G. Thermal radiator of the Peltier element;

H. Exhaust system of condensate collected by reactor B;

I. The high voltage terminal through which electric potential is applied to the corona electrode.

J. Ultrasonic atomizer used to increase humidity;

K. Vapour separation enclosure;

L. Humidity control valve.

The installation uses interconnected PVC tubes with a diameter of 50mm and a wall thickness of 1.2mm, to transport the humidified air from the source.

The condensing reactor is cooled with the help of a liquid with a high caloric capacity such as ethyl-glycol, hereafter called the cooling agent, circulating around the metal cylinder. The metal cylinder of the condensation reactor is surrounded by an outer jacket at a distance of 7 mm from the outer surface of the cylinder.

The coolant used occupies this gap. The circulation of the cooling agent takes place along a spiral path in a vertical, upward direction. This turbulent circulation is ensured by the offset positioning of the connecting pipes, the entry and exit of the thermal agent from the condensation reactor.

Given that the observed phenomenon is one of condensation, in order to collect the condensation formed in the cylinder and for the phenomenon to take place in the first instance, the temperature of the heating agent used must be lower (or at least equal) to the dew point temperature under the conditions in which the experiment takes place. Cooling the cylinder below the dew point value allows the condensed vapours to be retained on the inside of the cylinder; this is very important because the application of an electric field inside the cylinder is an exothermic phenomenon which through heat input can vaporize condensed water resulting in a moist air mixture [15].

By comparing the relative humidity at the reactor exit with that at the entrance, the result would not be able to correctly reflect the phenomenon in the conditions where an additional vaporization would take place right inside the cylinder. The condensate formed on the inside of the cylinder drains under the action of gravity and is evacuated outside through a collection port (detail "H").

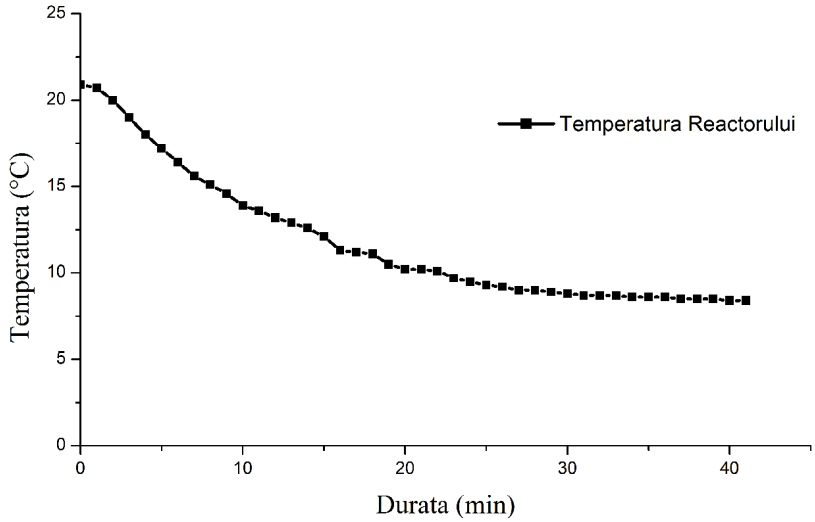


Figure 10. The characteristic of the cooling system and the temperature evolution of the condensation reactor over time.

The evolution of the cylinder temperature in the condensation reactor during the use of the cooling system can be observed graphically in figure 10. Starting from an ambient temperature of approximately 21°C, the cooling installation reduces the cylinder temperature to approximately 8°C. The temperature evolution characteristic shows a stabilization of the target value, respectively the dew point, after about 35 minutes of operation.

As long as the temperature of the condensing reactor remains constant the amount of water extracted from the humidified air mixture by cooling will be relatively constant.

Water extraction through this process will be considered intrinsic condensation, the contribution of the cooling system will be highlighted in the presented results. The efficiency of the system will be presented through a simple calculation procedure, which will be explained later.

3.3. Experimental setup by elements

The constructive elements of the experimental installation will be presented together with important details related to either the mode of operation or their role.

- **Condensation reactor assembly**

An overview of the condensation reactor is shown in figure 12. Both the thermal insulation made of spongy plastic material and the supply and exhaust pipes used for transporting the cooling agent can be identified on the outside.

The latter are also thermally insulated with the same type of material. At half the height of the condensation reactor, the electrical connection of the thermal probe necessary for monitoring the temperature of the reactor cylinder is visible.

In the lower part of the condensation reactor, the condensate discharge ports collected on the inside of the cold cylinder are visible, as well as the electrical connection collar that allows connection to the ground potential.

Figure 11 shows in detail from the upper part of the condensation reactor, the insulator supporting the corona discharge wire. The insulation of the connection conductor made of polypropylene and to which the electrical connection terminal is attached (Figure 9, detail "I") is visible. The corona discharge electrode is also visible.



Figure 11. View of the condensation reactor, detailing the corona discharge electrode insulator.



Figure 12. Condensation reactor assembly.

- **Condensation reactor temperature control system**

As previously presented, the cooling system is based on the circulation of a liquid thermal agent in a closed circuit. The route followed by the cooling agent is between the condensation reactor, which is the heat source, and two heat exchangers in intimate contact with two Peltier semiconductor elements. The role of heat exchangers is to extract the heat collected from the condensing reactor from the coolant.

The heat collected by the coolant has three sources of origin. First of all, it is the heat carried by the humidified air coming from the ambient environment.

The second source is the latent heat of condensation of the water that condenses on the inner wall of the cylinder.

Finally, by applying an electric potential to the corona discharge wire, a weak current will be established, but, considering the high voltage at which the phenomenon takes place, the heat input through the joule effect is not negligible (22).

Consequently, the cooling system will have to be dimensioned so that its cooling power is sufficient and has the ability to sufficiently reduce the temperature of the condensation reactor. The heat exchangers are connected by means of silicone pipes to the condensation reactor and they are thermally insulated on the outer surface with spongy material.

The two heat exchangers are of similar construction, being of industrial origin, made of copper, a material with good thermal transfer properties. The principle diagram of the experimental installation shows in figure 9, detail "D" the positions occupied by the heat exchangers.



Figure 13. Heat Exchanger Assembly (Top), Coolant Circulation, Detail (Bottom)

Figure 13 shows the exploded view of a heat exchanger and as a detail in the lower part the metal body, as its active part. The metal body is provided with fine channels, to increase the contact surface, so the cooling agent can easily give up the transported heat. To

ensure the circulation of the coolant in the system, a recirculation turbine driven by a BLDC synchronous electric motor is used. The appearance of the hydraulic turbine used by this system is shown in figure 14.



Figure 14. Coolant circulation pump.

The heat exchangers are mounted on Peltier type semiconductor cooling elements. The position of the Peltier thermocouples is identified on the schematic diagram in figure 9, detail "E". In turn, they are cooled with the help of two massive radiators made of aluminum and forced ventilation, identified in figure 8, detail "F" and "G".

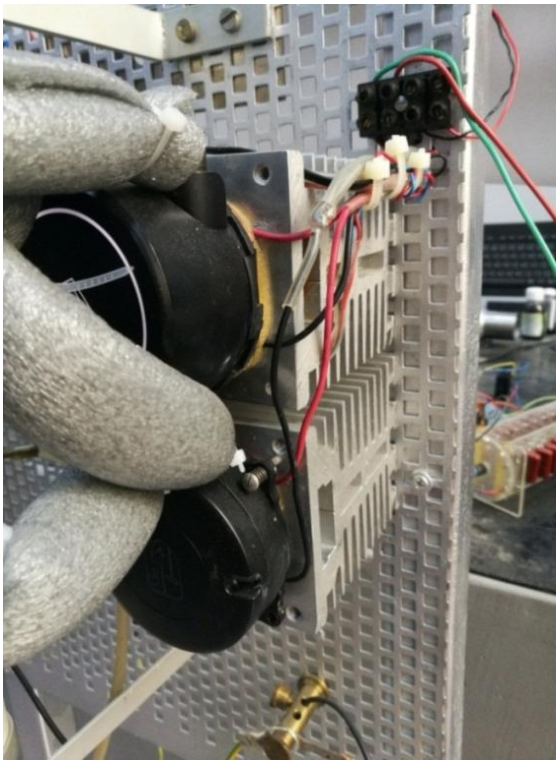


Figure 15. Assembly of heat exchangers with Peltier elements.

The Peltier elements are connected to a power supply that discharges a current of 6A, constant, optimal for the operation of the elements. When the thermodynamic regime is stabilized, the electrical power absorbed by the cooling system is about 100W.

The whole assembly of the heat exchangers together with the cooling radiators is shown in the picture in figure 15.

In order to highlight the evolution characteristic of the temperature of the cold cylinder during the operation of the cooling system, successive temperature determinations were made at equal time intervals, with the help of an electronic thermometer.

Its probe is positioned so that it can take the temperature in a precise way. Identified in figure 9, detail "H" the electronic thermometer used is visible in figure 16.



Figure 16. Digital thermometer.

- **Air humidification system**

Figure 17 shows the enclosure in which the water micro droplets are separated from vapour (figure 9, detail "K"); the water atomization device is also visible (figure 9, detail "J"). The atomizer is of industrial production and its principle of operation is the atomization of liquids with the help of ultrasound.

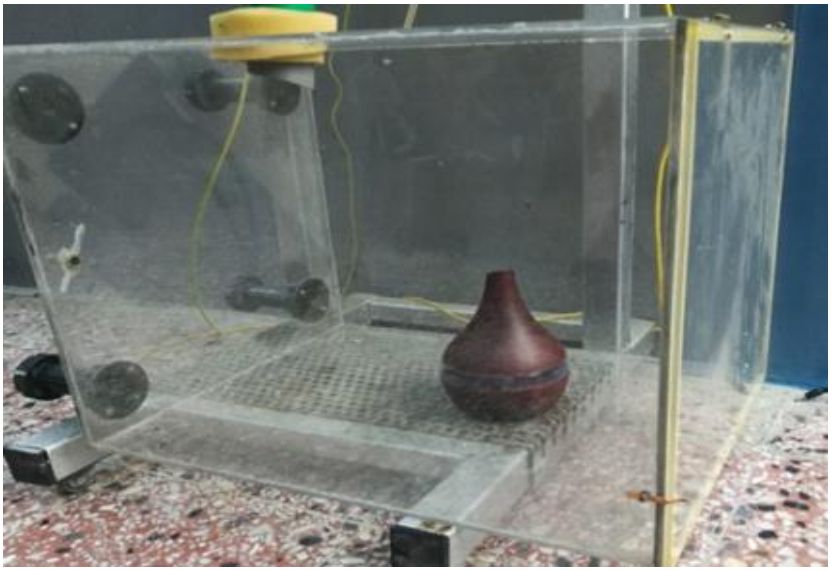


Figure 17. Separation chamber for the production of water vapor, in detail the ultrasonic liquid atomizer.

The high volume enclosure allows for the separation by gravity of the water droplets generated by the atomizer inserted inside.

In this way, a relatively high concentration of water can be obtained in an air flow without raising the temperature above the ambient value. The advantage of this approach lies in the

fact that the obtained moist air mixture will have a temperature approximately equal to that of the ambient environment and also as the pipes that transport it to the condensation reactor.

Since there are no temperature differences in this route, we avoid the suspicion of parasitic condensations that could affect the results of the determinations.

A turbulent flow of the humidified air mixture through the condensing system could further contribute to the overall effect of the system and it would be difficult to estimate how much of the measured result would be due to it [16].

The presence of such a pipe with a length much greater than that of the condensation system aimed at the formation of a laminar flow with as little turbulent flow as possible inside the condensation reactor. A first system for measuring relative humidity, considered to be the humidity entering the condensing system, was installed on this humid air supply route.

Inside the separation enclosure, an air mixture with very high humidity is obtained, and by adding a quantity of air from the outside, the desired humidity values can be obtained. To adjust the relative humidity value at the exit from the separation enclosure, a mixing valve was inserted (Figure 18). The actuation of the valve is performed electrically with the help of a direct current servomotor. Thus determinations can be made at various established humidity values.

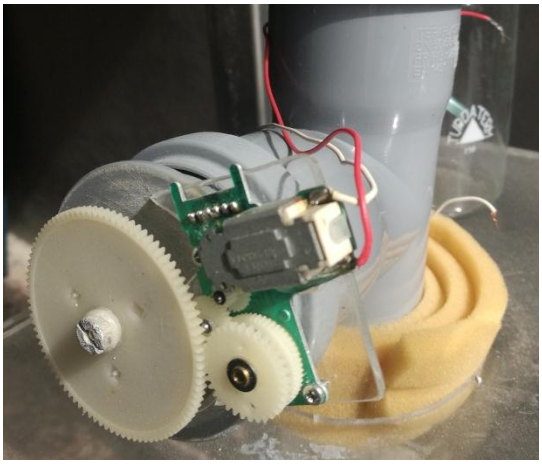


Figure 18. Mixing valve for adjusting relative humidity.

- **Measurement system**

In order to determine the changes due to the application of the electric field on the phase change that takes place inside the condensation reactor, it was necessary to implement a measurement system adapted to the experiment. Thus, a number of two devices equipped with relative humidity and temperature measurement probes were installed.

The probe of the first measuring instrument was inserted inside the pipe feeding the condensation reactor at a sufficient distance (600 mm) from the condensation reactor so as not to influence the laminar flow in the area of interest. The probe is shown in figure 19. This first measuring instrument will indicate the input humidity, the initial one, in the condensation reactor.

Given that the transport route of the humidified air mixture is made of PVC and the temperature gradient between the respective pipe surfaces is very small, we cannot suspect parasitic condensation in this area.

Moreover, during the determinations, inspections of this area were carried out to identify possible problems of this kind.



Figure 19. Relative humidity measurement probe at the entry into the condensation reactor.

In order to determine the value of the relative humidity at the outlet of the condensation reactor, another, equivalent measuring instrument was installed, the probe of which was inserted into the discharge pipe of the condensation reactor. The two measuring devices are shown in figure 20.

In the area where the two measuring instruments were placed, the exhaust pipe was shielded by sleeve with aluminum metal foil. This was connected to zero potential through a conductor equipped with a metal collar.



Figure 20. The hygrometers used in the setup.

Being the first part of the route downstream of the condensation reactor, a consistent electrostatic charge was suspected, the origin of which is the corona discharge phenomenon.

A significant number of charged particles will leave the corona discharge area and most likely cause accumulations of electrical charge along the escape route.



Figure 21. The hot wire anemometer used to determine the flow velocity.

The two measuring instruments were checked in advance for various values of temperature and humidity in order to achieve a correlation between their indications. The checks proved that a possible correction was not necessary, the indications being correlated to a large extent.

In order to verify and establish the speed with which the humidified air mixture circulates in the system exposed above, a hot wire anemometer was used. Its indications were correlated with the speed of the exhaust turbine, respectively with its supply voltage. The correlation was necessary so that, in the course of the determinations, the use of the anemometer was not necessary, it being sufficient to establish a certain supply voltage of the exhaust turbine. The anemometer used is shown in figure 21.

In order to avoid possible measurement errors, the presented anemometer has been calibrated beforehand.

3.4. Production of electric field, corona effect and space charge

The present installation can allow the quantitative evaluation of condensation in the presence of an electric field of various shapes, polarities and amplitudes. There are known studies carried out in the presence of an electric field of a fixed intensity and polarity, and it was desired to emphasize the effect in other conditions and to search for an efficiency of the phenomenon.

To create such a source, it was decided to create an electronic inverter fed from a low voltage source galvanic separated from the power supply network, something that increases the safety of handling as well as the possibility of connecting any of the terminals to the

ground potential, at your choice. Moreover, the presence of an alternating voltage could allow the application of a time-varying electric field inside the cylinder.

The condensation phenomenon could be influenced by the following mechanisms:

- water molecules can exhibit rotational movements in the presence of a variable or alternating electric field.
- micro particles in the moist air mixture could be set in motion relative to the water vapours by Columbian forces in the presence of the alternating electric field.

Those micro particles could collect water molecules in an accelerated regime.

Also, the water molecules can have their surface tension changed due to the potential hydrogen bonds made with the ions resulting from the presence of the corona discharge, a fact that could contribute to the acceleration of the condensation phenomenon.

3.4.1. AC voltage with DC component

Obtaining an electric field with variable intensity requires the application of an electric voltage that varies over time. Usually electrostatic precipitators are supplied with direct voltage. Less common are the cases where an alternating voltage with a different waveform is applied to the electrodes. Known, rare cases of electrostatic precipitators are supplied with AC voltage, usually sinusoidal.

A particular and still not sufficiently documented case is the one in which the electric supply voltage oscillates but does not change its polarity. The application of such a type of electric voltage will lead to the formation of an electric field with one direction but variable in intensity according to the form of the alternating current. The intensity variation of the produced field will be proportional in this case to the peak-to-peak value of the alternating voltage.

This type of electrical voltage is technically called AC voltage with a DC component or superimposed AC voltage.

Such an experiment carried out under different conditions compared to previous studies could highlight new effects on the condensation phenomenon.

To study the effects of a time-varying electrical voltage as described above applied to the corona discharge electrode, it is necessary to use a special design power supply.

3.4.2. High voltage power supply

A block representation of such a high-voltage source suitable for the proposed purpose is shown in figure 22. This could allow the simultaneous application of two independently adjustable and summed voltages, by putting them in series.

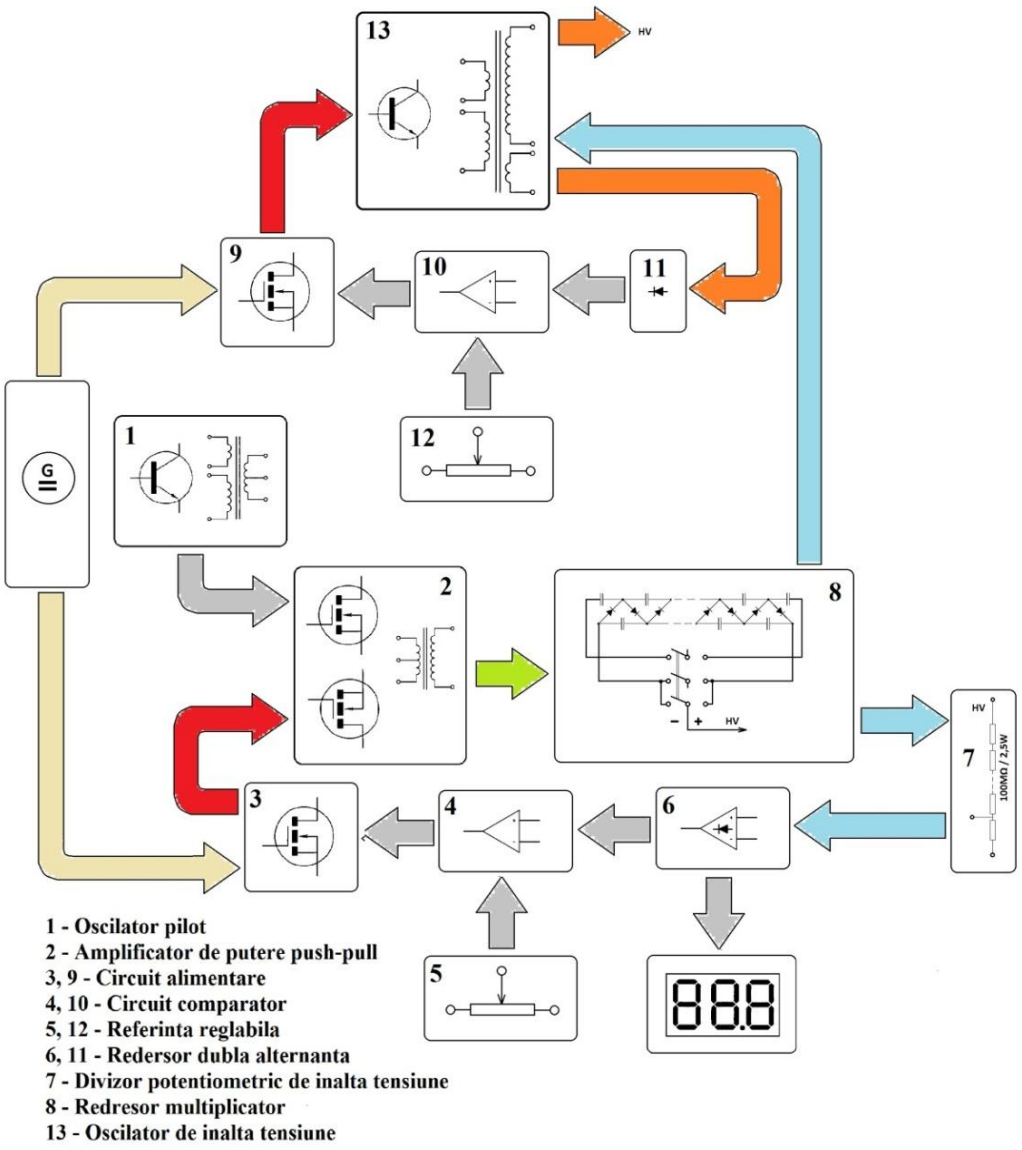


Figure 22. High voltage supply block view.

The power supply blocks have the following functions:

1. Pilot oscillator with LC tuned circuit with phase shifter transformer and symmetrical output.
2. The amplification stage, made with an output for a symmetrical electric transformer.
3. PWM power supply with variable duty cycle powering amplifier stage 2.
4. PWM power supply control circuit made with a voltage comparator.
5. Reference of the DC voltage regulation system.
6. Electronic rectifier without zero crossing.
7. High voltage potentiometric divider.
8. Rectifier-Multiplier in single phase rectification scheme with 26 cells, and featuring a reversible operation.
9. PWM power supply with variable duty cycle powering the self-oscillator stage 13.
10. PWM power supply control circuit made with a voltage comparator.

11. AC rectifier made with a full diode bridge.
12. Reference of the alternating voltage regulation system.
13. Self-oscillating power stage with step-up transformer.

The direct voltage thus obtained will be summed with the alternating voltage obtained in block 13 and finally the resulting voltage will be applied to the condensation reactor. Both voltage generation paths can be adjusted to achieve a specific output value independently by adjustment blocks 5 and 12.

For tracking, an electronic voltmeter is interspersed on the path of the direct voltage production system that will indicate the presence and value of the output voltage. The entire assembly will be powered from a DC voltage source.

3.4.3. The high voltage DC supply

To generate the direct voltage used in the experiment, a high-voltage inverter based on an alternating current rectifier-multiplier (block 8) with 26 cells and an alternating current generator was made.

The operation of the DC voltage generator takes place as follows:

1. Comparator circuit 4 will receive from reference 5 the desired voltage as a fraction in the ratio of 1000:1 and will compare it with the voltage brought by rectifier 6, if the result is above unity it will command PWM circuit 3 in the sense of increasing the supply voltage of circuit 2.
2. Power circuit 2 will receive symmetrical command from oscillator circuit 1 and will produce at the output an AC voltage with the ratio 20:500 of its supply voltage. The AC output voltage is proportional to the supply voltage received from circuit 3.
3. The alternating voltage generated by circuit 2 will be rectified by the rectifier-multiplier 8 and a DC voltage will be present at its output.
4. Circuit 7 will take the voltage present at the output of circuit 8 and inject it to rectifier 6 with a ratio of 1000:1.
5. The rectifier 6 will rectify the voltage received at the input of the comparator 4.
6. If the voltages present at the inputs of the comparator 4 are not equal, the PWM circuit 3 will be adjusted in the direction of increase or decrease so that the desired voltage is obtained at the output of the block 8.

The rectified voltage obtained from the rectifier 6 is also used to indicate the output voltage of the inverter by means of a self-scaling digital voltmeter.

In the experimental stages, it was found that the DC voltage inverter works without problems in the range -12 kV ... +12 kV and with a current of up to 0.5mA. Particular problems were the occasional punctures caused by condensation accumulations. Due to the strong capacitive character of the rectifier-multiplier used, and due to the fact that the step-up transformer used has a relatively small inductance in the secondary circuit (the working frequency being approx. 52 kHz), defects occurred through the breakdown of some diodes in the rectifier-multiplier component due to exceeding the specific current integral.

To avoid this shortcoming, a ballast resistance was introduced in the circuit that limits the current in the high voltage circuit to a value below the maximum limit allowed by the diodes used (20 kΩ limits the discharge current for 12 kV below the maximum value of 1 A of the diodes used). The ballast resistance influences to a small extent the output voltage value for currents up to 0.5 mA, being a maximum error of 100 V compared to the value indicated by the digital voltmeter with auto scale.

3.4.3. The high voltage AC supply

To obtain the alternating voltage, a step-up transformer and an electronic oscillator with inductive coupling were used. In order for the level of oscillations produced to be controlled and stable, an automatic adjustment system was introduced that allows adjusting and maintaining the output voltage in the 1-5kV range.

The operation of the alternator can be described as follows:

1. The comparator circuit 10 receives a fraction of the desired output voltage from the circuit 12 in a ratio of 1:500.
2. Circuit 11 rectifies a voltage produced by a measurement winding and applies the result to comparator circuit 10.
3. If the result obtained by the comparator 10 is sub-unit, it will command the PWM circuit 9 in the sense of increasing the output voltage. This applies to the self-oscillating circuit 13.
4. The self-oscillating circuit 13 contains an electric voltage-raising transformer with the ratio 20:8250. It will discharge an alternating voltage at the output of a value proportional to its supply voltage, coming from the PWM circuit 9.

An indirect measurement method without electric coupling was chosen. This method assumes the existence of an additional winding which, magnetically coupled with the secondary winding, will produce an AC voltage proportional to the output. The voltage available in this winding is used in automatic AC voltage regulation.

The transformer used is with two columns of the magnetic circuit, optimal for the separate placement of the low and high voltage windings and has a mobile branch through which the self-inductance of the resonant LC circuit can be varied by changing the common area. In this way, the frequency of the alternating current can be varied within wide limits.

The proposed power supply was previously simulated in the Proteus CAD 8 program to determine the main characteristics and to estimate a good operation.

During the simulations of the electrical scheme of the power supply, data related to the functional characteristics of the scheme were recorded with the help of measuring instruments present in the simulator. Thus, data were collected regarding the good operation of the direct voltage inverter as well as the output characteristic of the power source in operating condition with the parameters U_{DC} = 10 kV and Uca = 5kV.

Considering that the secondary winding of the alternating voltage source will be found under certain conditions at a very high potential (+/- 12 kV from the direct voltage generator) compared to the magnetic core used, specific electrical insulation measures must be taken. The chosen insulator, optimal for the available space, which has sufficient dielectric strength, is PET. This type of material gives high dielectric strength optimal for the situation in question. The entire electronic scheme is powered from a direct current source with a voltage of 19Vdc.

3.5. Method of conducting experiments

In order to determine the effect of applying the electric field on the water vapor condensation phenomenon, an experimental procedure was developed that takes into account the conditions in which it takes place and is adapted to the possibilities of the installation used.

Considering that the water vapour condensation phenomenon is complex and is related to the environmental factors in which it takes place, namely pressure and temperature, special measures were taken for the experiment to take place under controlled conditions.

At the same time, the performance of long-term determinations with numerous measurement points, at different humidity values of the air used or different flow rates, required a rigorous stability of the initial conditions. Thus, the experiments were carried out in the laboratory ensuring that the ambient temperature was between 19-22°C and a relative humidity of 40...45%RH; to obtain these conditions, it was necessary to use the laboratory's air conditioning system.

3.5.1 Applying high voltages

In order to correctly estimate the applied voltage, the waveform and the frequency, a P6015A Tektronix high voltage probe was used during the determinations, coupled to the axial electrode of the cylinder. The probe used with a division ratio of 1000:1 and a pass band of 75 MHz was coupled to an oscilloscope with a band of 20 MHz and considering the compound division ratio the values, polarity and frequency of the voltage applied to the discharge electrode can be recorded. For convenience, the humidity measuring devices, the voltmeter and the micro ammeter, as well as the oscilloscope used in the experiment, were recorded on video so that, later, the collected data could be centralized in tables according to the conditions of the respective determinations.

In order to determine the contribution of the application of the electric field to the phenomenon of condensation, determinations were made both by applying direct voltage with values included in the range specified above in steps of 1 kV, as well as combinations between direct voltage and alternating voltage with various frequencies, also in steps of 1 kV. Around the values where better results were determined, determinations were made by iteration with smaller steps, until the maximum condensation efficiency was obtained for the

model used. Last but not least, for the combination of alternating and direct voltages with the highest efficiency, a measurement of the phase shift between the alternating voltage and the current established in the circuit was performed by simultaneously acquiring the voltage and current on the screen of the electronic oscilloscope.

3.5.2. Determining of the condensation efficiency

In order to determine the degree of efficiency of the condensation, two devices with probes for measuring humidity and temperature were used.

During the experiment, it was aimed to reach a humidity of the air entering the condensation system as high as possible, the recorded values being up to 90-94 RH(%).

Also, the cooling system of the condensation reactor was activated and the stabilization of the temperature of the cold cylinder was expected. After reaching the desired temperature, the condensation reactor was fed with humidified air.

The probe of the first humidity measuring device was located in the first part of the upward path from the humid air conduction system to the condensing cylinder. In this position we can measure the input humidity. At the same time, it was ensured that the position of the probe was not a factor of disruption of the humidified air flow, by the formation of turbulences inside the condensing cylinder. The measured humidity was denoted by RH_{in}(%). To adjust the RH_{in}(%) humidity, the electric servo mixing valve was used, which allowed additional ambient air to be brought into the circuit.

At the exit from the condensing cylinder, the probe of the second measuring device was placed so that on the upstream path there is as little additional condensation as possible, other than the one that takes place inside the studied cylinder. The values read by this device were noted with RH_{out}(%).

3.5.3. Types of performed experiments

With the help of the experimental installation, the necessary determinations were made to establish the good functioning of the component parts and the whole assembly. These were generically called "predeterminations" and were not used in the evaluation of the experiment but more precisely in identifying the best method of performing the experiment.

During these pre-determinations, the sources of uncertainty of the experiment were identified as much as possible.

Through these pre-determinations, a procedure for carrying out the experiment was established to reduce measurement errors as much as possible. For this purpose, a method of determination was chosen by averaging the obtained results, by applying the electric potential in the direction of increase and decrease.

Thus, two sets of determinations were obtained at the same points from which the average was extracted. Such a method allowed obtaining more accurate results, repeatable determinations.

Thus, based on this established procedure, determinations were made of the influence of the electric field and the associated corona effect on the condensation of water vapour as follows:

- Determinations using the corona effect produced with direct voltage of both polarities performed at three humidified air circulation speeds, in order to establish the influence of the ionic wind generated by the electric field on the water vapour.
- Determinations that studied the influence of the polarity of the corona phenomenon on the condensation of water vapour. The species of charge carriers produced being dependent on the polarity of the discharge, we wanted to highlight the affinity of water molecules to one of the two cases.
- Another set of determinations was made using a high frequency alternating electric field. These determinations were intended to test the effect of this type of electric field on the condensation of water vapour.
- By summing the two types of voltages that can be obtained from the power source, determinations could be made using an electric field with variable intensity without change of direction. Thus, an exact voltage range, a minimum and a maximum, was determined experimentally, in which if the oscillation frequency is high, the dehumidification effect is intensified.
- Taking the previously determined voltage values, the oscillation frequency of the electric field was adjusted between certain limits. Thus, a graphic characteristic of the improvement of the condensation in this type of electric field related to its frequency was obtained.
- Determinations were also made on the waveform of the corona current. Thus, a capacitive character of the condensation reactor as an electric charge was highlighted. The acquired form of the current revealed high-frequency periodic oscillations similar to Trichel impulses.
-

3.5.4. Calculation method

During the determinations, in order to retain the water resulting from the condensation process and to influence as little as possible the measured values at the output of the system, the condensation cylinder is cooled by a system based on Peltier elements and thermal coolant below the dew point value. Due to this method of operation, there is an intrinsic, natural condensation in the system, caused by the presence of the cylinder cooled below the dew point temperature.

In order to correctly calculate the results obtained during the experiment, the values indicated by the humidity measuring devices were retained and the humidity differences between the inlet and outlet of the condensation reactor in the absence of the electric field were considered as the result of intrinsic condensation and noted with "$RH_{intrinsec}(\%)$". As a result, the condensation caused by the cold cylinder, the intrinsic condensation were extracted from the obtained values and only the differences were retained, these being noted with the indication "*Delta RH*(%)".

$$DeltaRH(\%) = RH_{in}(\%) - RH_{out}(\%) - RH_{intrinsec}(\%) \quad . \qquad (4)$$

In the relative humidity range used 60-94 RH(%), at the system entrance, the contribution brought by the cold cylinder in reducing the humidity at the exit was included in the range 9.1-10.5 RH(%). This is for a condensation reactor temperature between 8.7...10.5 ^{o}C.

The difference determined by humidity in the experiments for both polarities, the various intensities and frequencies of the applied field were reduced with this intrinsic contribution of condensation and the values obtained were considered to be only the result of the application of the respective electric field.

This fact was also proven by the temporary, arbitrary interruption of the electric field and the observation of the rapid return of the moisture values at the exit to the values previously measured without the electric field. Sets of determinations were made in both directions of voltage variation, both by gradually increasing the voltage and by decreasing it until the starting value, noting the obtained values. During the experimental determinations, the low values of the electric potential were excluded, which had no obvious effect in the phenomenon and for which the current intensity was below the lower measurement limit.

Chapter 4. Experimental results

Considering the predetermined characteristics that emphasize the dependence of If(U) (figures 6 and 7) on direct voltages, a series of experiments on the phenomenon of condensation using direct voltages were carried out.

4.1. The influence of the polarity of the corona discharge on the condensation of water

The first set of determinations measured the dependence between the efficiency of the condensing reactor and the polarity of the applied voltage under the conditions of using three flow rates of the air mixture in the installation (17 cm/s, 19 cm/s and 22 cm/s) and an input humidity in the range RH 92% - RH 94%.

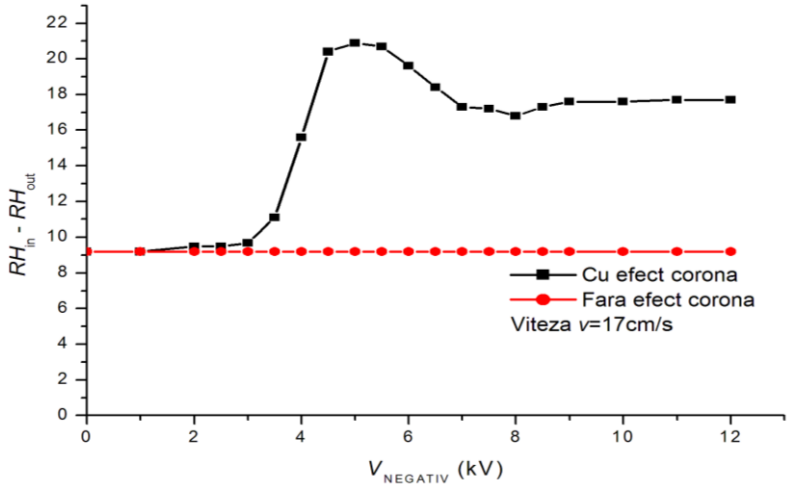


Figure 23. Condensation graph of water vapour at the speed v = 17 cm/s, in the presence of the negative corona effect.

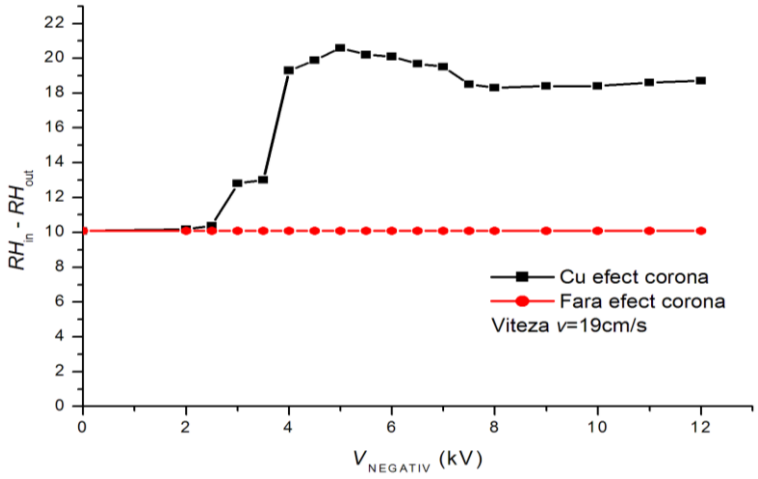


Figure 24. Condensation graph of water vapour at the speed v = 19 cm/s, in the presence of the negative corona effect.

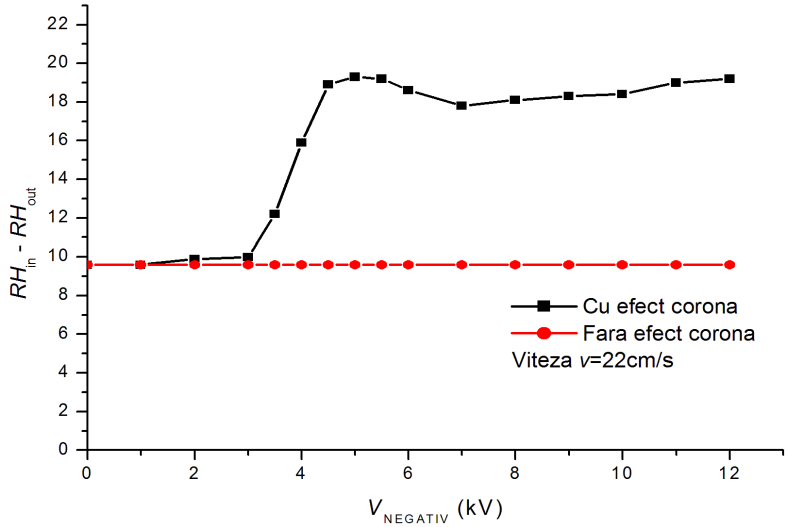


Figure 25. Condensation graph of water vapour at the speed v = 22 cm/s, in the presence of the negative corona effect.

The previous graphs (figures 23-25) show the changes brought by the presence of the negative corona effect on the phase transformation that takes place in the condensation reactor. The abscissas of the graphs express the value of the negative voltage with which the condensation reactor is fed. On the ordinates of the graphs, the difference in relative humidity measured during the experiment with the measuring devices specified in III.5.2 is expressed in percentage points.

Thus, the difference between the humidity of the air supplied to the condensation reactor RH_{in} (%) and the relative humidity measured at its output, *RHout* (%), at various values of the supply voltage, can be identified on the graph.

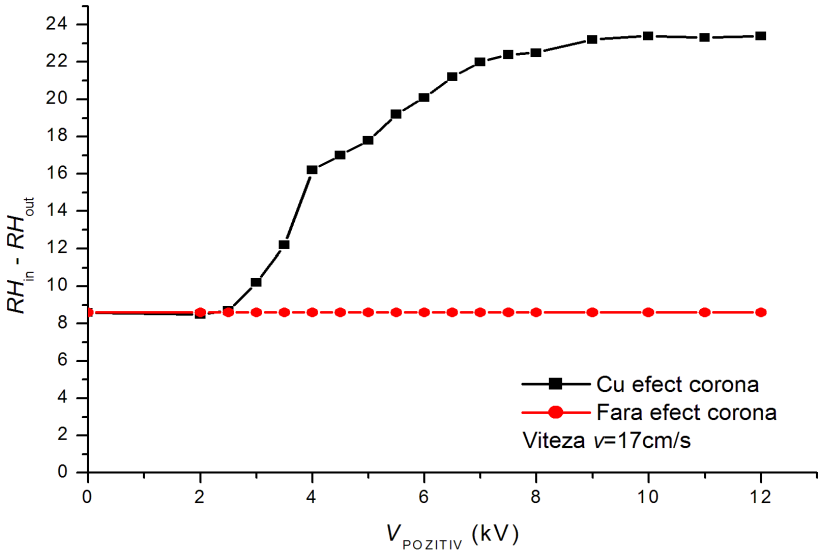


Figure 26. Condensation graph of water vapor at the speed v = 17 cm/s, in the presence of the positive corona effect.

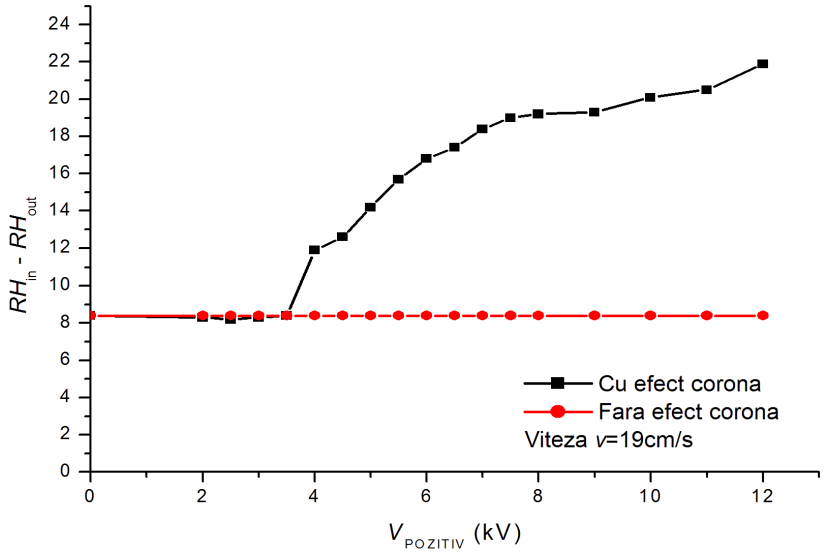


Figure 27. Condensation graph of water vapor at the speed v =19 cm/s, in the presence of the positive corona effect.

The two paths present on the graphs, identified by colour, show this difference in the two possible cases, respectively with the corona effect and the presence of an electric field or without these two.

In this way, the improvement brought to the water vapour condensation process by using the electric field effects can be easily identified. For example, when using the speed of 17 cm/s, the humidity reduction reaches a value of about 21% by using the effects of the electric field. Comparatively, the reduction achieved only by the condensation caused by the cold cylinder is about 9.5%.

For comparison, the results obtained by using the positive corona effect under the same conditions are also presented in the form of graphs in figures 26 – 28.

A first conclusion that is formed after analysing the obtained results is that the reduction of the relative humidity of the air measured at the exit of the condensation reactor presents important changes with the appearance of the corona discharge phenomenon, regardless of its polarity.

Regarding the dependence of this change in relation to the intensity of the corona discharge current, it was found that it is strongly non-linear, especially in the case of using negative polarity.

By analysing the results obtained, it was found that the results obtained in the case of using the positive corona discharge are better than in the case of using the negative corona effect.

Thus, for similar conditions in the case of using the positive corona discharge, the humidity reduction is improved by 2-3 percentage points compared to the one obtained by the negative corona effect.

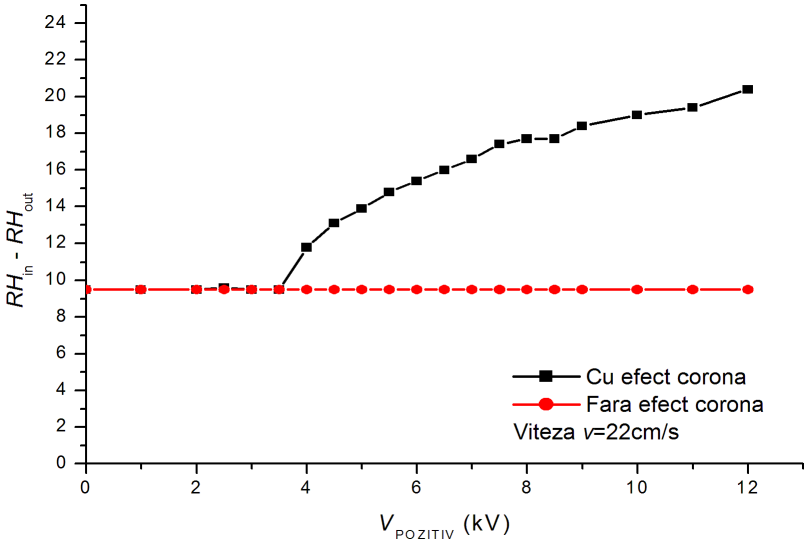


Figure 28. Condensation graph of water vapor at the speed v = 22 cm/s, in the presence of the positive corona effect.

If we consider the species of ions that are produced by each type of corona discharge, we can conclude that the phenomenon of water condensation is particularly favoured by the presence of positive ions. Moreover, the effect of the dielectrophoretic force on water molecules was previously presented in chapter II.3.

Previously, studies were presented that concluded, among other things, that there is an additional improvement of the condensation phenomenon in the presence of the positive corona discharge compared to the negative one. The main cause of this difference is the appearance of a dielectrophoretic force on the water molecules and micro droplets that imprint an ordered movement towards the cold cylinder of the condensation reactor, especially in the case of positive corona discharge.

The dielectrophoretic force manifests itself at the interface of water microdroplets with the surrounding environment (gas) and gives them a movement. Water, having the relative electrical permittivity ε_r much higher than the air from which it is extracted, will be pushed by the effect of positive dielectrophoresis towards the area where the space charge has a higher density. The effect of the electric charge carriers on the nucleation phenomena was previously exposed in II.2.

Regarding the effect of the corona discharge with negative polarity on water condensation, the determinations highlighted a sharp decrease in its benefits at higher intensities of the electric field. Simultaneously with the increase in the intensity of the electric field, the discharge current is higher and the positive ions produced by the secondary ionization are more and more concentrated around the corona electrode and further away from the cold cylinder of the reactor.

The need for the presence of positive ions around the cold cylinder of the reactor to favour water condensation is confirmed by the evolution of the graphs in Figures 26 – 28.

Regarding the movement speed of the micro-droplets of water towards the condensation cylinder, a decrease in the efficiency of the condensation phenomenon is

highlighted as the flow speed of the humidified air mixture is higher. The phenomenon is more accentuated especially for the case of applying positive potential and less for negative potential, the slope of the graphs confirming this trend.

According to the analytical model approached previously, in which the calculated ion wind speed turns out to be around 4.7 m/s, the obtained results do not support an important influence of the ion wind on the movement of micro droplets. This fact is most likely due to the numerous collisions that take place at the level of water molecules that show the elasticity characteristic of electrostatic bonds, as well as the reduced momentum specific to ions that have a much smaller mass than that of water micro droplets.

It can also be assumed that the dielectrophoretic force is the main engine of the movement of the micro droplets towards the cold cylinder and the presence of the ionic wind has very little relevance.

4.2. The influence of the AC corona discharge on the condensation of water

Featuring a high-voltage power supply of a construction adapted to this type of experiment, determinations were made on the changes that occur in the water condensation process using a sinusoidal alternating voltage.

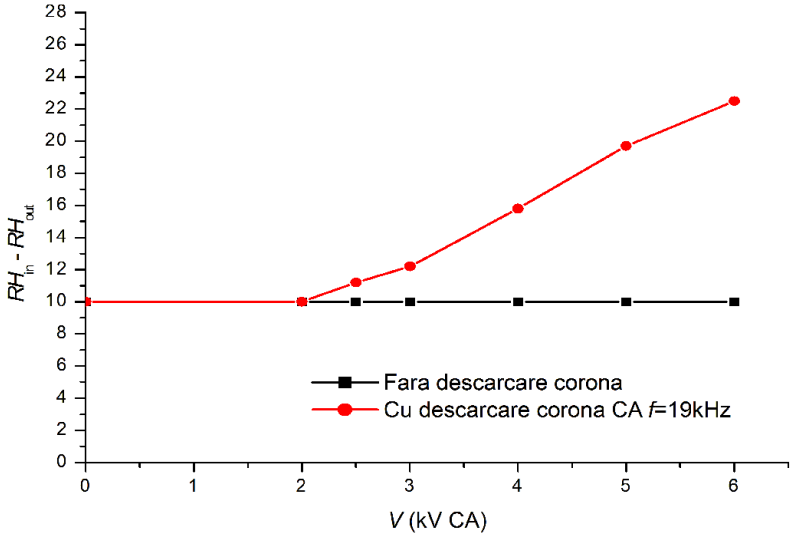


Figura 29. Caracteristica condensării vaporilor de apă în câmp electric alternativ cu efect corona la viteza v = 17 cm/s.

This type of voltage will create inside the condensation reactor a corona discharge of both polarities and an intense electric field, the direction of which will reverse at each alternation.

Figure 29 shows the characteristic obtained by using alternating voltage. The applied alternating voltage had a frequency of 19 kHz and the values on the abscissa refer to the effective value of the voltage.

The effect of applying the electric field is visible on the humidity value measured at the exit of the condensation reactor starting with a value of 2 kV. The approximately linear characteristic obtained in this experiment indicates an improvement in the condensation of water vapour under the action of the intense electric field and the corona effect even if alternating current is used.

The space charge produced during the corona discharge of one polarity will most likely migrate upon changing the direction of the electric field and for a short period of time in the condensation reactor section we will have a more uniform distribution of the concentration of the ion species present. In the case of unipolar discharges, this "zone" will have important variations in the concentration of charge carriers, these being grouped near the electrode with a reduced radius of curvature.

The charge carriers produced by a corona discharge in alternating current are of both species, but their recombination is fast and it would be expected that the influence on the condensation is not great. However, a sufficiently notable influence is found in this case as well as in the previous case of unipolar corona discharges.

4.1.3. Effect of the superimposed AC and DC corona discharge on the water condensation

As it was exposed in chapter III.4.2, the built-in high-voltage power supply, it allows the application of a voltage derived from the summation of two types of direct and alternating voltage.

Thus, determinations were made by applying an alternating voltage and summing it with a continuous voltage that was gradually increased up to the maximum value at which electrical breakdowns occur.

For clarification, it should be specified that the corona phenomenon takes place in alternating mode from the point of view of polarity as long as the direct voltage is lower than the peak-to-peak value of the alternating voltage. After this moment, a unipolar corona discharge occurs in the condensation reactor, the intensity of which is variable and respects the form and frequency of the alternating current. The amplitude of this variation is proportional to the amplitude of the alternating current used.

In chapter 3.5.4. a method for calculating the condensation efficiency was presented and in the following determinations it will be used. If in the previous determinations the value of the condensation produced by the cold cylinder of the reactor in the absence of an electric field was also present for example, the following determinations will eliminate it by the calculation method presented.

This intrinsic condensation will continue to occur, but for a clearer presentation, it was decided to be eliminated, keeping only the increase brought by the electric field and the corona discharge.

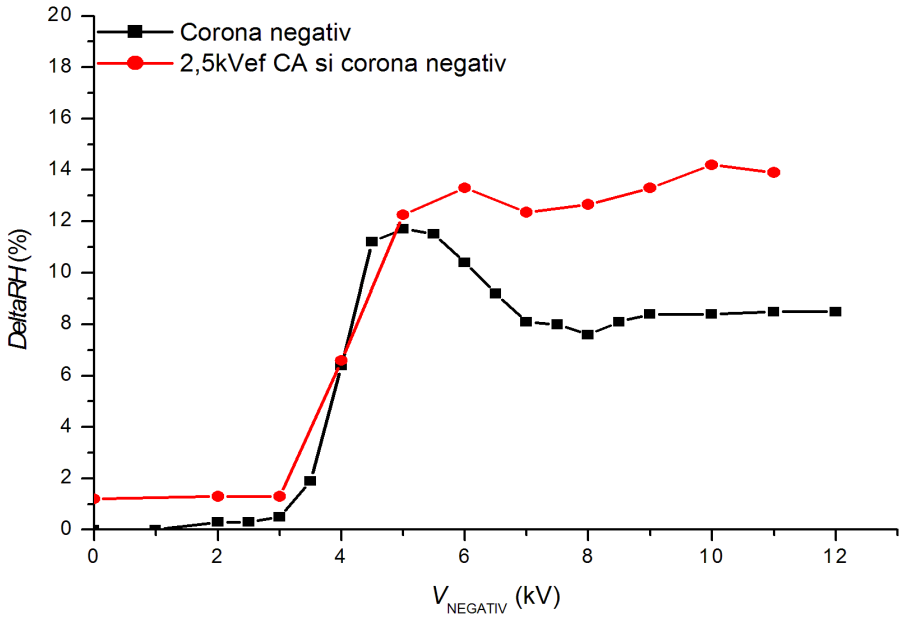


Figure 30. Characteristic of the condensation of water vapor in the electric field produced by an AC of 2.5 kV with a negative DC component, at the speed v = 17 cm/s.

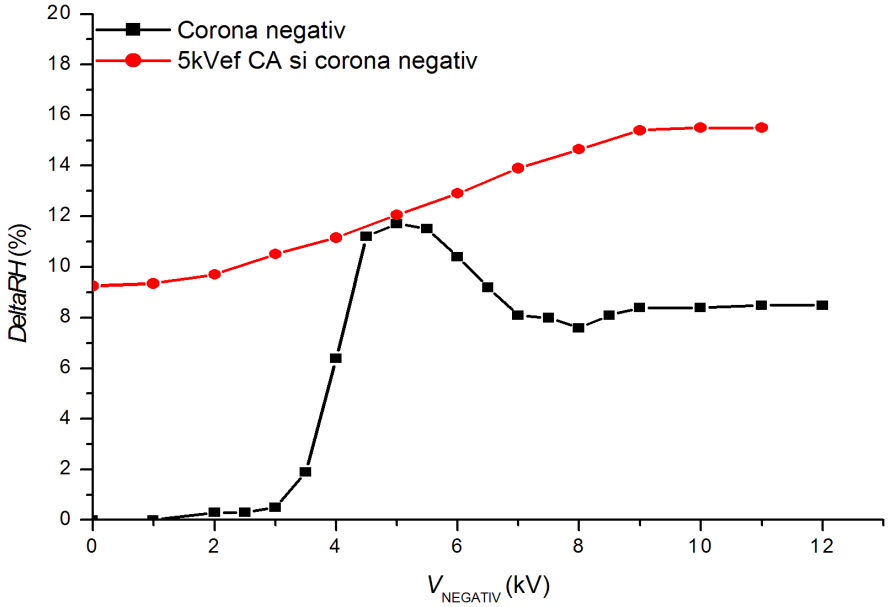


Figure 31. Characteristic of the condensation of water vapor in the electric field produced by an AC of 5 kV with a negative DC component, at the speed v = 17 cm/s.

Using an alternating voltage with an effective value of 2.5 kV, a determination of the humidity change at the outlet of the condensation reactor was performed by summing it with a negative direct voltage. The characteristic obtained is presented in figure 30.

Also in this graph is plotted for comparison the similar characteristic obtained by using the negative direct voltage without summation with the alternating voltage.

Figure 31 shows the characteristic obtained under conditions similar to the previous ones, but using an alternating voltage with an RMS of 5kV.

The obtained results reveal a linearization of the condensation improvement effect especially in the case of using the alternating voltage with the RMS value of 5 kV.

The downward slope observed in the case of using the negative corona effect (figures 23 – 25) at higher voltages, is greatly attenuated by the presence of the alternating voltage. This effect is valid both for the effective AC of 2.5 kV and for the value of 5 kV.

An improvement in condensation is highlighted at higher voltage values with a maximum obtained around 11 kV direct current and 5 kV AC, effective value.

The maximum value of about 15.5 percentage points additional to the intrinsic condensation, obtained in this way, demonstrates that by using the electric field and the corona effect as a generator of charge carriers, the condensation of water vapour can be substantially improved compared to a classic cooling system (chapter I). In the determinations made to obtain the characteristics in figures 30 and 31, the intrinsic condensation produced by the cold cylinder had the value of approximately 9.2 percentage points, the maximum value of the relative humidity difference measured being 24.8.

Comparing the values obtained for the condensation produced by the cold cylinder without the presence of an electric field and those obtained in the presence of the field, the improvement is 1.5 times.

Using this time a positive direct voltage, determinations were made in the same way as those previously exposed, obtaining the results presented graphically in figures 32 and 33.

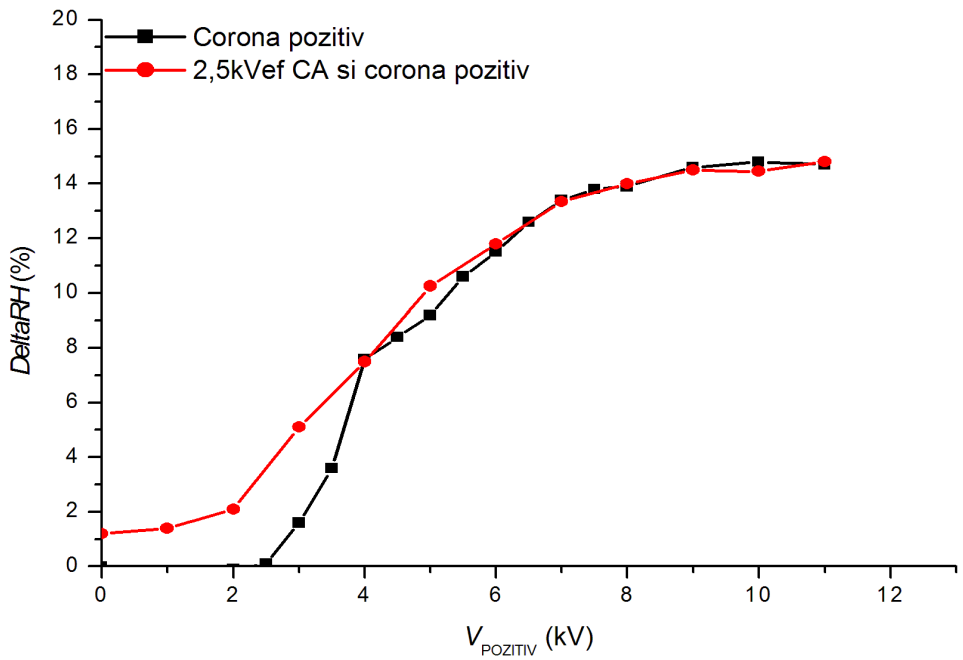


Figure 32. Caracteristic of the condensation of water vapor in the electric field produced by an AC of 2.5 kV with a positive DC component, at the speed v = 17 cm/s.

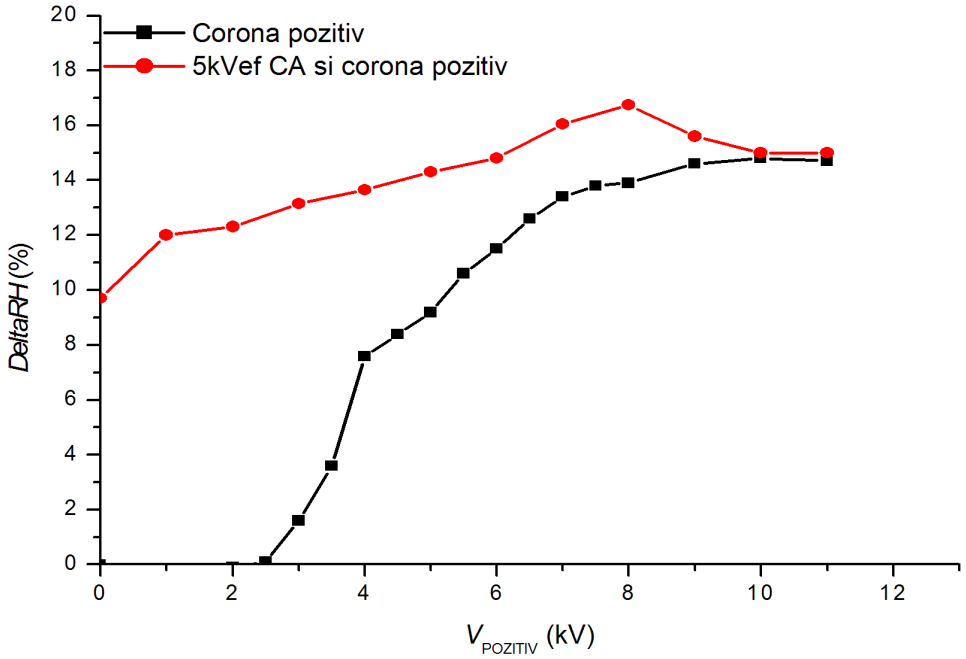


Figure 33. Characteristic of the condensation of water vapor in the electric field produced by an AC of 5 kV with a positive DC component, at the speed v = 17 cm/s.

According to these graphs, the trend of linearization of the effect is preserved, as in the case of the determinations presented in figures 30-31.

The effect of using alternating voltage here is much more pronounced for the case of using AC of 5 kV compared to the result presented in figure 31.

The case presented in figure 33 is special; judging by a pronounced increase in the effect that was observed at value of the DC voltage of 8 kV.

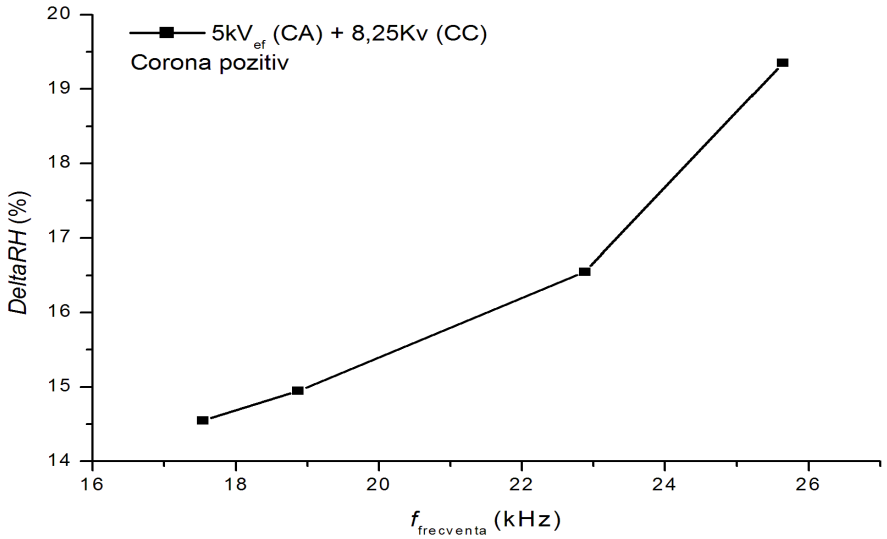


Figure 34. The frequency graph of the water condensation in the electric field produced by an AC current of 5 kV with a positive DC of 8.25 kV, at the speed v = 17 cm/s.

The improvement obtained in this area was up to 16.4 percentage points, better than the case presented in figure 31 where the negative corona discharge was used. Starting from these determined values, repeated experiments were carried out using DC voltage values around 8 kV as well as changes in the used frequency of the AC voltage.

The graph presented in figure 34 shows an improvement of the condensation in the reactor by up to 19.3 percentage points compared to the condensation that occurs in the absence of the electric field. The ratio obtained between the intrinsic condensation of the cold cylinder and the additional increase brought by the presence of the variable electric field is approximately twice.

This value was obtained at an alternating current frequency of 25.6 kHz, which was considered the upper limit of the high voltage power supply made for this experimental installation.

Also, for the above situation, the waveforms of the voltage and the intensity of the alternating current passing through the condensation reactor were determined.

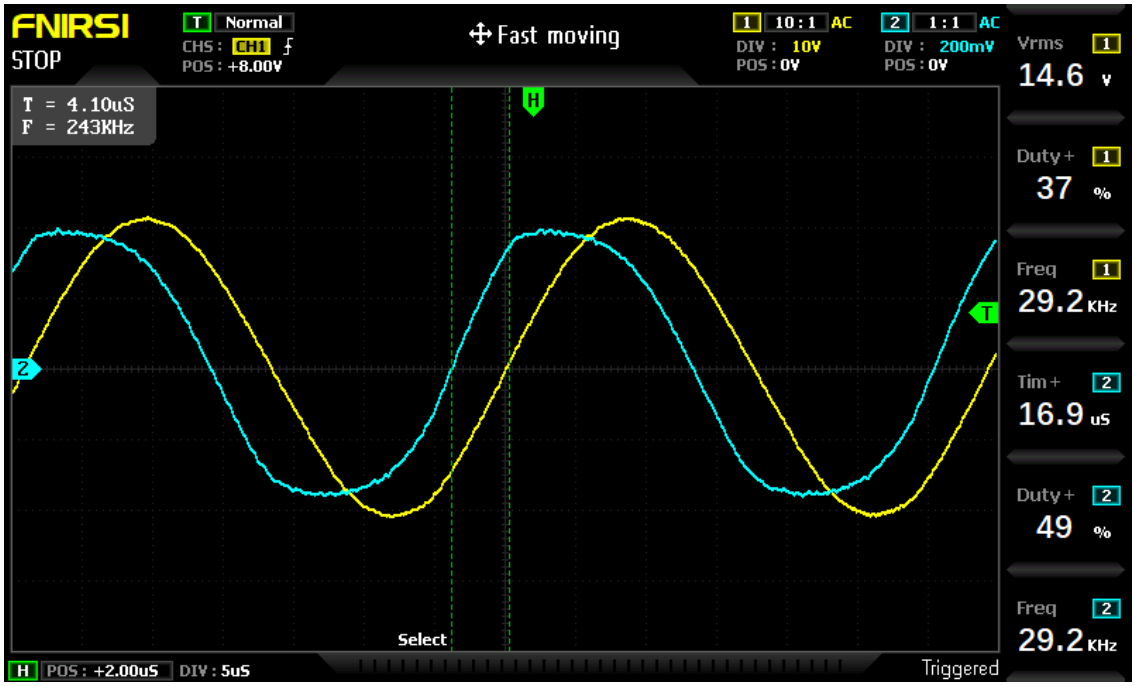


Figure 35. Waveforms for voltage (yellow) and current (blue) at 8.25 kV with alternating component of 5 kV rms and input humidity RH94%.

The determination was made with the help of an oscilloscope with acquisition using the Tektronix P6015A voltage probe, and to measure the current intensity a measurement shunt with the electrical resistance of 150Ω was made.

Through this specific determination, an alternating current intensity of 1.61mA and a phase shift of the current in front of the applied voltage of $\varphi=43^{o}$ were measured. The capacitive nature of the condensation reactor can be observed, which in the presence of water vapour with a high ε_r compared to that of the air in the mixture shows an obvious phase shift. The apparent power absorbed by the condensing reactor for the alternating component is 8.05 VA. This determined power is a part of the power absorbed by the electrostatic system, according to previous determinations from the point of view of the continuous component,

the absorbed power is $9.7 \bullet 10^{-1}$ W (8.25 kV and 120 μA). Also, the slight oscillation of the current flowing through the condensation reactor in the areas of maximum intensity was noted and which appeared only in the case of the positive corona phenomenon.

These small oscillations can be associated both with the non-uniformity of the positive corona discharges and with the Trichel [17 – 18] impulses characteristic of the corona discharge. In an attempt to determine the frequency of these oscillations, a maximum intensity around 1.21 MHz was obtained, the oscillations having a period of about 820 ns. The Trichel impulses of the corona discharges previously studied have length of μs and in the case of the present determinations the small oscillations recorded have similar durations.

4.3. Conclusions

The primary theme of the doctoral thesis was mainly aimed at studying the phenomenon of water condensation in a special reactor, in the presence of an intense electric field and of the space charge produced by corona discharges. The main effort was directed towards the creation of a special laboratory installation, adapted to the proposed theme, the development of experimental methods and procedures, the performance of a very large number of measurements and, last but not least, the processing and interpretation of the experimental data obtained.

A first important conclusion, based on the experimental results presented in the paper, refers to the fact that the contribution brought by the presence of corona discharges (regardless of their polarity) to the condensation phenomenon is a particularly important one. As mentioned above, this is explained by the fact that the presence of the intense electric field and the electric space charge determines the appearance of ponderomotive actions of electrostatic nature and dielectrophoresis forces that are exerted on electrically charged particles and, respectively, microparticles and water molecules. Also, the presence of ions contributes significantly to the intensification of the nucleation phenomenon. Last but not least, the electroaerodynamic phenomena induced by corona discharges play an important role in the production and intensification of the condensation phenomenon.

Another important observation, which emerges very clearly from the experimental data presented, indicates that in the case of applying a positive voltage to the corona electrode, the condensation efficiency is superior to that recorded in the case of applying a negative voltage. The explanations of such behavior are based on the nature of the ions generated by the corona effect, but also the strongly non-uniform character of the positive corona discharges which practically translates into the existence of discrete injection points located along the metal wire. It was found that the maximum condensation efficiency in the case of applying a positive continuous voltage was approximately one and a half times higher compared to the intrinsic condensation efficiency. In the case of negative discharge, a considerable decrease in the efficiency of the condensation process was highlighted for higher electrical potentials but also a slight increase in the outlet temperature, the probable cause being the Joule effect, corresponding to the corona discharge.

The results obtained also highlight the influence of the flow rate of the humidified air through the condensation reactor. With increasing air flow rate, a progressive decrease in condensation efficiency is observed in the presence of an electric field, regardless of the polarity of the applied electric potential. Of course, this is due to the fact that, with increasing flow rate, the time interval in which the air crosses the reactor decreases.

Regarding the use of an alternating voltage with a continuous component, the results obtained indicate a significant increase in the condensation efficiency. As presented in the paper, taking into account the fact that the bonds made by the water molecule are of electrostatic nature and that they present a certain elasticity, the application of a time-varying electric field influences the nucleation phenomenon to a significant extent. The possible explanation lies in the elasticity of the hydrogen bonds, weaker than the covalent ones, typical of the water molecule. The results obtained mark the premises of future experimental studies that will be dedicated to the influence of the frequency of the alternating component of the electric field on the condensation phenomenon. For such an approach, the need to generate high-frequency electric fields (up to two orders of magnitude higher than the maximum value used in this paper) can be anticipated.

Finally, the experimental results obtained in this study highlight the fact that the development of air humidity control installations or, as the case may be, water recovery from industrial processes or the atmosphere, which include elements generating intense electric fields and space charge, are a correct approach, which can bring important benefits in terms of operating efficiency.

4.4. Original contributions

In this paper, several elements of novelty and originality were mentioned in relation to the proposed topic, the laboratory installation made, the experimental procedures and, especially, the results obtained.

In summary, the original contributions resulting from the entire research activity carried out during the doctoral studies and materialized through this thesis can be mentioned:

1. Creation of an experimental laboratory installation for the study of water vapor condensation in the presence of an electric field and space charges. The installation was designed and built by our own means without using modules or components manufactured by industrial manufacturers;
2. Creation of an original corona condensation reactor equipped with a thermostated cooling system, which allows the study of the condensation phenomenon for a long time (on the order of hours);
3. Creation of a system for producing saturated humid air at ambient temperature, without using the water boiling process;
4. Creation of an automatic control system that allows obtaining different values of the relative humidity of the air used in the experiments;
5. Creation of a measurement system that allows the exact evaluation of the condensation efficiency of the corona reactor used in the experiments;

6. Creation of a high-voltage power supply to obtain types of high voltage with stabilized amplitude;
7. Creation of some determinations of the influence of the intense electric field and the space charge on the condensation of water vapor in the case of applying a high-frequency electrical voltage;
8. Creation of some experimental determinations regarding the influence of the frequency of the applied electrical voltage on the condensation efficiency;
9. Creation and practical use of some systems for monitoring the electrical parameters of the condensation reactor implemented within the high-voltage source designed and made in the laboratory;
10. Demonstration of the fact that in the presence of an alternating electric field with a continuous component, the condensation efficiency of a corona reactor increases significantly.
11. Plotting the condensation efficiency characteristics depending on the voltage, frequency and polarity values used.

4.5. List of original publications

1. S. -A. Vasiliu, C. -L. Popescu, A. Stanescu and L. M. Dumitran, "Efficiency of Water Extraction in an Electrostatic Wire-Cylinder System," 2023 International Symposium on Fundamentals of Electrical Engineering (ISFEE), Bucharest, Romania, 2023, pp. 1-5, doi: 10.1109/ISFEE60884.2023.10637018.
2. Alex-Ştefan Vasiliu, Laurentiu Marius Dumitran, "Effect of Superimposed DC and AC Electric Fields on Water Vapor Condensation in a Corona Reactor", Revue Roumaine Des Sciences Techniques — Série Électrotechnique Et Énergétique 70, No. 3 (August 30, 2025): 403–408. Accessed September 4, 2025. doi: 10.59277/RRST-EE.2025.3.20. Online: https://journal.iem.pub.ro/rrst-ee/article/view/1638.

4.6. Perspectives for further developments

Considering only the aspects exposed in the introductory chapter of this doctoral thesis, it can be considered that the subject addressed is one of great topicality. The experimental results obtained may constitute the seeds of similar future studies.

One of the future directions that can be developed (which has not been sufficiently investigated to date) is the influence of the electric field frequency on the condensation phenomenon. It is known that due to the elasticity of hydrogen bonds, the water molecule presents a resonance phenomenon at certain excitation frequencies. The development of a high-voltage generator, which can reach alternating voltage frequencies of the order of MHz, could provide answers to this problem.

Also, the development of numerical models that allow the simulation of the complex phenomena that occur in such reactors, can constitute an effective way of analyzing and optimizing their efficiency.

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