REVIEW-REPORT

of a PhD thesis

for the acquisition of the educational and scientific degree "doctor"

in professional direction 4.1 Physical sciences, Radiophysics and physical electronics

by defense procedure at the Faculty of Physics (FP)

of Sofia University "St. Kliment Ohridski" (SU)

The review-report was accomplished by: Professor DSc. Asen Pashov, Faculty of Physics at SU, as a member of the scientific jury according to Order No. RD 38-95/21.02.2023 of the Rector of Sofia University.

Topic of the PhD thesis: "Conversion of CO_2 in arc discharges at atmospheric pressure"

Author of the PhD thesis: Vladislav Valentinov Ivanov

I. General description of the presented materials

1. Information on submitted documents

The candidate, Mr. Vladislav Ivanov, has submitted a PhD thesis and an Author's abstract, as well as an autobiography, a bachelor's degree, a master's degree, a declaration of admission to the pre-defense, a declaration of authorship of the PhD thesis, a statement of contributions by the author (comparison table, FP), plagiarism protocol (Appendix 1), statement on plagiarism (Appendix 2), plagiarism report, scientific publications on the PhD thesis (3), according to the requirements of the Faculty of Physics at Sofia University "St. Kliment Ohridski".

The documents submitted by the candidate for the defense correspond to the requirements of the LDSCRB, LCLDSCRB and the Regulations for the terms and conditions for acquiring scientific degrees and occupying academic positions at SU "St. Kliment Ohridski" (RTCASDOAPSU).

2. Applicant data

Mr. Vladislav Valentinov Ivanov defended, with excellent grades, his bachelor's (2016) and master's (2018) degrees in "Communications and Physical Electronics" at the Faculty of Physics at SU "St. Cl. Ohridski", and the bachelor's degree includes an additional qualification - teacher of "Physics and Astronomy". Even as a student, Mr. Vladislav Ivanov actively participated in the group for the study of gas discharges and plasma, at the RFE department of the FP, where he worked with assoc. prof. Dr. Stanimir Kolev on the development of an asynchronous event-based kinetic model. Subsequently, from 2019, he was enrolled as a full-time doctoral student at the RFE department, supervised by assoc. prof. Dr. Stanimir Kolev. The topic of the doctoral study is aimed at the theoretical and experimental study of direct current (dc) discharges with a gliding arc, at atmospheric pressure and a current below 1 A, with a view on the dissociation of carbon dioxide (CO_2). In this regard, the doctoral student is part of the team in two large scientific projects, respectively, at the National Fund for Scientific Research (of the Ministry of Education and Culture) and

the National Center for Mechatronics and Clean Technologies. During his doctoral studies, Mr. Vladislav Ivanov showed a wide range of scientific interests, giving expression to his active participation and significant contribution to the overall work of the team. The high impact factor of the main scientific publications on the PhD thesis (IF: 4.004 and 7.84) is impressive, as well as the participation in a scientific conference with an oral report and winning the first prize for the best poster in the field of low-temperature plasma. Professionally, Mr. Vladislav Ivanov has remarkable experience and skills in software technologies for visualizations and simulations, which gives a positive impact on analyzing and solving complex physical problems. At the beginning of 2023, within the third year of the doctoral studies, Mr. Vladislav Ivanov fully covers the requirements for training and research work from the individual plan and, by the decision of the Faculty Council of FP, from the same year, he was dismissed with the right of defense.

3. General description of the candidate's scientific achievements

The researches on dissociation of CO_2 are motivated by the development of ecologically clean technologies, which is the main direction in the current development of the industry. A key factor in these technologies is their energy efficiency. In this regard, the application of an arc discharges at atmospheric pressure appears as one of the efficient methods for the effective dissociation of CO_2, which, in turn, makes the research in this area, of which the present PhD thesis is a part, extremely **relevant and significant**.

The scientific achievements of the candidate, reflected in the PhD theses, are expressed in **two articles in journals with an impact factor** [B.1 and B.2] (respectively, quartiles Q1 and impact factor 4.004 and 7.84 (Scopus)) and **one conference report** [B.3], published in full text (quartile Q4, refereed, without impact factor). The candidate is the **lead author with a major contribution** in all three scientific publications [B.1, B.2 and B.3] on the PhD thesis. The candidate has **three participations at scientific conferences**, of which two poster presentations [B.1 and B.3] and one oral presentation [B.2]. It should be noted that one of the poster papers [B.3] won the first prize, for the best poster in the field of low-temperature plasma. Apart of the publications on the theses, the candidate has one conference paper [Г.1] published in full text (quartile Q4, refereed, without impact factor).

The scientific publications included in the PhD thesis **completely meet the minimum national requirements** (according to Art. 2b, paras. 2 and 3 of the LDSCRB) and, accordingly, to the additional requirements of SU "St. Kliment Ohridski" for the acquisition of the educational and scientific degree "doctor", in the relevant scientific field and professional direction.

Based on the **provided documents** – author's statement of contributions (comparison table, FP), plagiarism protocol (Appendix 1), statement on plagiarism (Appendix 2) and plagiarism report – it can be stated with full conviction that:

The scientific publications included in the PhD these **do not repeat those from previous procedures** for acquiring a scientific title and academic position.

There is **no proven plagiarism** in the submitted PhD theses and Author's abstract.

4. Characterization and assessment of the candidate's teaching activity (if there is a requirement for this in RTCASDOAPSU)

In the RTCASDOAPSU and the internal rules of the FP, there is no requirement for teaching activity. However, I would like to note that during his doctoral studies, Mr. Vladislav Ivanov led the practical exercises for the course "Space and gas discharge plasma simulation ".

5. Content analysis of the scientific and scientific-applied achievements of the candidate in the materials for participation in the contest

The researches on the PhD thesis are part of the work of the author's collective, to which the candidate also belongs, on the theoretical and experimental study of dc discharges with a gliding arc (at atmospheric pressure and current below 1 A), with a view to the dissociation of CO_2, within two projects:

"Investigation and optimization of CO_2 dissociation in a gliding arc discharge", National Scientific Research Fund, MES - KP-06-OPR 04/4 of 14.12.2018;

European Regional Development Fund within the Operational Program "Science and Education for Smart Growth 2014 - 2020 Project CoE "National center of mechatronics and clean technologies" BG05M2OP001 − 1.001 − 0008 − CO1.

The work on the PhD thesis is theoretical and experimental, and the experiments were carried out entirely in laboratory A402 of the FP at SU.

The abstract is in Bulgarian and English; it is clearly structured and fully reflects the content of the PhD thesis.

The PhD thesis includes an Introduction, three Chapters, a Conclusion, a Bibliography, a List of Figures and a List of Tables. Its total volume is 124 pages, containing 45 figures, 4 tables and 84 cited literary sources. The exposition is of a high scientific style and technically meticulously designed. The results are presented with a deep understanding of the researched problems as well as the methods and techniques used.

In the Introduction of the thesis, after a brief overview of the dissociation mechanisms, the theory of dc discharges and the application of arc discharges for dissociation of CO_2, the goal and set tasks are clearly formulated. **The main objective** is to study the properties of dc discharges (30 – 200 mA) with magnetic stabilization and gliding arc, in the configuration of flat diverging electrodes, at atmospheric pressure, with a view to the dissociation of CO_2. **The specific tasks** are:

1) Investigation of the effect of gas flow and magnetic force on the behavior of a magnetically stabilized arc discharge in argon, by means of a developed two-dimensional numerical model.

2) Construction (and equipping with the relevant components) of an experimental setup for the study of arc discharges at atmospheric pressure.

3) Experimental study of different discharge configurations for dissociation of CO_2, at atmospheric discharge and low currents (25 – 200 mA).

4) Investigation of the behavior and properties of the discharge at low currents (below 200 mA) and analysis of its mode of operation.

The formulation of the tasks fully corresponds to the purpose of the PhD thesis.

In Chapter 1, an in-depth and fully comprehensive literature review based on the use of 53 sources is made, in view of the purpose and tasks of the PhD thesis. Essentially, this part examines the different types of dc discharges, presents the theoretical description of processes in gas discharge plasma, summarizes the main characteristics of the CO_2 molecule and presents the specifics of its dissociation. At the end of this part, the results known from the literature on energy efficiency and the degree of dissociation "conversion" of CO_2 at different discharges are summarized.

Chapter 2 of the PhD thesis presents the theoretical studies on the qualitative behavior of dc discharges with transverse magnetic stabilization of the arc, at atmospheric pressure and low currents (below 1 A). They are based on one scientific publication [B.1] (quartile Q1, impact factor 4.004 (Scopus)) in which the candidate is the lead author. His contribution is essential, expressed both in the development of the model (accounting for the effects related to the external magnetic field and the gas flow) and in obtaining and analyzing the numerical results. Currently, there is no data available on citations and reflection of the candidate's results in the works of other authors.

Essentially, Chapter 2 examines the first task formulated in the Introduction of the PhD thesis and reflects the first four scientific contributions presented in the Conclusion.

Within the framework of this task, a theoretical model based on the fluid theory of plasma, of a magnetically stabilized arc discharge, accounting for its external electrical circuit, was developed. The aim is to study the effect of the gas flow and the magnetic force on the spatial and temporal behavior of a magnetically stabilized arc discharge at atmospheric pressure and low currents (below 1 A). The model is two-dimensional, for the cross section of the arc, with a constant electric field along its length and the presence of a transverse external magnetic field. The model is applied to argon instead of CO_2, which is well argued in the thesis. (The type of gas does not change the general behavior of the discharge, on a qualitative level, and modeling gases with complex kinetics is extremely difficult.) The candidate has undoubtedly coped with the task, which is clearly determined by the presence of a scientific publication in the Q1 quartile. The obtained numerical results of the developed model can be summarized in the following way: The intervals of gas velocity are determined, in which magnetic stabilization of the arc is achieved (i.e., the magnetic force and the friction force of the plasma with the gas flow are balanced). The existence of three behavior modes was established, depending on the distance between the side walls (W_D) and the diameter of the arc (r_{arc}) – formation of a stable arc in the middle of the gas channel ($W_D \approx r_{arc}$), sticking to one of the walls ($W_D > r_{arc}$) and centrally oscillating arc ($W_D >> r_{arc}$) – and physical reasons for this behavior have been identified. Some basic characteristics of the arc – force and effective coefficient of friction with the gas flow and the effective radius of the positive discharge column – are obtained by applying a solid-state-in-moving-fluid model.

These results are clearly reflected in the first four scientific contributions of the candidate, indicated in the Conclusion of the PhD thesis. They significantly enrich the existing knowledge, in the field of plasma physics, about the behavior of dc discharges with transverse magnetic stabilization of the arc, at atmospheric pressure and low currents (below 1 A). Also, they have the necessary potential for application in practice, which is done in the next Chapter of the PhD thesis.

In Chapter 3 of the PhD thesis, the experimental studies on CO_2 dissociation are presented. They are based on two publications [B.2 and B.3] (respectively, quartile Q1, impact factor 7.84 (Scopus) and quartile Q4, refereed, without impact factor) in which the applicant is the lead author, which undoubtedly determines essential contribution to them. Currently, there is no data on available citations and reflection of the candidate's results in the works of other authors.

In essence, Chapter 3 considers the remaining three tasks (from 2 to 4) formulated in the Introduction of the PhD thesis, and their results are reflected in four scientific and two "Personal" contributions, presented in the Conclusion.

The first task set in this part is the construction of an experimental setup for CO_2 dissociations, based on a gliding arc/glow discharge, with external magnetic stabilization. The task is fully accomplished, and it is essential to note that the candidate takes a major part in the design, construction and equipping of the entire experimental setup, as well as software for processing the experimental data from the measurements. In the Conclusion of the PhD thesis, this is reported as "Personal Contributions".

The second task in this part is related to an experimental study of CO_2 dissociation at atmospheric pressure in low-current discharges with gliding arc and external magnetic stabilization. Mainly two quantities were investigated – degree of conversion of CO_2 and energy efficiency of the process – for three configurations of the discharge and different flow of the supplied gas. This choice is logical and well-motivated in the PhD thesis. The first configuration studied is classical, without the presence of an external magnetic field. It allows the identification of the effects associated with its application in the other two configurations. In the second configuration, the magnetic force accelerates the arc, providing a shortening of the time between ignition and extinction of the arc. In the third configuration, the magnetic force slows down the arc, which ensures its stabilization and increases the time of plasma phase. This configuration corresponds to the theoretical studies presented in Chapter 2 for a magnetically stabilized discharge. The candidate did an excellent job of completing the entire task, and it should be noted that an analysis of the uncertainties was also performed here. The obtained experimental results (conversion ~ 8% and energy efficiency above 30%) are in very good quantitative agreement with similar studies from the literature. At a qualitative level, the following trends in discharge behavior were found: For all configurations, an increase in gas flow leads to a decrease in CO_2 conversion and an increase in energy efficiency. The configurations without stabilization (1 and 2) maintain a high conversion value for a wider gas flow interval, but are unstable and less efficient than those with stabilization. The configurations with magnetic stabilization show high efficiency, but only at low values of gas flow. Also, the transverse

instability effect of a stabilized arc in a gas flow – at a gas channel width greater than the effective diameter of the arc – derived from the numerical model in Chapter 2 is experimentally confirmed.

These results are set out in the candidate's fifth and sixth scientific contributions given in the Conclusion of the PhD thesis.

The shown effects of the application of a transverse external magnetic field and the gas flow rate on the dissociation of CO_2, in a gliding ark discharge (below 1 A), form the general trends in the behavior of this type of discharges, which significantly enriches the existing knowledge in this area. These trends have a basic character for the research and practical development of CO_2 dissociation devices.

Within this task, the influence of the material of the electrodes and the presence of side quartz glasses, limiting the arc and the gas flow in a transverse direction, were also investigated. It was found that: Lateral discharge confinement has a positive effect on conversion and energy efficiency. Electrode material with higher thermal conductivity provides higher conversion, but at lower energy efficiency. These results are not included in the candidate's contributions indicated in the PhD thesis, but should be taken into account with their scientific-applied nature.

The third task in this part is on the experimental study and determination of the discharge regime operation, in the configurations with and without magnetic stabilization. In the performance of this task, a fast I-CCD camera (PI-Max) was used, through which the temporal and spatial evolution of the discharge was observed, in combination with synchronized measurement of the electrical parameters of the discharge. The execution of the assigned task is impeccable. The qualitative analysis of the cathodic processes shows that the discharge can operate both in glow and in arc regime, and with regard to the dissociation of CO_2, the latter provides optimal operation. It is shown that by means of the applied methodology it is possible to estimate the current density and the intensity of the electric field in the region of the positive column of the arc.

These results are reflected in the last two (seventh and eighth) scientific contributions of the candidate, from the Conclusion of the PhD thesis.

Their character has a pronounced scientific and applied orientation.

At the end of Chapter 3, an additional section is presented in which a wall-stabilized arc discharge in a cylindrical geometry is considered. This configuration is considered as a future direction for the development of the work and is not part of the specific tasks of the PhD thesis. However, its potential is clear: Realization of an experiment whose geometry and configuration allows the application of one-dimensional models, which would significantly facilitate the study of the processes related to the complex kinetics of CO_2.

The conclusion of the PhD thesis is standard, including a brief description of the researched problems, a list of the candidate's scientific contributions, a list of publications and participation in conferences, as well as acknowledgments.

6. Critical notes and recommendations

The only critical notes on the PhD thesis and the Author's abstract are of a purely technical nature, related to the presence of some typographical errors and inaccuracies such as: redefinition of designations and physical quantities; partial use of foreigners, typos in some expressions (pressure tensor (p. 37) and (1.44), (1.61), (1.64)) and the lack of literature reference to others (the kinetic energy mobility (1.63), the value of the coefficient β in (1.64), and Fig. 1 of the Author's abstract); presence of undefined quantities (in equation (9) from the Author's abstract); at the end of the literature review (Chapter 1) the advantage of considered in the PhD thesis discharge is not stated and "Personal Contributions" should be given as "Additional Contributions". The noted inaccuracies are mainly in the overview part of the PhD thesis and the Author's abstract. Their number is very small and they do not change the positive impression of the high level of literary awareness, exposition, analysis, accuracy and completeness of the obtained results, as well as their relevance and significance.

7. Personal impressions of the candidate

I do not know the student personally, but my colleagues whom I trust, know Mr. Vladislav Ivanov as a person with a high level of theoretical and practical knowledge, showing methodicality, thoroughness and independence in his work, as well as a developed approach to the analysis and interpretation of the obtained results.

8. Conclusion

After having familiarized myself with the presented PhD thesis, Author's abstract and other materials, and based on the analysis of their significance and the scientific and scientific-applied contributions contained in them, I **confirm** that the scientific achievements meet the requirements of the LDSCRB and The Regulations for its application and the relevant Regulations of the SU "St. Kliment Ohridski" for **the acquisition of the educational and scientific degree "Doctor"**. In particular, the candidate satisfies the minimum national requirements in the professional field and no plagiarism has been found in the PhD thesis, abstract and scientific works submitted for the competition.

I give my **positive** assessment of the PhD thesis.

II. GENERAL CONCLUSION

Based on the above, I **recommend** the scientific jury to award **the educational and scientific degree "Doctor"** in professional direction 4.1 Physical Sciences, Radiophysics and Physical Electronics to Mr. Vladislav Valentinov Ivanov.

21.05.2023 Prepared the review-report: .....

(prof. DSc Asen Pashov)