FONDUL SOCIAL EUROPEAN
Investeşte în oameni
Programul Operaţional Sectorial pentru Dezvoltarea Resurselor Umane 2007 – 2013
Axa prioritară 1 „Educaţia şi formarea profesională în sprijinul creşterii economice şi dezvoltării societăţii bazate pe cunoaştere"
Domeniul major de intervenţie: 1.5 „Programe doctorale şi postdoctorale în sprijinul cercetării"
Titlu proiect : Cunoastere, inovare si dezvoltare prin burse doctorale (CID-Doc)
Cod contract: POSDRU/187/1.5/S/155536

UNIVERSITY **POLITEHNICA** OF BUCHAREST

Faculty of Mechanical Engineering and Mechatronics
Department of Thermodynamics, Engines, Thermal and Refrigerating Equipment's

PhD THESIS ABSTRACT

The influence of fine bubbles generators architecture on the dissolved oxygen concentration in water
Influenţa arhitecturii generatoarelor de bule fine asupra creşterii concentraţiei de oxigen dizolvat în apă

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Bucharest

2017

SUMMARY

PREFACE

The elaboration of a Ph.D. thesis in "Mechanical Engineering" domain requires a special scientific training, comprising a wide area of knowledge from various fields such as mathematics, physics, chemistry, electricity, materials resistance, mechanics and others. But the challenge, considering the educational standards of the University Politechnica of Bucharest, consists of more than the assimilation of knowledge or a simple filtering of the information essence. The real challenge is to be able to find solutions for a better future at the crossing of various complex areas. This is one of the fundamental values of the University Politechnica of Bucharest, with which the present work tries to align.

I would like to thank Mr. Prof. emeritus dr. eng. Nicolae Băran from the Department of Thermotechnics, Engines, Thermal and Refrigeration Equipment, who was my PhD coordinator and directed me with goodwill and patience on the sinuous road of building a theoretically and experimentally useful core, in the context of the work that I proposed. I also thank Mr. Dean Prof. emeritus eng. Alexandru Dobrovicescu and Mr. Director of the Department of Thermotechnics, Engines, Thermal and Refrigeration Equipment, Conf. dr. eng. Valentin Apostol for the support they offered me in the accomplishment of my work. At the same time, I thank the teaching and the auxiliary staff of the aforementioned department for their support in this doctoral thesis.

I thank the members of the doctoral committee:

- President: Prof. dr. eng. Octavian Donţu, from F.I.M.M.;
- Referent: Prof. dr. eng. Tudora Cristescu, from I.P.G. Ploiesti;
- Referent: Prof. dr. eng. Gabriel Ivan, from U.T.C. in Bucharest;
- Referent: Prof. emeritus dr. eng. Valeriu Panaitescu from the Faculty of Energetics,

who had the patience to read this paper and to offer a series of advice for its improvement.

When conducting my experimental researches, I was also assisted by As. dr. eng. Mihaela Constantin, As. drd. eng. Beatrice Tănase and eng. Mădalina Zamfir, to whom I would like to address my special regards.

Finally, I would like to thank my family for their moral and material support in the accomplishment of this work.

I dedicate this work to my beloved family,
who helped and encouraged me
through all the process of elaborating my thesis.

Ph.D. student eng. Rasha Mlisan (Cusma)

MAIN NOTATIONS

∗ Roman letters
a – the specific interface area [m^2/m^3];
ak_L – mass transfer volumetric coefficient [s^{-1}];
C – current mass concentration of the transferrable component in liquid phase [kg/m^3];
C_s – mass concentration of the transferrable component at saturation [kg/m^3];
V – volume [m^3];
∗∗ Abbreviations:
OD– oxygen deficiency;
EPA – United States Environmental Protection Agency;
G.B.F. – fine bubble generators;
∗∗∗ Greek letters:
α_0 – O_2 percent of the air instilled into the tank [%];
ε – void fraction;
η – dynamic viscosity [Ns/m^2];
η_{ox} – oxygenation efficiency [%];
ν – kinematic viscosity [m^2/s];
ρ – density [kg/m^3];
τ – functioning time [s].

INTRODUCTION

The paper, summing up 147 pages, 119 figures and 15 tables, is rationally structured in 8 chapters, to which are added in the beginning: the Preface, the List of Main Notations, the List of Figures, the List of Tables, the Introduction and in the end, the Conclusions, Bibliography and Annexes.

In the Preface, the author makes short references regarding the researches on the influence of the architecture of the fine bubble generators on the wastewater oxygenation and gives thanks to the people who in one way or another have contributed to the moral support necessary to complete the doctoral thesis.

In the Introduction, some elements of the addressed problem and the theoretical and practical framework of the PhD thesis developments are presented. Thereby, the choice of the research area is justified, several general aspects regarding the oxygenation phenomenon of the wastewater are presented, the objectives of the study are listed and a general presentation of the paper is made.

Chapter 1, Current state of research on water oxygenation processes, addresses the need for aeration of free-surface waters, lists the main physical properties of water and highlights the dissolved oxygen content as the most important indicator of water quality. A classification of water aeration systems according to several criteria is performed; for instance, depending on the procedure of obtaining an interphase contact surface, the movement of the active aeration device, the aeration gas, the gas introduction system. The surface, medium and high depth mechanical aeration systems are briefly described. The pneumatic aeration systems are emphasized, especially the fine bubble generators. The conclusions of the chapter highlights that the best aeration system is the pneumatic type, particularly noticing the fine bubble generators, with orifices manufactured through spark-erosion or micro drilling.

Chapter 2, Theoretical study of water oxygenation processes, refers to the complex problem of researches on the aeration phenomenon. First of all, the issue of mass transfer, including the presentation of Fick's first and second law, is examined. Particular attention is paid to the numerical integration of the equation of oxygen transfer rate to water, an ordinary differential equation that can be solved through numerical methods. The author opts for the Euler method, a step-by-step and explicit algorithm method, which she presents in detail. From the calculation methods of the volumetric transfer coefficient known in the specialty literature, the theory of the two films (based on the fact that the gas molecules have to cross the two films existing on each side of the gas-liquid interface) and the penetration theory (applicable to the turbulent mass transfer, for the gases that are poorly soluble in water) are outlined by the author. In this chapter, an analysis of the geometric and functional parameters that intervene in the process of water oxygenation is performed. The conclusions of the chapter refer to the need to analyze the factors involved in the equation of oxygen transfer rate to water and the influence of the bubble generator architecture on the increase in the dissolved oxygen concentration in water. Finally, some personal contributions of the author are highlighted.

Chapter 3, Theoretical and experimental researches on fine bubble generators, presents two types of fine bubble generators, consisting of perforated plates, designed and manufactured for a theoretical and experimental comparative study: a circular shape bubble generator, in which the orifices are positioned in a circular pattern, respecting the required conditions for the ratio between the thickness of the perforated plate and the diameter of the orifice and the distance between the two orifices on the same line and the diameter of the orifice; a fine bubble generator with a perforated rectangular plate, respecting the same constructional features related to the orifices and the thickness of the perforated plate. The purpose of the researches is to make a comparison between the two types of fine bubble generators, circular and rectangular. The variation curves of the dissolved oxygen concentration in water were theoretically obtained in report with time, through the numerical integration of the differential equation of the oxygen transfer rate in water for the two types of fine bubble generators. The same curves of variation of the dissolved oxygen concentration in water as functions of time, for the two types fine bubble generators, have been experimentally determined using a modern laboratory facility, equipped with performant measuring and control equipment's and data recording and processing systems. The theoretical and experimental researches have led to the conclusion that the rectangular shape bubble generator is more efficient than the circular shape type in regards to increasing the dissolved oxygen content in water in the same operating conditions (inlet air flow rate, compressed air pressure, volume of aerated water, aeration time) and the same constructional features (regarding the orifices and the thickness of the perforated plate). A series of personal contributions are listed within the chapter.

Chapter 4, Research on the influence of the shape and dimensions of a fine bubble generator on the dissolved oxygen concentration in water, is an important part of the doctoral thesis. The influence of the air input orifice diameter on the dissolved oxygen concentration in water is studied. The author proposes a new generation of fine bubble generators in which the air dispersion orifice with diameters of 0.1 mm, 0.3 mm and 0.5 mm are processed through micro-drilling (with a special micro-processing machine, KERN Micro, which has an accuracy of ± 0.5 μm). By running the computational program for the numerical integration of the differential equation of the oxygen transfer rate in water, the graphical representation of the variation of the dissolved oxygen concentration in water as a function of time for the three types of the fine bubble generators corresponding to the three orifice diameters, is generated. The efficiency and effectiveness of the oxygenation process for the three types of generators are determined. The conclusions of the chapter point out that all three types of generators provide rapid and efficient oxygenation of the wastewater, but from the comparison of the three versions, while keeping a constant air flow rate and the hydrostatic load, the fine bubble generators with 0.1 mm orifice are the most efficient. The personal contributions of the chapter are also listed.

Chapter 5, The influence of the bubble generator network architecture on the dissolved oxygen concentration establishes the distance between two orifices on the same line, considering that this distance must exceeded the diameter of the final air bubble at the exit from the water layer (in order to avoid bubble coalescence), using an appropriate computation program. The researchers are continued by establishing the distance between two orifice lines, studying the architecture of the fine bubble generator network located on the foundation of a water tank in the two versions known in the literature: fine bubble generators composed of porous diffusers that create bubble columns and fine bubble generators with micro-drilled orifice plates that create bubble curtains. The correlation between the dissolved oxygen concentration in water and the number of fine bubble generators is studied. The conclusions of the chapter point out that the distances between two orifices on the same line and between two lines, for fine bubble generators with micro-drilled plates, are determined taking into account the diameter of the orifice and the hydrostatic load, while simultaneously respecting the condition for avoiding the bubbles coalescence. The use of a larger number of fine bubble generators significantly shortens the time required for the oxygenation process. The personal contributions of the chapter are also listed.

Chapter 6, Analysis of the energy consumption in the water oxygenation processes is required in order to determine the optimal number of fine bubble generators that will lead to the smallest energy consumption, in conjunction with a reasonable oxygenation time. For the fine bubble generator with orifices of 0.1 mm, knowing the volumetric flow rate and the input air pressure and estimating the efficiency of the compression process, the mechanical power required at the compressor coupling was calculated. Considering the time duration of the oxygenation process for the operation of 1, 2, 3 and 4 fine bubble generators, determined in the previous chapter, the corresponding energies were calculated and the graph of the required mechanical energy variation was plotted according to the number of fine bubble generators.

Chapter 7, Conception and design of the experimental installation, begins with the presentation of the scheme, whose complexity is represented by the existence of three parts: mechanical, electrical and electronic. The main qualities of the experimental installation are mentioned and the operation process is described, emphasizing the possibility of instantaneously measuring the oxygen concentration in water. The polarographic probe of the oxygen meter performs a rotation motion, transmitted through a rack belt from an electric motor. The conclusions of the chapter refer to the performance of the experimental installation, which allows high precision measurements and is equipped with modern digital measuring instruments.

Chapter 8, Experimental researches on the influence of the architecture of fine bubble generators on the dissolved oxygen concentration, defines as the objective of the experimental researches, the study of the influence of an orifice diameter and the distances between the orifices for the three versions of fine bubble generators with plates perforated by the doctoral student, through micro-drilling, as well as the study of the influence of the fine bubble generator network architecture on the dissolved oxygen concentration in water. The purpose of these researches is to compare the experimentally obtained results with the theoretically ones, in order to validate it. The measuring instruments used for the experimental researches are presented: digital thermometer (including a microprocessor that analyzes the data received from the temperature sensor), digital differential manometers (composed of a piezo-resistive transducer and an electronic microprocessor with digital display), flow meter (rotameter), and oxygen meter (with polarographic probe). The measurement methodology is also presented.

Experimental researches are conducted regarding the influence of an orifice diameter and the distances between the orifices, on the dissolved oxygen concentration in water, for the three types of fine bubble generators studied in Chapter 4; the experimental results are presented in tables and graphically and compared with the theoretical results, a satisfactory concordance being noted. An experimental study has been performed regarding the influence of the architecture of the fine bubble generator network on the dissolved oxygen concentration in water, placing 1, 2, 3 and 4 identical bubble generators in the water tank. The conclusions of the chapter refer to the confirmation of the theoretical results obtained previously. The author's main personal contributions are highlighted.

Conclusions, the last part of the PhD thesis, are systematized in three parts. The general conclusions of the study are highlighted, emphasizing the importance, modernity, complexity and topicality of the issues addressed and summarizing the conclusions of each chapter. The **original contributions** of the researches are presented, following the order of their appearance in the paper. Several directions of future researches in the studied area are also proposed.

The bibliography is representative and modern; containing reference papers in the studied domain, and is composed of 111 titles. Previous papers of the thesis author, related to solving the objectives of the thesis, are also mentioned.

The appendix contains the **List of papers published by the author of the doctoral thesis**, highlighting articles published in ISI-rated journals with impact factor, articles published in BDI-rated journals, articles published in the volumes of national and international scientific events, a paper in the Scientific Bulletin of UPB and a book, to which the doctoral student is the first author or co-author.

The **Contributions** and original developments of the thesis author are important. They can therefore be emphasized, in the order of appearance in the paper:

Theoretical Contributions

- An extensive analysis of the theoretical, numerical and experimental state of the art of researches on the influence of fine bubble generators architecture on the dissolved oxygen concentration, based on an extensive documentation, a rigorous selection of the specialized bibliography and also taking into account her own activity in the area, taking place in recent years.

- Identification and presentation, in a coherent scientific way, of the problems related to the analysis of the hydro-dynamic and geometric parameters involved in the water aeration process and to the numerical integration of the differential equation of the oxygen transfer rate to water.
- Elaboration of a theoretical study regarding the comparison of two types of fine bubbles generators, circular and rectangular, with orifices performed through spark-erosion; the curves of variation of dissolved oxygen concentration in water in time were obtained by numerically integrating the differential equation of the oxygen transfer rate to water for the two types of fine bubble generators and concluding that the rectangular shape is more advantageous.
- The graphical representation of the variation of the dissolved oxygen concentration in water in time and the determination of the efficiency and effectiveness of the oxygenation process for three types of rectangular fine bubble generators, with different orifice diameters, resulted from the computation program that performs the numerical integration of the differential equation of oxygen transfer rate in water.

  The study of the influence of the fine bubble generator network architecture on the dissolved oxygen concentration in water, based on which the distances between two orifices on the same line and between two lines are determined, considering the diameter of the orifice and the hydrostatic load and respecting the condition of avoiding bubbles coalescence.
- The analysis of the mechanical energy consumption according to the number of fine bubbles generators placed in water and the determination of the optimal number of fine bubble generators for minimal energy consumption.

Numerical Contributions

- The detailed expression of the Euler numeric method, with separate steps and explicit algorithm, for integrating the ordinary differential equation of the oxygen transfer rate to water, together with the presentation of the logical calculation scheme.
- The determination of the variation of the dissolved oxygen concentration in water in time, considering the initial and the saturation concentration of oxygen, at a given water temperature, appropriately choosing the integration step and elaborating the program for the graphical representation of the oxygen concentration variation in time.

- Design and development of a calculation program for determining the final diameter of a bubble, depending on the hydrostatic load and the diameter of the orifice.
- Construction of the curve representing the variation of the required oxygenation time, according to the number of fine bubble generators to study the influence of fine bubble generator architecture on the oxygen concentration in water.
- Development of a calculation program for the determination of the energy consumption curves and the curves that describe the time duration of the oxygenation process in regards to the number of fine bubble generators.

Experimental Contributions

- Conception and design of the laboratory workbench for the experimental study of two types of fine bubble generators, circular and rectangular, with orifices performed through spark-erosion, equipped with performant measuring devices (digital thermometer, digital differential manometers, rotameter, oxygen sensor with polarographic probe, electronic recording and data processing system).
- Specifying and detailing the purpose and methodology of the experimental researches, indicating the succession of the measurement steps.
- Experimental study of the influence of an orifice diameter and of the distances between the orifices, for the three types of fine bubble generators with perforated plates manufactured by the Ph.D. student, as well as the study of the influence of the fine bubble generator network architecture on the dissolved oxygen concentration in water.
- Analysis of the influence of the fine bubble generator network architecture on the dissolved oxygen concentration in water, by placing 1, 2, 3 and 4 identical bubble generators in the water tank.
- Suggestive presentation of the obtained experimental results, in table and graph form, for all the researched cases and the comparison between the experimentally determined results and the theoretically obtained results (resulting in a good similarity) in order to establish the most favorable architectural type regarding the increase rate of the dissolved oxygen concentration.

The author suggests some possibilities for further researches development.

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