Summary of the Ph.D. theses

Examination of thermoacoustic phenomena in project work

Tamás Beke

Supervisor: Dr. Katalin Papp

Doctoral School of Physics

University of Szeged
Faculty of Science and Informatics
Department of Experimental Physics

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1. Introduction

Considering the science education system of the EU we can state that there is an alarming decline in young people's interest in science studies and mathematics. For the future of Europe it is crucial to develop the education of natural sciences, and for this it is necessary to act on local, regional, national and EU-level. Teaching Physics and other Science subjects with the traditional methods are unintelligible and considered unnecessary for most students; this situation needs to be improved. The scholastic natural scientific projects answer the purposes as a collaborative, knowledge-sharing method. In this work I was going to examine the characteristics of the project method in the science studies.

There is an obvious need for preparing young people for a future that will require profound scientific knowledge and an understanding of technology. Science literacy is important for understanding environmental, medical, economic and other issues of modern societies. In my thesis I wish to introduce the project method which is suitable for popularize science subjects (physics, chemistry, biology, geography, IT) on different levels of education from primary school to university.

In the introductory part of my thesis, I introduced the problems which may occur recently while teaching science subjects. I paid special attention to the situation of science subjects and to the problems of their teaching and learning. The aim of the second part of my thesis was to view the role of motivation in the learning process of science subjects. In this chapter I presented the possible pedagogical usage of project method. In the course of the theoretical review, I presented the methodological development of project method. I introduced the different definitions of project method; I emphasized their similarities and differences. I presented the pedagogical opinions of different countries' teaching practices regarding the development and changes of project method as a teaching-learning strategy. I examined the pedagogical understanding of project method in general then I focus on the school environment, science subjects and above these, on physics.

These kinds of projects can be rather useful for fellow teachers as they help in making learning and teaching of science subjects more interesting, with their varied usage of the presentation of knowledge. It enables the diverse improvement of students' competence.

In my thesis I presented a project type of physical measuring and examination task with Rijke tubes. The aim of our project was while students enlarged their knowledge about thermoacoustics; on the one hand they developed their applied information technologic (IT) skills, while on the other, their cooperative skills were improving as well. Our school project promoted a pedagogy using an inquiry-based approach that succeeds to develop excitement around science; presented the processes and methods of science together with its products and promoted a wide range of practices including inquiry based activities, hands-on/minds-on operations and group projects.

At the beginning of the 3rd chapter I introduced the basic notions of thermoacoustics, the significant trends of it, and their relations to other fields of researches. I reviewed the specialized literature of the topic in the same chapter. In the 4th chapter I presented my aims, in the 5th chapter I gave an account of a series of measurements done with Rijke tubes, in which I set an example of linking different science subjects. In the 6th chapter I presented the simple model of Rijke tube; in the 7th I showed the further developed version of my model.

Though my thesis discusses two fields (pedagogical methodology and thermoacoustical research) but they are closely related as we cannot share our knowledge of a particular material if we do not study it on research level but simply on educational level.

2. Scientific background of the thermoacoustic project

Thermoacoustic (combustion) instability can appear in a thermal device (engine) when the unsteady heat release is conjoined with the pressure fluctuations. A cavity or chamber of a thermal device possesses certain acoustic properties; if the heat, released in the system, depends on fluctuations of pressure and velocity, a feedback loop is formed and this effect can destabilize the whole thermodynamic system. Thermoacoustics study dealt with conditions under which thermal interaction can result in the excitation of the acoustic modes of the system.

Thermoacoustic oscillations play important roles in various technical applications; for instance, in jet or rocket motors, thermoacoustic engines, pulse combustors, industrial burners. The Rijke tube is a resonator cavity with natural or forced mean flow and a concentrated heat source (generally a heated grid). It is a convenient thermodynamic system for studying the fundamental physics of thermoacoustic phenomena and thermoacoustic instabilities, since at certain values of the main system parameters a loud sound can be generated. This vibration phenomenon is similar to that in real-world physical devices prone to thermoacoustic instability.

Important thermoacoustic phenomena are the acoustically unstable combustors: gas turbine engines and jet engines are susceptible to combustion instability, which is a special case of thermoacoustic instability. Pressure and flow oscillations inside the engine can lead to unacceptable levels of vibration and enhanced heat transfer that degrade the propulsive efficiency of the engine or even destroy the set-up.

3. Objectives and the methods of investigation

The relation between thermodynamics and acoustic is still not thoroughly understood by the scientists who deal with thermoacoustic. In order to control the acoustically unstable combustors the properties of the thermoacoustic processes have to be well known. The thermoacoustic processes are rather complex, therefore a theory, which is able to describe the interactions and their consequences for any thermoacoustic device uniformly are still lacking. In this study I presented some features of this nexus.

In order to describe and to predict these interactions I developed two models. The evolution of my models, their verification and the explanation of the thermoacoustic processes were based on experimental observations and experiences. Rijke tubes were used for the experiments.

The aim of my work was to study Rijke-type thermoacoustic processes and group project methods; in order to do so I completed studies in different subjects and goals are presented in the dissertation as follows:

- My aim was to determine how the main parameters of the Rijke tube influence the unstable state of thermoacoustic system.
- Most of the preceding articles have not paid enough attention to the transition between stable and unstable state and the conditions of the process. My goal was to determine this phenomenon and answer the questions and to deliver accurate experimental results for the transition from stability to unstable state and the reverse way.
- My next goal was to develop a mathematical model for the thermoacoustic oscillations in the Rijke tube. I wished to fine this model, in order to characterize the behaviour of the Rijke tube better.
- One of my aims was to develop a computer program for determining stability-instability boundary of the Rijke tube. I allocated the stability-instability border-line with the help of this numerical method. I investigated the role of boundary conditions and the usability of this model.

- If the Rijke tube can get excited at the given parameters, then I investigated the fundamental and the high order harmonics of the system. During the measurements I found that the previously calculated frequencies slightly differed from the measured ones. My goal was to evolve a perturbation scheme to explain the alteration of frequency. If the position of the mesh or the power that heats the mesh changed, the frequency of the voice changed as well. I examined it in my paper as well.
- My goal was to analyze the effects of thermoacoustic project work on students. I examined the pedagogical utility of the method and its expedience regarding the medium and long term performance of students in different subjects. My aim was to prove the reason and utility of project work in pedagogical aspect.
- I examined the attitude of students towards project work with the help of questionnaires. My aim was to show that project method is well-suited for motivating students.

In the 1st step of the project we had experiments with 7 different Rijke tubes. The first goal of our project with heated Rijke devices was to ascertain the transition to unstable state as a function of the main thermoacoustic system parameters. We can vary three primary parameters (heated mesh location, mass airflow rate and power supplied to the heating element) independently. We employed slow warming-up method then we had the following procedure for allocating the boundary between stability and instability: for each mesh's position, a set of mass airflow rates values is selected to cover the range when transition to instability is possible. The critical power is the minimal value of power, above which the thermoacoustic system becomes unstable. This can be found from the balance of thermoacoustic energy addition and acoustic losses. Stability boundaries were determined for four heater locations: 1/8, 1/4, 3/8 and 5/8 of the tube length.

4. Results

4.1 The summary of the pedagogical results

4.1.1 The examination of the possibilities of integration in science subjects

I have revealed the possibilities of the complex, integrated education of science subjects. The method to organize studies around a given topic is a new approach in teaching physics in our country. I have shown that the organization of science subjects into such topics can help to integrate weaker students into teaching-learning procedure. I have chosen comprehensive, integrated and interactive topics which are suitable for revealing and presenting significant basic cultural historical and scientific knowledge and effects which overstep the connection of individual subjects. Besides experiments and computer simulations, with modelling simple and more complex processes I have collected science historical facts and curiosities. In my paper I presented how physics can be completed over the compulsory material with knowledge that hopefully more students can find interesting (Beke, 2009ab).

4.1.2. The initiation of theoretical and experimental backgrounds of investigation

In my thesis I have presented the basic notions of thermoacoustic, the relevant researches and its connections to other researching areas, and the literature of this topic has also been reviewed. In our country this topic has not been treated profoundly, so my paper can be regarded as a supply of this deficiency (Beke, 2011b).

After examining the literature of thermoacoustics I collected, transformed and developed experiments which can be carried out with cheap equipments which can be found in every school. These experiments help teachers of physics to perform students' experiments with simple equipments. The experiments collected and transformed by me can be modified to fit for students from secondary school to university; with the examination of Rijke tubes, the development of complex thermoacoustic phenomena can be understood (Beke, 2009cd).

4.1.3. The motivation effect of the application of project method

In the course of my research I examined the effects of the usage of project method on the motivation level of students in primary and secondary education. I claim that project method in science subjects can successfully be used in case of primary and secondary school students; it helps students to develop a positive attitude towards science subjects (Beke, 2011c).

At the end of our thermoacoustic project I examined how the attendance of our students in the experiments affected their schoolwork. I have shown that those who attended in the medium and long run have improved in their performance of physics and IT, and they have performed in tests more equally. The students attending in the project work obtained a better performance by 8.2% in Physics and by 5.5% in Information Technology contrary to their previous performance. The control group in this case consisted of 78 secondary grammar school students. (Members of the control group did not take part in the thermoacoustic project.) In the results of the control group the performance of students have changed neither in Physics nor in Information Technology. The changes in their performance were less than 1%. On the basis of my experiments I found that integrated science projects are suitable for improving students' performance in various science subjects (Beke, 2011c).

I have been examining the effects of participation in a project work on the attitude of students towards project work with the help of questionnaires. First of all, I wanted to know in reference to science subjects how project work had affected their stance to the subject. Therefore I made the students fill in questionnaires regarding all the projects done at school during the years. (On the whole students volunteered in the experiments.) Analyzing the answers it became obvious that students welcomed the different projects and they felt the purpose and the usefulness of their work. All the project exercises affected the attitude of the students in a positive way; the greatest improvement was observed in integrated science project works (Beke, 2011c).

4.2 The summary of scientific results in the thermoacoustic project

Our thermoacoustic project work has been carried out with three primary intentions. My first aim was to investigate the behaviour of gas heated Rijke tubes with grammar school students. The second goal was to obtain data for the stability boundary of thermoacoustic oscillations in the electrically heated Rijke pipe. My third aim was to develop two mathematical models, and with the help of these models I could determine the transition to instability and explain the phenomena observed in the measurements.

4.2.1 The impact of parameters on thermoacoustic phenomena

I experimentally demonstrated that regarding the main parameters of thermoacoustic system (the geometric data of the Rijke tube, the position of the pipe, the transmissivity of the réseau, the position of the mesh, the mass airflow rate and the heating power) there are a minimum and a maximum threshold value for the given parameter. I found novel that for each tube for each parameter there is a minimum threshold value below which no self-sustained acoustic oscillations may be possible, and there is a maximum threshold value for the given parameter above which the excitation is eliminated. So far research papers have only mentioned the minimum threshold value of heating power and airflow rate generally. I ascertained according to our experiments that there is also an inferior and a superior threshold value of the foregoing parameters. In case of the heating time of the mesh only a minimum threshold value can be marked. I presented if the thermoacoustic system can be excited, there are always such combinations of parameters in which the preceding unstable system becomes stable, i.e. when the tube sounds; only with the alteration of one parameter it is possible to stop the unstable state of the tube, namely the sound fades (Beke, 2009cd).

I ascertained newly that the issuing of the sound is dependent on the location of the tube, grid position (x_r), heating power, mesh temperature, mass airflow rate, heating time and the porosity of mesh. I developed a method in which the main system parameters can be varied and controlled independently in the experiments (Beke, 2010a).

4.2.2 The modelling of thermoacoustic processes

Thermoacoustic instabilities in real thermal devices are very complex phenomena; my goal in the modelling was the investigation of the most important factors; thus a simplifier mathematical theory involving heat transfer, acoustics and thermoacoustic interactions is discussed to get the transition to excited state. The general behaviour of the stability-instability boundary has been captured from my 'simple' model (Beke, 2010a).

The method to obtain the stability-instability boundary at a given position of the grid was the following: for the fixed mass airflow rate, the power was increased until the excited regime is attained; the stability curve has been determined for four heater locations ($x_r=L/8$, $x_r=L/4$, $x_r=3L/8$ and $x_r=5L/8$). I found that the general shape of the stability-instability demarcation curves resemble distorted parabolas in all grid position; there is an optimal value of the mass airflow rate when the heating power is needed to excite the system is minimal (Beke, 2010a).

I ascertained that my simplified model greatly underestimated the test results generally. In the intermediate flow rate range the error is about 30% – 50%, and in the low and high flow rate range the error is about 40% – 100%.

4.2.3. Advancing of the model, examination of the stability of system

My next goal was to develop an advanced theoretical model based on the 'simple' model that would describe the transition to thermoacoustic instability more accurately than the previous simplified model. Thermoacoustic instabilities in the Rijke tube are dependent on the properties of the eigenacoustic modes and on the processes of heat addition to airflow, so I had to carry out a detailed heat transfer analysis aimed at determining the temperature field and heat release in the thermoacoustic system. I made some theoretical considerations to generalize the Rijke-type thermoacoustic processes. I presented that the heat transfer process in the system includes natural heat convection, forced heat convection, heat conduction and thermal radiation (Beke, 2010d). A numerical computer simulation procedure underlays as basis of my heat transfer analysis of the system. I developed a new approximate one-dimensional quasi-steady heat transfer model using energy conservation equations, it was proper for lower and moderate supplied power at intermediate mass airflow rate.

If the energy input exceeds acoustic losses in the thermal device, the thermoacoustic system becomes excited. I investigated the acoustic boundary layer losses, sound radiation losses at the nose pipes and the damping mechanism in Rijke tube was discussed too. I developed a numerical algorithm for determining stability-instability boundary of the Rijke tube. The stability-instability border-line was allocated with the help of iterative methods (Beke, 2010d).

4.2.4. Computer simulation programme based on the advanced model

With the help of my iterative numerical procedure the critical power can be determined, so I was able to find the boundary limit between stable and excited states of the system (Beke, 2010b). It can be seen a great improvement achieved in the accuracy of the results by the advanced theoretical model compared to the numerical results obtained by the simplified model. (In the simplified model, the computed stability–instability boundary corresponded to the heating power level sometimes not more than half as large as that obtained during the experimental tests generally.) I presented that applying my advanced model the agreement was much better: in the intermediate mass airflow rate and heating power the numerical results befitted with the experimental data very well. Both low and high ranges of system parameters, where assumptions for some parts of the modelling were not perfect, errors were more frequent, but I can state that my advanced model predicts better results than the simplified model. I have shown that the computed stability–instability boundary obtained from my advanced model can be used for approximate estimations of transition to the excited state. In the range of intermediate airflow rates the results were close to the experimental data, the error was about 10% –15% in my advanced model (Beke, 2010b).

The goodness of my simple and advanced model can be judged with the help of relative errors between the critical power based on the models and the critical power determined by measurement. In the end of my experiments I calculated the extent of relative mistakes at different mesh positions and at different airflow intensity. I compared my models to others models according to the extent of relative errors. I found that in case of my simple model the relative mistakes were between 28% and 43%. Relative errors of my advanced model were between 14% and 30%, but there was a certain range of airflow intensity where the rate of relative errors was under 5%. On the basis of relative errors, my advanced model is more punctual than other researchers' models.

I executed numerical simulations in order to simulate the thermoacoustic processes in the different fields of operation. The computer simulation model was implemented in C++. I found the results to be in good agreement with my theoretical predictions. Using my advanced model for the Rijke tube I demonstrated that in the presence of the weak linear coupling between the modes, there is a small shift in the system frequencies (Beke, 2011a). The discrepancy of frequencies in my advanced model is less than 1% on the average which is better than any other rates.

5. The use of results

The main theme of my thesis was the investigation of thermoacoustic instability with the help of Rijke tubes. In this work I wished to present a projects work in which we can examine thermoacoustic phenomena with easy-to-prepare tools at school. We performed the experiments with the tubes in team work. Basically we used cheap apparatus that can be found in every school. I demonstrated that not only the students' knowledge about thermoacoustic vibrations was developing in our school project, but also their problem-oriented thinking and scientific model-thinking and their ability to apply computer and use IT in Physics lesson, and besides these, their social skills were improving as well (Beke, 2009a-d).

I have tried all the experiments collected and improved by me in real teaching environment. The experiments can be carried out by simple everyday equipments. I presented them to those who were interested every year, with which I helped the wider spread and usage of thermoacoustic experiments in teaching physics (Beke, 2010c).

I have presented the possible usages of project method to fellow teachers of physics at teacher training conferences which I have helped the wide spread of this method in teaching science subjects (Beke, 2010c). In the course of the thermoacoustic project I examined the usefulness of the method and its effectiveness regarding the medium and long term performance of students. The feedback of teachers and students reinforces my view that project method is absolutely suitable for teaching science subjects both partly and totally. I have found the development of teaching methods based on project work useful and necessary.

In the future I would like to elaborate more topics and materials with the help of project work. There are still some problems to solve about the Rijke tube (for example vortex shedding mechanism and accurate model of the hysteresis effect at the stability-instability borderline); no proper solutions have been born for these problems yet. The results that were attained in the projects encourage me to further study the topic.

Publications related to the theses

Beke, T. (2009a) Termoakusztikus jelenségek vizsgálata iskolai projektfeladatban. *A fizika tanítása*, **17** (4), 7–14.

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