LIFETIME OF AIRBAG INFLATORS: PERSPECTIVES FOR A BETTER UNDERSTANDING AND PREDICTION OF AGING MECHANISMS

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Abstract

The main focus of this work is to dissert and elaborate on how the lifetime of airbag inflators can be predicted and what needs to be understood from the mechanisms involved. First, the current problem with the standard testing of airbag inflators is identified to establish a baseline on how to address this issue. Then some of the work performed at ICT and some developed methods related to the aging are listed and briefly described: They range from propellant related investigations such as stability analysis of propellants, phase transition analysis with X-ray diffractometry, ballistic testing on aged propellants and newly developed mass flow characterization methods all the way to material related methods such as steel aging and oxidation characterization.

After describing what have been done and investigated so far, it is possible to give an impression on the perspectives of how the problem can be addressed and what can be gained by bringing together different techniques and methods within a multidisciplinary approach to better understand the aging mechanisms, to better predict the aging processes in airbag inflators and to establish what is still needed to achieve both. The scope is not to give a specific solution for the current problem but to list which alternatives there are.

Introduction

40 years after their development, airbag inflators are still a key element of passive automotive safety systems. These devices are designed to rapidly release a certain amount of gas to inflate all necessary airbags for satisfactory restraint during a car accident [2]. The prediction of the lifetime of airbag inflators is currently of great interest. It presents one of the biggest challenges in the field of energetic materials and safety engineering due to the broad range of factors involved and the complexity of the system itself. Even though there are plenty established approaches for environmental simulations and aging tests, a fully understanding of aging mechanisms with a multivariable approach is lacking. As recent events have shown, carrying out strict aging tests during the inflator's development even surpassing the established standards does not guarantee failure-free on-field compliant inflators [3] [4]. An in-depth knowledge of aging mechanisms of inflators as a whole (from the propellant up to the metal casing) could have a big impact on how the inflators should be tested and the aging of new propellants can be predicted on different inflator configurations during the development to avoid any sort of future field issues. The idea is to give an impression of how aging programs are developed and performed to validate inflators (like in SAE/USCAR-24). Based on the experiences during investigations at Fraunhofer ICT, the programs should be improved to characterize the aging behaviour and performance of airbag inflators [5].

Basis of airbag inflators

To understand the subject of this paper, which is the development of an aging program of airbag inflators, the latter must be properly described. Airbag Inflators are energetic devices designed to (rapidly but controlled) provide a certain amount of gas in order to deploy an airbag. These devices are an integral and vital part of restraint systems, and are considered passive devices in the field of automotive safety [2]. Depending on the source of the gas, airbag inflators can be roughly classified in three different classes: pyrotechnic, stored-gas and hybrid inflators (which use a combination of both pyrotechnics and storage gas) [2]. The basic components of pyrotechnic airbag inflators are: the primary charge (ignitor), the secondary charge (propellant), a filter assembly, and the housing. Since the only source of gas is the combustion of the propellant, the output performance is dictated by both the ballistic properties of the propellant (pellet geometry, heat of explosion and burning rate according to the Vieille's Law), and by the geometry of the airbag inflator itself (free volume and outflow area) [13]. In the case of stored gas, or pressure vessel type inflators, these are filled with an inert gas or a mixture of inert gases. The output performance depends mainly on the pressure at which the gases are stored and the outflow area of the inflators. Hybrid inflators are a combination of both these types, so their output performance depends practically on all the parameters mentioned above [2]. There are also dual stage inflators, which can be deployed with different output levels. Two main fire modes are common: full output in which both stages are activated with a small or no time delay between the stages; and first stage only, in which only the main stage is deployed, while the second stage is activated with a large delay as a “disposal deployment”.

Current validation of airbag inflators and aging programs

In the field of safety technology, passenger safety is paramount. The validation of restraint and airbag systems is of vital importance due to the increasing demand of safety requirements, reliability, costs and industry standards [2]. The correct implementation of a plan for design verification and product validation is absolutely necessary in the development stages of every inflator assembly for any airbag module [8]. The industry follows and normally even surpasses the guidelines established in specification compilations like SAE/USCAR-24 in North America and AK-LV in Europe to accomplish a thorough design verification and product validation as stated in the report [3]. To establish the technical validation and performance requirements of airbag inflator assemblies is a main concern of Society of Automotive Engineers, Inc. (SAE) and of the United States Council for Automotive Research (USCAR). These specifications are outlined on SAE/USCAR-24 and can be roughly classified in 2 different groups: the functional requirements and their correspondent validation test requirements. Some of the specifications are related or directly addressed to the aging and/or the environmental conditioning of airbag inflators, which is the main focus of this paper. The most fundamental validation procedure applied not only for aged inflators, but in virtually all cases is the “J2238 Airbag Inflator Ballistic Tank Test Procedure” [2][3][8]. Some valuable information can be retrieved by applying this procedure on aged or artificially aged inflator assemblies regarding the ballistic properties of the system, especially if the inflators begin to show noncompliance to the validation requirements. Nonetheless, there are some inaccuracies in the way this data reflects the outflow performance of the inflators especially in onset (0-20 ms after ignition) as stated in [5]. This will be further discussed in this paper. The remaining specifications in SAE/USCAR-24 considered to be related to or addressing the aging of inflator assemblies are listed below:

Functional validation requirements:

- Autoignition, High Temperature Oven Performance/Autoignition of Heat Aged Inflators
- High Temperature Oven (HTO) and Auto Ignition Performance
- Accelerated Heat Aging and Auto Ignition Performance
- Inflator Thermal Shock Resistance
- Inflator Dynamic Shock Resistance
- Inflator Vibration/Temperature Resistance
- Inflator Salt Spray Resistance
- Inflator Humidity Resistance
- Inflator Performance and Variability Limits
- Propellant Stability

Validation test requirements:

- Accelerated Heat Aging Test
- Accelerated Aging with High Temperature Oven (HTO) Test
- Accelerated Aging with Bonfire Test
- Accelerated Aging with Slow Heating Test
- Inflator High Humidity/Heat Age Test
- Inflator Sequential/Environmental Test
- Inflator Thermal Shock Resistance Test
- Dynamic Shock Test
- Vibration - Temperature Cycle Test
- Humidity Resistance Test

Virtually, any developed aging program is strongly or at least partially based on the above mentioned specifications. Evidently, many of the Design Verification tests (DV tests) cannot be contained in these specifications. It is up to the OEMs or the inflator´s fabricants to establish which path to follow to cover every aspect to be considered in regard of the aging of propellants, inflator assemblies and airbag modules. However it can be asserted that OEMs and fabricants adhere strictly to the standards of the validation requirements and even use these guidelines to perform DV tests and validations tests with even higher standards [3][4]. Some other aspects explored by many fabricants beside the specifications in SAE/USCAR-23 are investigations and testing of crystal phase transition of propellant components during aging, water absorption/desorption rates and effects on the structure of pellets, tablets and other propellant geometries [3]. Consideration of design of experiment (DOE) using a DV/PV matrix is nowadays widely used. As indicated in plenty functional validation requirements and validation test requirements above, a subsequent output performance validation is mandatory. This validation is performed using the ballistic tank test procedure [3][8].

The problem with the current aging methods

In recent years, one of the most notorious and discussed cases in the field of airbag inflators has been the problem with PSAN-propellant (phased stabilized ammonium nitrate) based inflators resulting even in deadly incidents [3]. The propellants show abnormal high burning rates, which causes the inflators to burst instead of achieving a normal deployment. Even though during development (from propellant up to the module) validation testing had strictly followed prescribed specification and many different approaches had been taken to understand the aging mechanisms of the inflators, some inflators failed to function properly arguably due to aging related issues. This has shown how the specifications prescribed for validation of aged inflators have failed to reproduce or to reflect the real aging mechanism and that many of them remain unknown [3][4].

One shall not make generalizations about the technical requirements that are in place, since the anomalies occurred in specific instances for PSAN based inflators, but there is definitely room for improvement. For the technical validation requirements to reproduce the condition of many inflators in-use around the world, these should be tailored, what of course is a monumental task almost impossible to achieve. After reviewing the above mentioned technical specification prescribed in SAE/USCAR-24 some conclusions can be drawn:

- Many of the testing results are validated by visual inspection and/or have pass/fail criteria in terms of bursting, leakage, activation, etc.
- Many of the tests require a subsequent validation of the ballistic properties of the aged/stressed propellant using closed tank tests.
- Many tests wisely address factors strongly associated with aging mechanisms like heat, temperature, thermal and dynamic shock, humidity, and mechanical vibration.

Pass/fail criteria may fail to discriminate many inflators that does not burst, present leakage or fail ignition, but their performance is already out of compliance. Of course if these tests (as they are) are combined with tank tests, the discrimination process is certainly more accurate. However as learnt from previous projects and experimentation at Fraunhofer ICT, performance data from tank tests contain implicit energy losses from the tests assembly itself, plus the data is obtained by the calculation of a cumulative process inside the tank (integration of mass flow=pressure build up); this renders the data inaccurate specially in the onset region [1][5]. To properly describe the onset region of the outflow process is essential in order to predict if the variations are going to produce an inflator failure (bursting).

As mentioned many factors that come into play in aging mechanisms are considered in the validation tests but a cross-correlation between all of the factors and statistical robustness is lacking. Indeed many other approaches have been explored also by Fraunhofer ICT among many others especially in the field of crystallography, surface analysis, CT-Scan, Water Absorption-Desorption rate and effect analysis, chemical stability, etc. but unfortunately they have not shown any concrete findings, due to the lack of an aging program that encompasses all of the possible factors and that can recreate the reality with sufficient redundancy and reproducibility. This should be the ultimate goal: to develop an aging method that reproduces the field conditions. A complete understanding of the possible mechanisms involved in the aging of airbag inflators is unfortunately lacking.

Related research at Fraunhofer ICT

The Fraunhofer ICT has been actively involved in the endeavors and efforts to try to understand and explain what caused the anomalies with the PSAN based inflators [3][4]. Many approaches from Thermogravimetric analysis, X-ray diffraction, scanning electron microscope and computer tomographic analysis have been considered and performed in order to understand the phenomena behind the anomalies. One of the most promising analysis programs has been the investigation of water absorption/desorption with temperature combined with the propellant crystallographic analysis by means of X-ray diffractometry, ballistic characterization and CT-Scan of the propellant surface. There have been efforts to develop statistical data analysis methods in order to "crunch" the huge amount of sets of data with proper DOE planning. It needs to be mentioned that in order to find experimental conditions that reflect the reality a large set of test conditions must be combined. Independently, there have been investigations to characterize the influence on materials and metals in energetic systems, or in systems that involves energetic materials such as the propellants in airbag inflators. The results of all the investigations regarding the propellants and the materials have yielded interesting findings but a complete understanding of the mechanisms involved has not been grasped yet. There is a big piece missing in a correct characterization of aged inflators and it is an aging method or program that reproduces the real aging of inflators as exactly as possible.

As mentioned, the performance characterization is a required step in almost every validation test described in SAE/USCAR-24. In particular for the ballistic and performance characterization of airbag inflators, some progress has been made. A combined effort between Fraunhofer ICT and AUDI AG yielded a new mass flow characterization method that can replace the J2238 Airbag Inflator Ballistic Tank Test Procedure [5]. This is important since it has been found that the tank test delivers inaccurate performance data especially in onset region, which is vital in order to detect dangerous burning rate behaviour of the inflator [1][2][5]. A brief description of the characterization method is given below:

New mass flow characterization method

The proposed measurement system encompasses basically two different experimental setups:

- A so-called *"Pressure-Temperature Setup"*, in which the temperature of combustion gases is determined by means of emission spectroscopic measurements. The inflator's internal pressure is measured using piezoelectric sensors [10][11][12]:.

- A so-called "Pendulum setup" which is an adaptation of a ballistic pendulum where thrust is estimated by means of "particle image velocimetry" using high-speed cameras. The pressure at the exit plane of the inflator or the deflection nozzle is also measured by a piezoelectric sensor.

The mass flow determined by both measurement setups can be compared and cross-validated [5]. An internal verification for each generated mass flow curve is possible by means of mass flow integration and then comparing this value to the real weight (mass) loss of the inflators [2]. The performance data from both experimental setups can be combined and averaged in order to calculate a definitive mass flow and/or temperature identifier as input for the airbag system simulations. A schema of the measurement method is below:

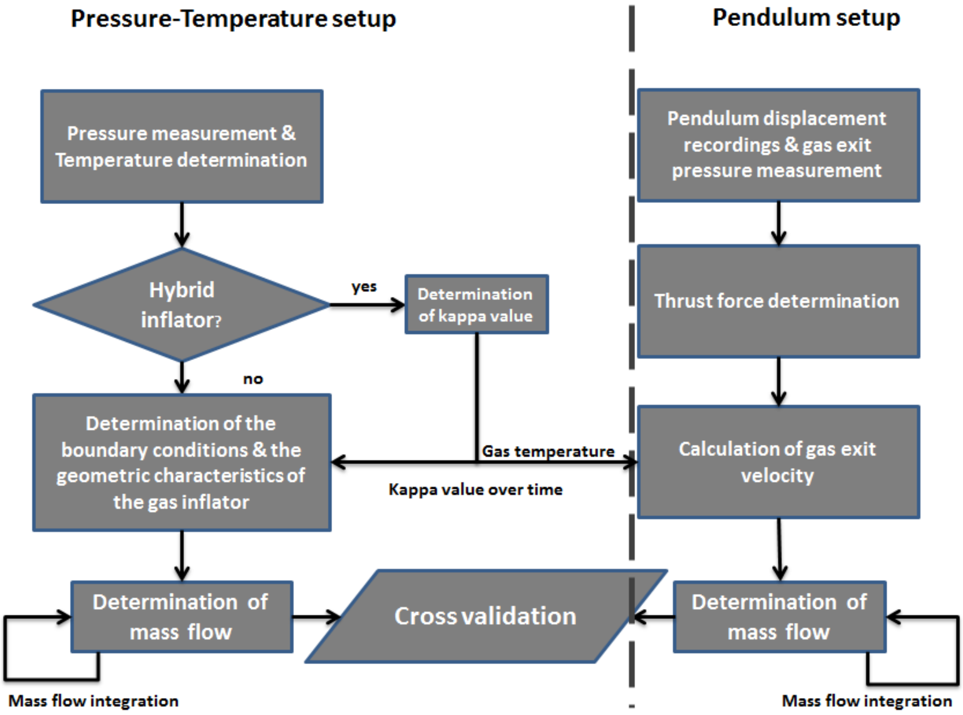

Figure 1: Mass flow determination method schema

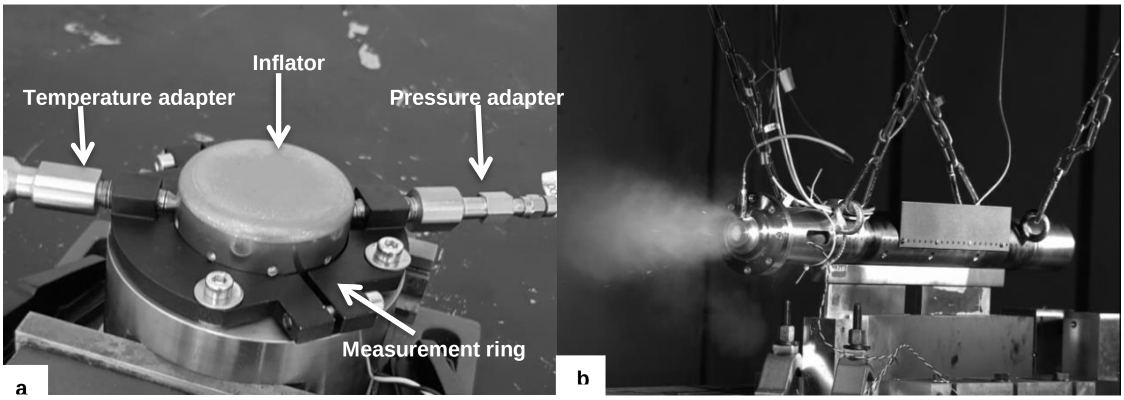

Figure 2: a) P-T setup, showing its components; b Side view of the "Pendulum Setup" after ignition

It is important to note that this measurement system is based on the redundancy of two different ways to determine the mass flow and other performance parameters of airbag inflators. A cross validation of two independent mass flow curves strengthens the data quality and confidence. This should also be replicated for a new aging method or program and emulated by any other validation. That is why the experiences during the development of this measurement system can be used as base for the research to understand aging mechanisms and to develop an aging method.

Next steps towards the prediction of aging mechanisms and an aging method

In the previous sections of this paper, it was discussed how the validation of airbag inflator assemblies is carried out, how they are artificially aged and which approaches have been explored in order to better understand the mechanisms involved. The multidisciplinary studies range from the chemistry of the propellants, process engineering of the manufacturing of airbags, material science, metallurgy, crystallography, and the development of a new performance characterization method for airbag inflators. And even though there has been an extensive work from all across the industry and the field of safety technology, the goal has not yet been achieved. It is neither the intention nor the scope of this paper to offer a complete solution to the problem, but to assess all the different established validation methods and approaches performed and investigated at Fraunhofer ICT or by third parties and to elaborate a roadmap for the steps necessary to develop the expertise or competence to further investigate and predict the aging mechanisms of airbag inflators. After reviewing the available information of investigation carried out at ICT as well as in investigation carried out by third parties and that prescribed in technical validation requirements, three main paths have been identified to address different aspects of the issue of understanding and predicting the aging of airbag inflators.

1. **Fundamental research and data bank creation from test battery**: the research addressing the aging mechanisms of airbag inflators or the factors involved has ramped up in recent years. However the efforts have been scattered around specific propellants and/or cases, which has not allowed shedding some light on the mechanisms involved as a whole. The proposal here is to refocus the investigation in 4 main aspects which arguably contribute to the aging process: Chemical aspects, physicochemical aspects, mechanical aspects, and the statistical aspects. A more careful look should be taken at what entails every aspect based on an extensive research, but here are some research focal points that appear to be common ground in the available literature [3][4][6].

    - Chemical aspects: Degradation and stability, oxidation, sensitivity, solid-solid reactions, metallurgy analysis, formulation and new replacement compounds.
    - Physicochemical aspects: Kinetics characterization, crystallographic phase transition, water absorption/desorption, thermogravimetric analysis, calorimetry.
    - Mechanical aspects: Material resistance characterization, heat effects, vibration, porosity characterization and structural changes, surface characterization.
    - Statistical aspects: Design of experiments, parametrization of phenomena, data correlation and investigation of interaction between parameters.

    After researching what involves each of the aspects and selecting innovative experimental techniques, the study and testing shall be performed at three different system levels: primary component (the different independent substances and parts), component interaction (for example interaction in the finished propellant), and inflator

assembly level (testing of the interaction of all the parts such as propellant and metal housing put together). All this performed by a comprehensive regime of test conditions varying temperature, humidity, mechanical vibration, pressure and propellant geometry.
This will render a massive test battery, which should be carefully designed and refined, and it will provide the information to create a data bank. The idea is for example to understand what entails the chemical degradation of just guanidine nitrate (GUNI) (primary component level) at different temperature conditions, and then characterize the hygroscopicity at different temperature and humidity regimes. Then for instance to understand the kinetics of guanidine nitrate with several oxidizers (component interaction level) and crystal structure phase transition using X-ray diffraction by different temperatures and humidity. Then, e.g. a fully formulated GUNI-propellant has to be taken to study the water absorption/desorption rate at different temperature/humidity conditions and its effects on the porosity and crystallographic structure of the propellant pellets with different geometries and to correlate this with the mechanical resistance to vibration or shock with different intensities. And finally perform ballistic characterization of complete GUNI based modules (inflator assembly level) exposed at different regimes of temperature, humidity, vibration, and time. As it can be observed the idea is to not only understand the independent mechanisms involved in the aging of all the components of the inflator, but to understand the interaction of many combinations and configurations of its components. Some innovative and promising techniques, tools and know-how, which have been used or developed at Fraunhofer ICT, can be applied for the purposes of this research. These are X-ray diffraction with conditioning chambers to vary temperature and humidity, long duration conditioning chambers for water absorption analysis, thermogravimetric analysis with heat flow, emission spectroscopic temperature estimation of combustion gases, scanning electron microscope, computed tomography scan, gas chromatography.

2. **Aging program development and technical requirements revision:** The large amounts of data obtained at the previous step should be analysed applying extensive statistical analysis. This will serve to have a very comprehensive look at the different mechanisms involved in the aging process of inflators. The goal is to develop an aging program that can reproduce the field conditions as exactly as possible. This can be a general aging program but most probably it will be tailored, since the broad variety of airbag inflator's types, components and conditions around the world is immense. A big part of the work after finding a suitable aging program or methodology on how to adapt aging programs to different inflators is the revision of the technical requirements outlined in SAE/USCAR-24. Many Pass/fall criteria such as visual inspection should be complemented with parametrized values defined by what the fundamental investigation revealed. The current performance validation method should be replaced by a method that better describes the onset of the outflowing process, such as the proposed ICT mass flow characterization method, or by any other method with similar data accuracy such as those proposed in [1][2]. As discussed in in a previous section, the test redundancy and robustness is vital [5], so a cross correlation between the results of validation tests should be mandatory. The performance characterization of aged inflators can be a way to determine the life time of the inflators. Normally for products, the lifetime is reached when

it does not work as intended. This has to be the case for airbag inflators as well. The fall/pass criteria should not be when the inflator bursts or cannot be activated. The fall/pass criteria should be when the inflator does not deliver the intended performance.

3. **Identification of Field indicator and monitoring.** Once a proper aging program is develop all the results of the validation tests and characterization can be compared with real field inflators. This has the purpose to validate the aging program methods and to define if the real aging mechanisms have been fully understood. So for example if using an aging program to artificially age an inflator 5 years, the technical validation test results should comply with an inflator that has been 5 years on field under the same conditions. Using statistical analysis of all the data some corrections can be done to the models in a continual improvement cycle. Here the cooperation between research entities and manufactures is paramount. If the aging program is accurate enough some field indicators that are plausible to be constantly monitored like humidity, temperature, vibration or the presence of an easy-to-detect gas can be used to indicate if the airbag inflator assembly has reached its lifetime and needs to be replaced. This would be the ultimate goal of a safety approach to address the issues in recent years.

Conclusions and outlook

The field of airbag inflators is a very dynamic world, where different airbag types, with different configurations, chemical substances and components are constantly being developed to satisfy the requirements of an industry that uses the inflators in a very varied set of driving and environmental conditions. The research and technical requirements put in place have fallen short to predict the behaviour of aged inflators due to a lack of understanding of the mechanisms involved. This was clearly shown by the anomalies presented in PSAN-propellant based inflators. Refocusing the research efforts in understanding the aging mechanisms combining innovative experimental tools, like those currently being applied and developed at Fraunhofer ICT, has shown promising results but there is still a large way ahead. Among this experimental techniques, the most promising going forward are crystal structure phase transition analysis using X-ray diffractometry, porosity characterization by means of CT-Scans in combination with water absorption/desorption investigation and performance characterization by means of emission spectroscopic temperature estimation. A three step process is proposed in the current paper as starting point toward the prediction of the lifetime of airbag inflators. These steps are investigation of aging mechanisms, development of an improved aging program and monitoring of the characterization of artificially aged inflators and field inflators in order to achieve a continuous improvement cycle. The specifications prescribed in SAE/USCAR-24 should be revised upon the results thrown by an extensive investigation, and they should also be supplemented with a new performance characterization method based on data redundancy and improving the robustness of the results.

References

1. H. Kratz, J. Fernández, A. Heym, A. Kato, Characterization of the performance of airbag inflators by thrust measurement method, Takata Petri AG, IPASS 2009, pp. 295-307.
2. Ch. Jung, K. Thomas, Characterization of the performance of an airbag inflator, TRW Airbag Systems GmbH, IPASS 2005.
3. United States Department of Transportation National Highway Traffic Safety Administration (NHTSA), Report of TK Holdings INC. pursuant to paragraph 33.a of November 3, 2015 consent order, New York, 2016.
4. Orbital ATK for independent Testing Coalition, Takata inflator rupture root cause summary report, 2016.
5. P. Yurrita, N. Edelmann, T. Klahn, J. Neutz, Mass flow determination of airbag inflators, 14th International Symposium and accompanying Exhibition on Sophisticated Car Safety Systems (Airbag Symposium), Mannheim, 2018, V9/1 – 9/23, 2018
6. A. Gao, Y. Oyumi and T. Brill, Thermal decomposition of energetic materials 49. Thermolysis routes of mono- and diaminotetrazoles, *Combustion and Flame,* vol. 83, pp. 345 – 352, 1991.
7. E. Hahne, Technische Thermodynamik, Technical Thermodynamics, 3rd ed. Oldenburg Verlag, 2000.
8. SAE International, USCAR inflator technical requirements and validation SAE/USCAR-24, USA, 2004.
9. T. Zahariev, Berechnung der Durchströmung und der Kennwerte von Sicherheitsventilen, Calculation of the flow and characteristics of safety valves, (PhD Thesis), Otto-von Guericke-Universität, Magdeburg, 2001.
10. W. Eckl, V. Weiser, M. Weindel, N. Eisenreich, Auswertemodelle zur Bestimmung der Temperatur- und Molekülverteilung in Festtreibstoffen, Analysis models for the determination of temperature and molecular distribution of solid propellants, 30th International Annual Conference of ICT, Karlsruhe, 1999, pp. 112/1 – 112/10
11. T. Klahn, S. Kelzenberg, A. Kessler, G. Billeb, T. Fischer, Free Field Emission Spectroscopy on Enhanced Blast Explosives via Spectrometer Combination, 41st International Annual Conference of ICT, Karlsruhe, 2010, pp. 107/1 – 107/9.
12. T. Klahn, G. Billeb, V. Weiser: A highspeed NIR-spectroscope to investigate ignition and combustion of propellants and pyrotechnics, 35th International Annual Conference of ICT, Karlsruhe, 2004, pp. 161/1 – 161/9.
13. J. Neutz, Untersuchungen zur Erzeugung kalter Reaktionsgase auf Basis pyrotechnischer Kaltgasgeneratoren, Study on the generation of cold reaction gases based on pyrotechnic cold gas inflators (PhD Thesis), Dissertation, Universität Karlsruhe,2012.