Investigation of Pressure Rise in Automotive Airbags

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Abstract. Safety is a widely spread topic in engineering, from specific producing processes to everyday life. Innovation of passenger cars belongs to the frontline of industrial sector. Higher and higher performance motors, more streamlined vehicle dynamics, more reliable autonomous vehicles, and minor noise and vibration are the most expected developments what customers prefer. However, it is not allowed to forget automotive safety, which effectiveness prevents fatalities to drivers and passengers.

A very important part of this safety system are the airbags. Frontal airbags aim at preventing serious injuries from impacts of the driver's or passenger's head or upper body against the steering wheel or other parts of the vehicle. Worldwide almost every vehicle produced with frontal or front-seat passenger airbags. Their improvement and investigation of operation is a main role of production. Pressure rise and gas temperature in bladders are significant information related to their operating mechanism.

Many investigations can be found in literature which describe the occurring processes during the explosion. Most of them are computational or experimental ones, and others sets up mathematical models. This paper presents options of modelling pressure rise in automotive airbags and inflators.

Keywords: Automotive · Airbag · Pressure rise · Review

1 Introduction

Nowadays, safety is one of the essential line of vehicle design to minimize the occurrence and consequences of traffic collisions. Active and passive safety systems are the main types are applied in automotive engineering.

Active safety or primary safety features are mainly the ones that work to prevent the risk of collision or accident. They are often electronic, computer-controlled components which include braking systems, traction control systems and electronic stability control systems. Based on signals of various sensors, they help the driver to control the vehicle. Passive or secondary safety systems are not working until they become active during an accident to help minimize the damages. These systems are including seatbelts, various types of airbags and reinforced vehicle-body structures [1]. Every system in passenger cars are designed and produced besides strict regulations and standards and most of them checked by TÜV [2].

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2 Airbags

Airbags are representative safety devices in passenger cars which can absorb the energy of crashing and preventing personal injuries during accidents. D'Elia et al. [3] investigated, that head and torso protecting dual airbag systems can reduce driver death injuries statistically significant (41.1% less in the odds of death or injury across the body region, and 48.0% less on the head, neck, face, chest and abdomen).

However, their inadequate design can cause significant harms in human body, such as abrasion, laceration and contusion injuries to the face, arms [4] and wrist depending on body mass index (BMI), height of the passengers, design of airbags, etc. [5–7]. Høye [8] studied effect of vehicle weight to seriousness of injuries, and found, that in case of frontal collisions and belted drivers, airbag can significantly prevents drivers' fatalities (–37%) in heavy vehicles. The heavier the vehicle, the prevention is more effective. Gabauer and Gabler [9] found, that combination of airbag and seatbelt in safety can decrease risk of death injuries. Improvement of airbags is a constant process, which results more safety motor vehicles. MacLennan et al. [10] studied effectiveness of second generation airbags compared to the first generation one.

2.1 Main Parts of Airbag Systems

An airbag system usually contains three typical components. The crash detection part of the system contains multiple acceleration sensors or "impact sensors", and their electronics to relay the signals which they generated. Based on the seriousness of the impact, the airbag system may be activated. Than an inflation module initiates gas generation by initiators (with its thermal resistance) [11], which fills the airbag cushion itself [12]. Under normal operating conditions, initially all of them are take place inside the housing. When an airbag is activated by the impact sensor, ignitor activates propellant pellets, which generates gas and with this, positive internal pressure rise in airbag cushion. During this act, the textile cushion expands and restraining forces over different areas of the body.

Figure 1 illustrates typical pressure-time profiles for the combustion chamber (upper diagram) and a standard discharge test tank (lower diagram). Main inflator parameters are shown on the figures [13].

Pressure rise in airbags is a precisely controlled process, because of preventing human injuries. Both during the process of product development and in the quality control of production it gets special attention. Through measurements and computational simulations, the smallest differences and deficiencies can be filtered.

The aim of this paper to discuss common models to simulate pressure rise in automotive airbags.

2.2 Types of Airbag Systems

In the early stages of airbag development, they were intended for use only frontal crashes. Since then many varieties have been developed for various types of accidents: for side, rear, rollover or frontal crashes. Two main types are available of airbag systems, depending on the direction of impact: for frontal impact, driver side and

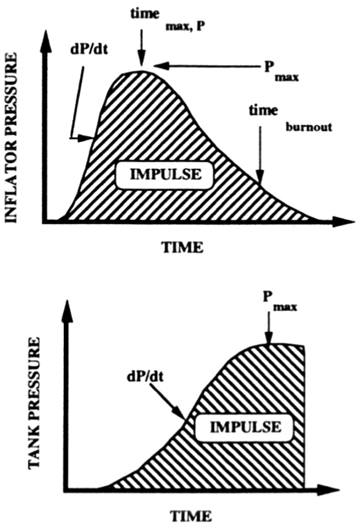


Fig. 1. Pressure histories of pyrotechnic inflator [13]

passenger side airbags can be used; and in case of side impact only one type is applicable [14].

Frontal airbags are designed as cushions to absorb kinetic energy of the forward motion of the body by deformation and compression of the bag and by forcing out the filling gas through vent holes. The airbag should be deflated in 1–1.5 s after the crash to ensure the free movement of the driver or passenger after the collision [12].

By contrast, the purpose of the side airbag is not to absorb the energy of the collision, but to isolate the passenger from the location of the crash. These types have not any vent holes, because they must keep their inner pressure.

Driver Side Airbag. This module takes place in the middle of the steering column of the vehicle. The duration of the inflation period is between 30 to 45 ms. The nominal volume of a driver side airbag is between 60 to 65 L, and its nominal peak pressure is about 2–3 bar_g [12].

Passenger Side Airbags. Passenger side airbag is mounted in the dashboard and its volume is approximately 150 L. Its peak pressure is approximately 1–2 bar_g when activated. The inflation process takes 50–65 ms [12].

Side Impact Airbags. Most of the side impact airbags are mounted in the seats of the vehicle, but in earlier types they located in the doors. Their inflation time is 10–20 ms. Because of the smaller space between the door of the vehicle and the body, their volume is about 6–20 L, and peak pressure is 9 bar_g [12].

2.3 Inflators and Propellants

In automotive industry, many types of inflation devices are applied for different airbags and knee bolters, and actuators for automatic seat belt tensioners. For vehicle airbag systems, inflators or gas generators can be classified into three major groups based on the configuration used to produce gas for the airbags [15]. The first group is referred as "pyrotechnic", which inflates the airbag rapidly by gas production. Gas production is achieved by chemical reaction on solid propellants. The second group is "augmented" or "hybrid" inflators. In these, hot gases produced from solid propellants are mixed with compressed, high-pressure stored gases before they filled the airbag [16]. To avoid the propellant-specific disadvantages of pyrotechnic and hybrid pyrotechnic inflators, a third design has been developed that excludes completely the use of solid propellant. This type is called Heated Gas Inflator (HGI). These have cylindrical shape and are initially filled to very high pressure (200–500 bar) with a gaseous mixture of fuel and oxidizer. The most common fuel is hydrogen and the remaining gas is a mixture of oxygen and nitrogen. When the igniter initiates combustion of the fuel and air mixture, at a pre-defined pressure, a burst disk at one end of the inflator breaks and allows the gas to exit to a small diffuser plenum where the gas is vented into the airbag. These vents are oriented in a radial fashion so that there is no net force exerted on the HGI [13].

Propellants are used in automotive industry, are mainly sodium-azide (NaN_3), non-azide propellants with azodicarbonamide (ADCA) or double-based propellants (DB). The most common propellant used in the earliest pyrotechnic inflators was sodium azide (NaN_3) mixed with metal-oxides (e.g., CuO or Fe_2O_3), flame accelerants (e.g., $NaNO_3$) and small amounts of inert binders (e.g., SiO_2). The mixture of fuel, oxidizer and binder is consolidated into milligram-sized "grains" or larger tablets using a mechanical press [13].

Their decomposition properties are studied by Berger and Butler [17]. Authors investigated several thermophysical properties of these types, including flame temperature and chemical composition of produced gases, the amount of produced gas per mass of applied condensed phase propellant, the condensed-phase products of the propellants, and the toxicity of produced gases. Desirable results would be a large amount of produced gases, and a lower flame temperature. They found, that sodium-azide propellants had the lowest flame temperature besides large number of moles gaseous products. They found an inverse relationship between the flame temperature and the amount of non-gaseous products, too.

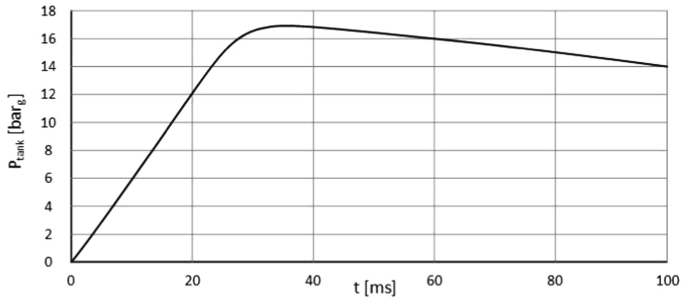
Dangers of Inflators. Besides many advantages, sodium-azide itself is highly toxic commodity, its toxicity is comparable with sodium cyanide [18]. An inflator module generally contains approximately 60% (w/w) of sodium azide blended with other ingredients in a closed metal canister. When the airbag is activated, rapid chemical decomposition takes place in the inflator, but some of the remaining materials are seeps into the drinking water and the soil. Betterton et al. [19] suggest in their work to couple sodium azide with hypochlorite (OCl^-) in aqueous solution to neutralize it with rapid kinetic reactions.

However, not only propellent material can cause serious harms in environment. Failures generated by structural failure can be dangerous to passengers. This is the reason why destructive testing phase exists in inflator developing process. Inadequate crimping of inflator tube can cause rigidity in the material itself. Investigation of the process can prevent further injuries caused by the inflator [20].

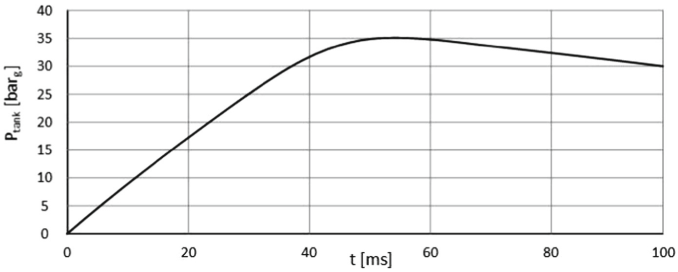
2.4 Testing Methods

During developing process of new inflators and airbags, tank tests are performed to obtain the characteristics of the inflator. Tests are performed in a closed tank with constant volume. There are pressure transducers inside the tank to measure gas pressure inside. The gas component information for the inflator discharge flow (obtained from the airbag supplier) is listed. In this way different gas generators can be compared by their parameters as burning rate, pressure and temperature histories [21].

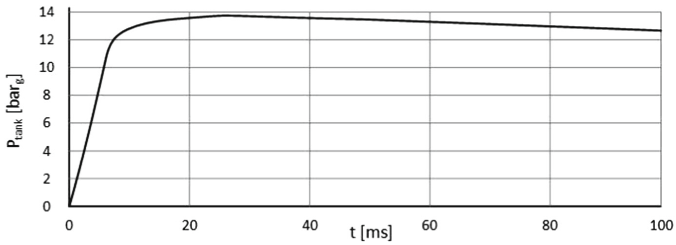
Figure 2 illustrates typical pressure-time profiles of different inflator during tank tests [12]. Similar curves are shown in the work of Tabani [14].



a) Driver side inflator tank curve; volume of the tank: approx. 100 liter



b) Passenger side inflator tank curve; volume of the tank: approx. 100 liter



c) Side impact inflator tank curve; volume of the tank: approx. 28 liter

Fig. 2. Pressure histories of different pyrotechnic inflators [12]

3 Opportunities of Airbag Inflator Modelling

3.1 Thermo-kinetic Modelling of Chemical Reactions

Specifics of chemical reactions are highly depending on initial pressure and temperature, so these factors are also significantly affect the functioning of the propellants.

One of the first description of analytical modeling associated with Cruise [22], who detailed some procedures for determining chemical equilibrium, and detection of produced gases and condensed phases. Author gave some methods to estimate velocity and mass flow out of nozzles. Finally, program code of the method described above is given.

Alkam and Butler [16] set up a thermal simulation model for a passenger-side pyrotechnical gas generator with NaN_3 propellant. Based on chemical kinetic package of CHEMKIN, and using the software AIM, they made mathematical model of the gas generator, and investigated effect of ambient temperature to the pressure impulse in the airbag and in the measuring rigid tank (which simulates the airbag itself at a constant volume), and heat loss through combustion chamber and tank walls. They found, if the ambient temperature rises from 230 K to 320 K, the tank pressure impulse increases by 50%, the combustion time decreases by 35%, the maximum tank pressure increases by 20% and its maximum temperature increases by 27%. Nowadays, essential role to ensure the same working parameters to the airbags amongst different circumstances of collisions.

Guo et al. [23] studied effects of moisture content to thermal decreasing of solid propellant. They composed a model based on thermo-kinetic reactions to investigate changes of thermal stability due to amount of water in case of multi-nitro ester and double base propellants. They found that higher moisture content cause lower activation energy and decreasing pre-exponential factor of double-base propellant and keeps constant for multi-nitro ester propellants. Amongst these circumstances, auto-ignition and explosion may occur easily. More care should be taken for propellants with water during manufacture, storage, transportation and practical use.

3.2 Mechanical Modeling of Airbag Cushion

From a thermal point of view, the major difference between tank test operation and a real automotive airbag test is the heat transfer throughout the tank wall, besides energy loss by airbag cushion during the inflating process. Sinz and Hermann [24] investigated airbag deployment by developing 3D Navier-Stokes model in their study, through an example of a driver-side airbag. The airbag inflation modelled as an expanding volume with fixed rectangular membrane elements as boundary. The developed research CFD code is a three-dimensional Euler-Code for compressible fluids. For the time integration, first order explicit method and 4-Step-Runge-Kutta method were implemented. For the solution of the problem, the commercially available LS-DYNA was chosen, but with shorter computation time than originally available solvers in it.

Bendjaballah et al. [25] evaluated the performance of deploying of a passenger side airbag with Finite Element Methods in LS-DYNA. They simulated different material thicknesses from 100 to 250 μm, and investigated displaces of the cushion and pressure rising inside. They found that thickness of the fabric has a significant impact to these properties.

3.3 CFD Analysis of the Flow from an Inflator Module

Not only mechanical or thermo-kinetic analysis, but CFD investigations are essential for complex study of airbag systems. Work of Hoffmann et al. [26] showed that vertical position of the holes of the compact gas generator module (in case of passenger side airbag) has a decisive influence on the flow from the housing to the airbag (e.g. jet deflection angles), and accordingly, pressure distribution along the inner surface of the bag. The CFD module of MADMYO was used to simulate fluid flow, with adaptive mesh refinement. The CFD deployment analysis as part of a restraint system simulation allows prediction of the effectiveness of any kind of airbag (folding pattern) designs to mitigate occupant injury values caused by the thermodynamic inflator energy transfer during early inflation through occupant airbag contact interaction (out-of-position load case).

3.4 Analytical Modeling

Analytical models can be easily coupled with commercially available FEA or Multibody Dynamic simulation software, like Ansys or Ls-Dyna. This gives the capability to analyze the influence of modification of the gas generator to the whole crashing process. Furthermore, analytical models can easily implement with new features or variations of estimation methods.

Alcala et al. [27] composed Matlab/Simulink analytical model (with block modelling technique) to simulate chemical reactions in the inflator and changes of tank pressure in case of out-of-position test of a driver side airbag. They took into consideration the design parameters of the inflator, the exact amount of propellant, geometry of pellets, the chamber volume, the heat exchanges through the walls, chemical reaction and flame propagation rates, initiation efficiency, temperature dependencies of material properties, and so on. The model calculates the mass flow rate at the output of the inflator and the induced pressure in a closed tank test according to SAE J2238 [28]. The model is capable for both toroidal and tubular inflator simulations. It has been validated on baseline performance at normal validation temperatures in Europe (−35 °C, 23 °C, 85 °C). The model error has been compared with the acceptance production corridor for USCAR (United States Council for Automotive Research) specification and presented a very good agreement. The deviation for time specifications is, for all pressure levels, under 1% while pressure deviation is less than 7%.

Seo et al. [29] studied changes in component mass and temperature in case of some modern propellants with one-dimensional mathematical analysis and experimental studies. They solved the main conservation equations for mass and energy in constant volumes. The mass conservations for species in each zones of inflator, can be written according to the extended Damköhler-equation, considering mass fractions, mass flow rates, mass source terms in each species, and regression rate of solid propellant grains. Energy conservation equation can be also derived for each species in every inflator zones. Assuming cylindrical shapes of propellants, instantaneous surfaces can be estimated in every time step. With chemical reactions and basic equations, amount of products and generated heat and pressure is closed tank can be estimated. Authors studied four propellants with different compositions, and compared the results with measurement data with good agreement. They used classical Matlab software to run the calculations.

Im et al. [30–33] approached the problem in the similar way, however they completed theoretical models with FEM simulations using LS-DYNA software. They studied pyrotechnic and hybrid inflators in combustion chamber and with gas plenum.

Zanker [13] investigated heated gas inflators. Author gave a complex mathematical method which considers gas-phase flow fields for real, compressible fluids and non-ideal states. Simulation method were validated for some different examples, e.g. shock tube, constant volume explosion, isentropic venting, and detonation.

Not only gas generation, but heat transfer from hot airbag exhaust gases has an important role in proving the needed hardness of the airbag cushion (and its inner pressure), and burning injuries of the passengers. Mercer and Sidhu [34] studied its effect with a mathematical model for thermal conditions of the airbag and its gases. They found, that large vents of the airbag should be used to ensure that the heat flux per unit area is minimized and the vents should be positioned to minimize the impact on skin particularly the hands and forearms of drivers.

4 Conclusions

Most commonly known part of vehicle passive safety system are airbags, and their design process requires extreme caution. Before the serial production, the airbags must be subjected to many tests and simulations, to precisely create their ultimate parameters. Some simulation methods are used by engineers, several of them reviewed by the authors. However, their combinations give the most accurate results.

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