

# THE ANALYSIS AND EXPERIMENTAL DEVELOPMENT OF ASPIRATED AIRBAGS FOR CONVENTIONAL AND AUTONOMOUS VEHICLES

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## ABSTRACT

As a part of the Automated Driving Systems (ADS) strategy, the developed aspirated inflation system is applicable for conventional and autonomous motor vehicles where larger airbags are required and the location of vehicle occupants is less precise. It is built to provide for the air entrainment into an airbag from the car passenger compartment. The objective is set to inflate a 50 L airbag within 30 ms with an aspiration ratio,  $A \geq 4$ . Advantageous features of the offered system are a much smaller (less than 1/3) gas generator and stopped airbag deployment on contact with an occupant that eliminates out-of-position occupant injuries.

Regarding engineering, the aspirated inflator is a supersonic pulse ejector designed on the basis of Prandtl-Meyer effect realization. The modeling includes numerical flow simulation combined with subsequent engineering design, fabrication, and experimental testing of models. The results are presented for the “cold-gas” inflator testing where the gas generator operation is imitated by a jet generation from a compressed-air tank using a specially designed high-speed valve. Such an approach enables the verification of the numerical procedure and calculation results obtained for “cold” and “hot-gas” cases. The experimentally found “cold-gas” aspiration ratio is in a good agreement with the numerical prediction varying within  $A=3.1 - 2.1$  depending on a particular design and the operational motive pressure. For the gas generator case, the aspiration ratio values are calculated to be  $\geq 4$ .

Several different designs of the supersonic pulse aspirator are modeled, designed, manufactured, and tested including outer and inner circumferential slit nozzle and multi-nozzle systems. To meet the engineering requirements, multi-stage multivariate studies of measured pressure fields and airbag inflation process are performed.

## INTRODUCTION



*Figure 1. Safety is our goal*

According to NHTSA, the Automated Driving Systems (ADS) must handle the whole task of safe driving by ~2025. The automation is successively provided by technology development both in hardware and software areas starting from cruise control and seat belts within 1995-2000 to lane departure warning, blind spot detection, automated emergency braking, traffic jam assist, self-parking, adaptive cruise control, and many other systems showing features of partially automated safety.

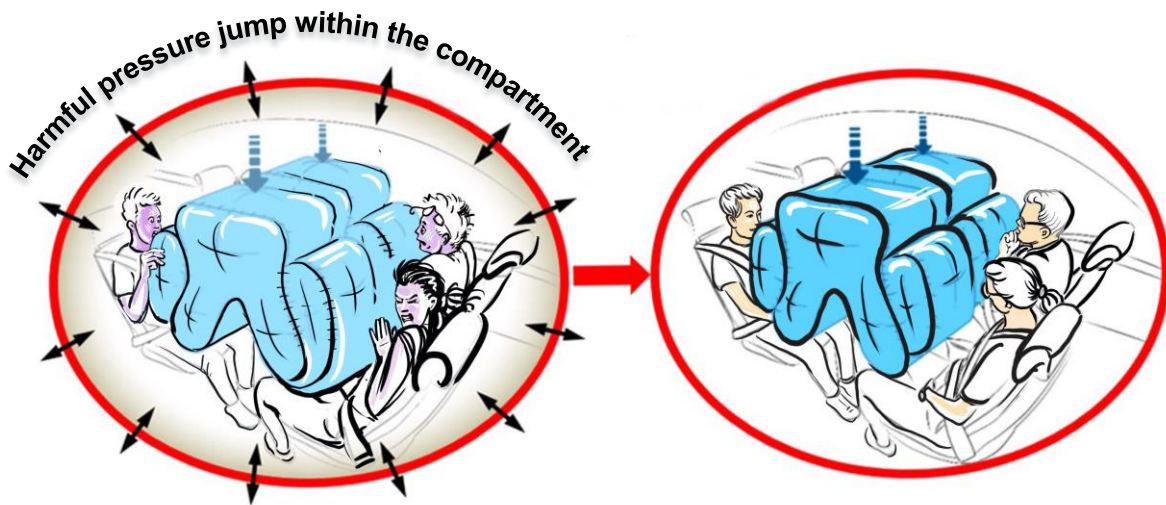
In this connection, the herein offered system of airbag aspirated inflation can significantly contribute to the further development of safety systems up to fully autonomous vehicles with arbitrarily located occupants.

The initial goal is to develop a supersonic pulse ejector for an airbag inflation system to cause air aspiration from a car compartment into the 50-60 L airbag to inflate it within 30 ms with the aspiration ratio above 4. This technology

should have an application potential for larger airbags such as passenger side airbags, side curtain airbags, side-impact airbags and airbags for autonomous vehicles.

The main advantages of the offered aspirated inflator are as follows [1-5],

- the airbag stops deploying on contact with an occupant;
- the required gas generator is less than 1/3 the size of conventional gas generators (see e.g. [6]);
- most of the gas to inflate the airbag comes from the passenger compartment that prevents sudden pressure jump within a vehicle compartment (Figure 2);
- injuries to out-of-position occupants are eliminated;
- the need for staged airbag deployments is eliminated;
- the need for satellite crash sensors for frontal impact sensing is eliminated;
- occupant weight and position sensors are not required.



*Figure 2. Illustrated impact of big deployed airbags: operation with conventional (left) and aspirated inflator systems (right)*

The driver side system development comprises numerical modeling and laboratory experiments including the engineering aspirator design and its operation testing in a range of motive pressure values causing air entrainment. Achievement of high performance characterized by the aspiration (entrainment) ratio was realized through a search of an optimal geometry combined with an optimal operational mode.

Numerical simulation provides initial guidance on the aspirator geometry and flow parameters for two temperature regimes. The “cold-gas” regime strictly corresponds to experiments in the compressed-air facility equipped with a high-speed valve which are performed in the Laboratory for Advanced Aerodynamics & Interdisciplinary Research, National Academy of Sciences of Ukraine. Experimental results enable to verify the numerical procedure and calculation results as well as to distinguish flow features overlooked in the numerical studies. The “hot-gas” regime models the aspirator operation with a gas generator; it is tested experimentally using the commercial airbag gas generator technology in the laboratory of the Shanghai East Joy Long Motor Company.

## **METHOD OF INVESTIGATIONS AND INSTRUMENTATION**

The research approach consists in matched and feedback-connected numerical and experimental investigations. As guidance to build a supersonic ejector, the Prandtl-Meyer flow is considered [3, 5]. A supersonic jet-flow generated by a small gas generator should change its direction over the blunt angle coupling between a nozzle and a mixing chamber which causes a suction wave similar to that of Prandtl-Meyer flow. It is the proper pressure distribution in this area which motivates ejection of the atmospheric air into the mixing chamber.

Thus, the basic task of numerical simulation is to roughly determine the device geometry with its particular linear and angular dimensions which would create the required pressure fields in the inflator. To determine optimal operational parameters for the given geometry, instantaneous and integral gas-dynamic parameters are found for viscous incompressible gas using nonstationary Reynolds equations. To validate the numerical

problem formulation and used assumptions, 2 cases of “cold air” and “hot air” inflator operation are considered numerically. The first one imitates the laboratory conditions of the inflator operation using the compressed air tanks as a high-pressure source. The second one, models the situation of the inflator operation using a small pyrotechnic gas generator as the motive pressure source.

Obtained recommendations on slit, nozzle, mixing chamber parameters for a range of high motive pressure are taken as a basis for the engineering design which resulted in the detailed technological drawings and precision manufacture of the model.

The experimental task is to provide, thorough measurements of pressure fields in the aspirator system, a description of the jet behavior and, consequently, the air entrainment process. In addition to the measured values of aspiration ratio for different models and their operation conditions, this is visualized with the video recordings of airbag deployments using a high-speed camera.

**Experiment arrangement. Test models.**

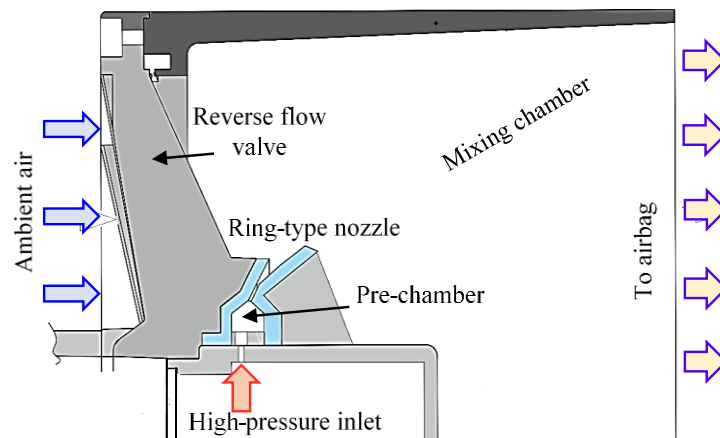
The “cold air” system operation is realized experimentally due to the specially designed universal high-speed valve (UHSV-1). Its basic parameters are given in the Table 1.

*Table 1.*

*Basic operating parameters of the UHSV-1 high-speed valve*

Opening time	≤ 0.004 s
Closing time	≤ 0.005 s
Pressure range	0.6-6 MPa
Temperature range	+5 °C ÷ +65 °C
Supply voltage	80±6 V
Material	Steel 14X17H2
Dimensions	79 mm x 125 mm x 141mm
Weight	3 kg

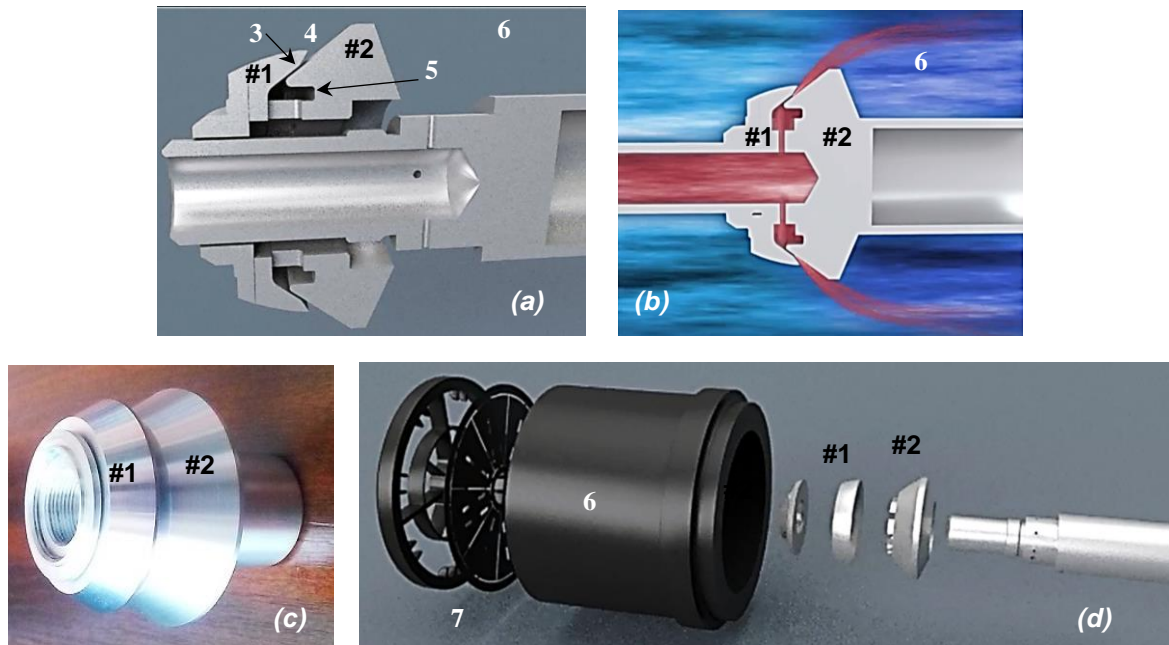
These parameters enable to form a motive pulse jet from the nozzle to initiate the ambient air entrainment into the inflator mixing chamber as it is shown in Figure 3.



*Figure 3. Sketch of an axisymmetric design of the aspirated inflator according to the numerically outlined geometry*

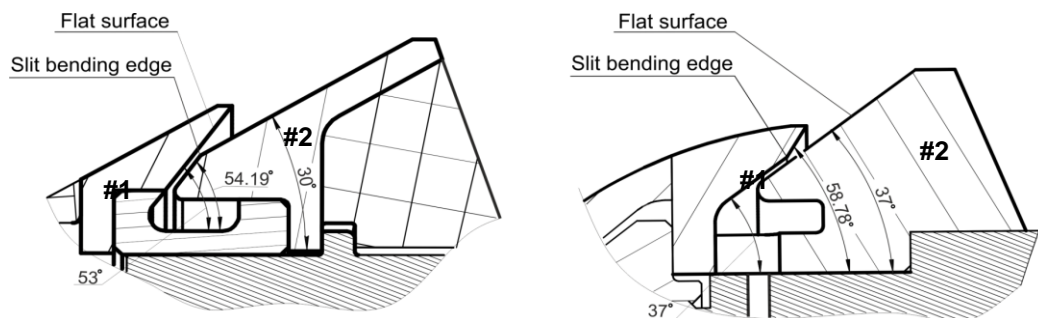
A nozzle for the supersonic flow is designed to match the output pressure in the jet with the pressure in the mixing chamber. Consecutive investigation stages covered a range of varying angles of the slit and nozzle opening, slit width, geometry and sizes of pre-chamber and mixing chamber to determine an optimal set of design parameters.

Several aspirator models were designed, manufactured and tested as is partly described in [2-4]. They are axisymmetric following an overall design of the system to be located in the steering wheel. An essential feature of the first set is an external slit relative to the mixing chamber, i.e. the motive ring-type nozzle was located close to the internal wall of a mixing chamber. The second type combines aspirators with an internal slit ejecting the ring jet closer to the aspirator axis. The second type is considered here with its design illustrated by Figures 4 and 5.



**Figure 4. Internal-slit aspirated inflator: 3D model (a); aspirator operation (b); fabricated test model (c); aspirator assembly (d).  
 #1, #2 – two metal disks forming a relevant nozzle geometry for a supersonic jet injection,  
 3 – slit,  
 4 – nozzle,  
 5 – pre-chamber,  
 6 – plastic mixing chamber/housing,  
 7 – reverse flow valve**

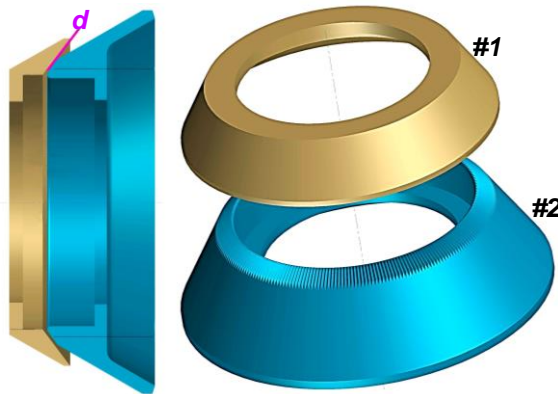
The sharp bent edge of one of the metal disks #1 or #2 is designed to realize the Prandtl-Meyer flow conditions. The whole design of the supersonic pulse ejector is to be substantially different from known ejectors made for operation in stationary flow conditions. Two basic design modifications of the internal-slit aspirator are shown in Figure 5. Other tested modifications embrace combinations of varied linear and angular dimensions of the basic aspirator elements like a slit, nozzle, pre-chamber, location of a motive pressure outlet in the pre-chamber, and mixing chamber including its shape, cylindrical or conical.



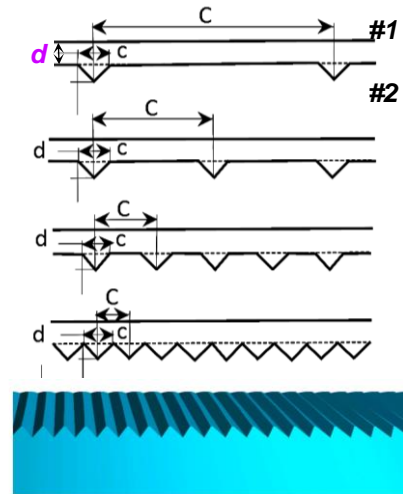
**Figure 5. Geometry of the slit initiating aspiration in the internal-slit aspirator design, 2 versions:  
 (a) aspirator #1; (b) aspirator #2**

Overall dimensions were maintained the same according to the engineering requirements, i.e. the aspirator length is no more than 117 mm, its diameter is 120 mm.

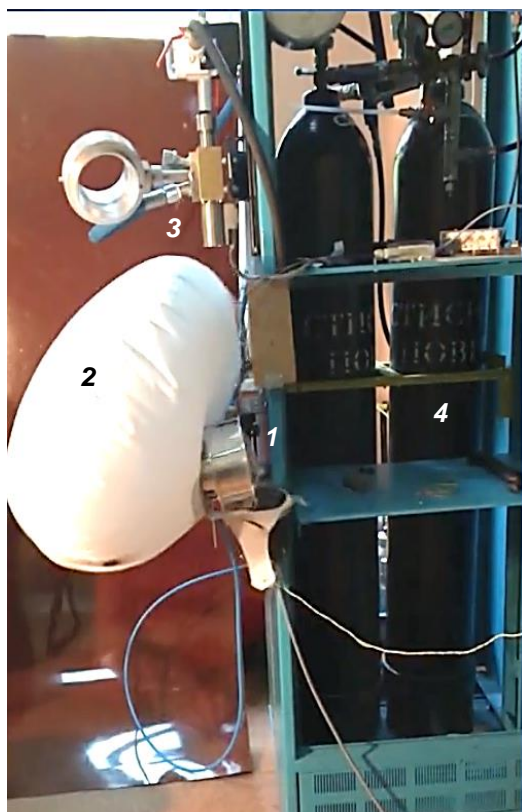
Finally, an attempt was made to stabilize the supersonic jet with streamwise grooves over the #2 disk with the circumferentially regular spacing (Figure 6, a) for several values of a filling factor,  $F=c/C=6.7\%$ ,  $13.3\%$ ,  $26.7\%$ ,  $53.3\%$ ,  $100\%$  (Figure 6, b) [see 7-9]. Effective slit width was calculated to vary within  $d=0.35\text{mm}$ — $0.45\text{mm}$ .



**Figure 6, a. Grooved disk #2 modified to stabilize behavior of the supersonic jet**



**Figure 6, b. Grooved surface with various filling factors**



**Figure 7. Experimental facility [2, 4, 10]:**

- 1 – aspirated inflator model;**
- 2 – airbag;**
- 3 – high-speed valves;**
- 4 – compressed air tanks, 0-100 bar**

(2-10 locations shown in Figure 8, b). A number of other pressure probes are mounted so as to measure static pressure values along the mixing chamber wall (11-15 locations) and in the pre-chamber (probe location 1).

### Experimental facility

The stage of experimental testing of the inflator operability started from the design and manufacturing of the compressed-air facility (Figure 7) and a number of appliances including the automated data acquisition and processing system, pressure-probe rakes, the aspiration ratio stand, etc.

During testing, the air is pumped into the 40-L high-pressure 250 bar tank by the high-pressure PE-100W compressor up to 100 bar. From this tank, air goes to the 40-L receiver of 150 bar through a reduction valve. The reduction valve is adjusted according to the range of motive pressure values,  $P_m$ , required in experiments. The UHSV-1 electronically controlled and the alternative commercial KB-20 pneumatically controlled high-speed valves are switched in the pneumatic tract. High-pressure sensors for 1-70 bars are mounted after each valve to measure pressure losses. Due to very short opening and closing time, high-speed valves form a jet flow within 20-40 ms similar to gas generators to initiate the ambient air entrainment as it is shown in Figure 4, b. Excessive pressure in the airbag is 0.2 bar that stops the inflation process.

The measurement program aims at the determination of the supersonic jet location and behavior inside a mixing chamber to find conditions for stable air entrainment. For that, corresponding to the particular inflator design, the pressure-probe rake (Figure 8, a) is fabricated to measure dynamic pressure at the mixing chamber outlet

Other series of experiments were conducted under the same conditions with an airbag mounted to the inflator outlet. The process of airbag deployment is recorded using a high-speed 1000 f/s camera. It enables the analysis of the visualized inflation process together with corresponding measured pressure distributions.

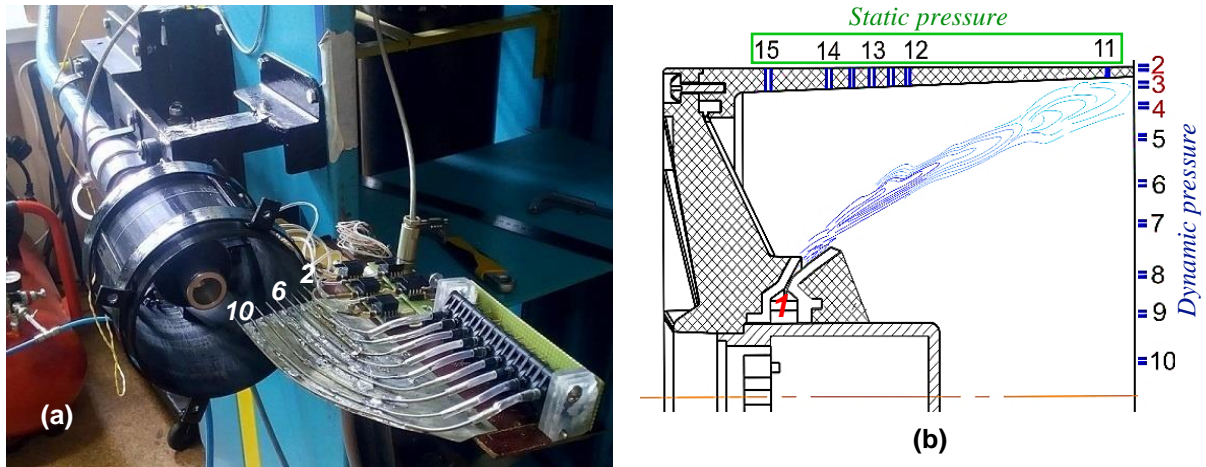


Figure 8. Pressure probe rake (a) and numbering of pressure probes (b)

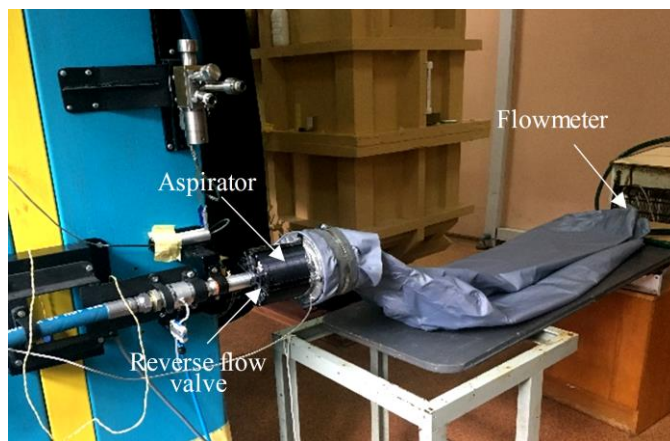


Figure 9. Stand for aspiration ratio measurements

The series of experimental tests is completed with measurements of the aspiration ratio values depending on motive pressure for every tested inflator design. Figure 9 shows the stand for aspiration ratio,  $A$ , measurements. It uses a 200 L bag mounted to the inflator outlet and to the flowmeter to measure the air volumes with and without the operating aspirated inflator:

$$A = \frac{V_{bag \text{ with aspiration}}}{V_{bag \text{ without aspiration}}}$$

Automated remote control of experimental runs and simultaneous data processing is illustrated in Figure 10.

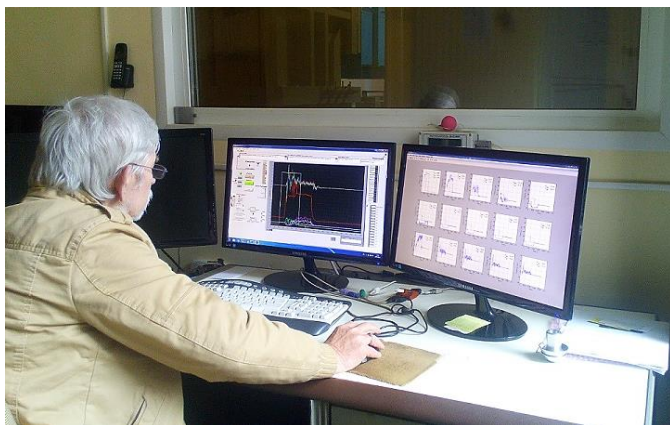


Figure 10. Automated remote experiment control

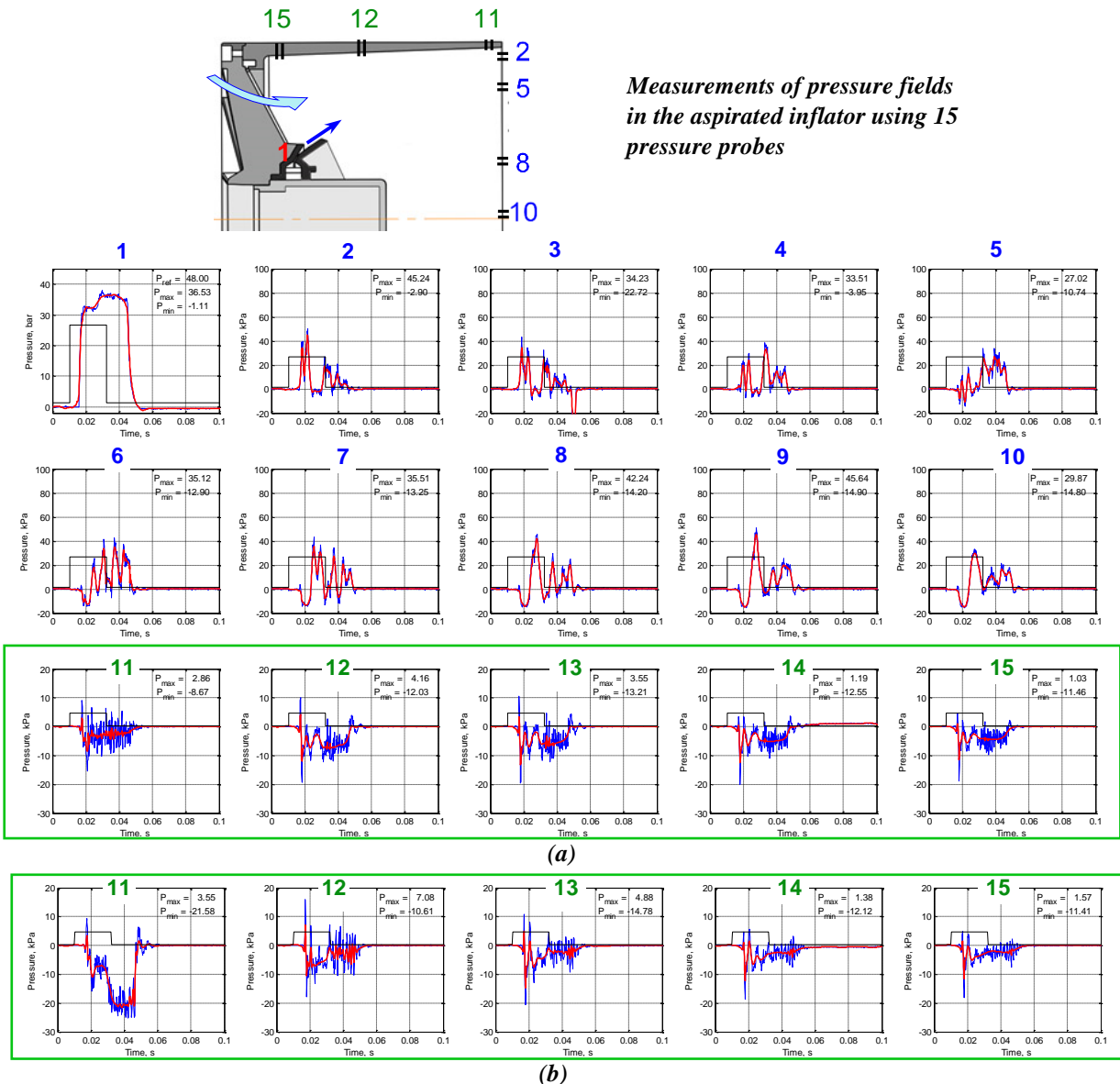
## RESULTS AND DISCUSSION

The key feature of the formulated multivariate problem is a certain compromise between an optimal aspirator geometry with its specified dimensions and optimal parameters of its operation. This compromise is the only solution to satisfy the given engineering requirements. Thus, it is important to determine experimentally the ranges of acceptable operational parameters for an outlined aspirator design such as motive pressure  $P_m$  as well as a dominant jet direction and intensity within the aspirator housing (mixing chamber) which would result in the best air entrainment.

## Pressure measurements

Pressure fields are measured in a process of air aspiration using 15 pressure probes distributed around the mixing chamber interior and in the inflator nozzle (Figure 8). #1 probe measures pressure in the nozzle, ##2-10 probes register the dynamic pressure at the exit from the mixing chamber, ##11-15 probes show the static pressure along the mixing chamber wall. The obtained patterns of the type shown in Figure 11 enable the reconstruction of the jet behavior (intensity, shape and location) to determine its optimal location for best aspiration for a given aspirator model depending on the operational motive pressure  $P_m$ . The latter is correlated with a video-recorded airbag inflation process as well as with the measured values of aspiration ratio. For instance, jet instability can result in a significantly decreased entrainment of ambient air despite growing  $P_m$ .

The ejecting slit width,  $d$ , is a key parameter varied in experiments stepwise as 0.25, 0.35, 0.40, 0.45 mm within a pressure range of  $P_m=18-60$  bar. Sets of measurements are made for  $P_m$  growing with a step of  $P=1-3$  bar.



**Figure 11.** Measured dynamic pressure, 1-10, and static pressure, 11-15;  $d=0.4$  mm;  $P_m = 48$  bar (a); measured static pressure, 11-15 probes;  $d=0.4$  mm;  $P_m = 51$  bar (b)

Figure 11 shows a pretty wide jet flow with a moderate intensity distinguished by probes 2-10. Vacuum static pressure provides the air suction from the aspirator inlet with a reverse flow valve.  $P_m$  increased from 48 to 51 bar shows an area in the axial part (6-10 probes) with a formed reverse flow though maintained suction along the aspirator wall (Figure 11, b). A possibility to eliminate this flow instability was investigated on the basis of

earlier fundamental flow control studies [7-9]. Here, it was implemented using a modified disk surface shown in Figures 6 and 12. Formed circumferential flow regularity resulted in a much more intense flow in the aspirator mixing chamber especially near its peripheral part registered by ##2-5 probes. Simultaneously, it noticeably reduced the axial reverse flow.

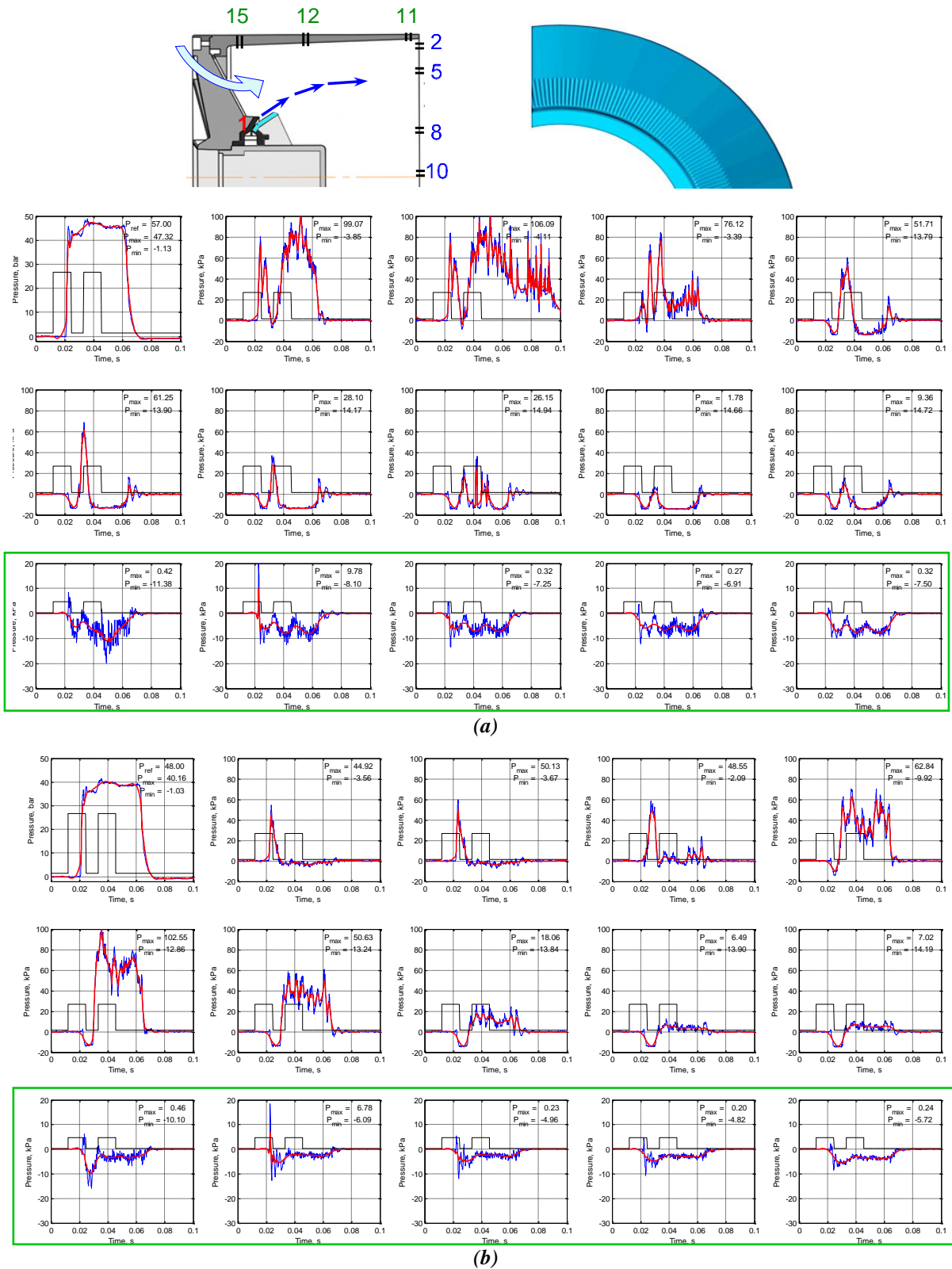


Figure 12. Measured pressure fields in the aspirated inflator with a grooved surface of #2 disk, filling factor  $F=53$ , 3% (see Figure 6, b);  $d_{eff}=0.4$  mm;  $P_m = 57$  bar (a) and  $P_m = 48$  bar (b).



The modified design with  $F=53.3\%$  resulted in the slightly enlarged slit width from 0.35 to 0.4 mm and demonstrated its operability in a wider range of motive pressure. Results of Figures 12, a, b obtained for  $P_m = 57$  bar and 48 bar as well as for the values beyond this range do not differ as drastically as in the case of a smooth disk surface, while the values of suction pressure are more uniform along the aspirator mixing chamber.

### Airbag inflation

A high-speed camera was used for video-recording of the airbag inflation within 30, 35, 40 ms, the inflation time having been regulated by a high-speed valve. Aspirators with a varying slit width were tested in a pressure range of 24-60 bar with a step of 3 bar. Figure 13 shows a sequence of pictures characterizing the airbag process inflation using optimized operation parameters for the aspirator design of Figure 5, a.  $P_m$  increased to 50 and 55 bar also showed good airbag inflation.

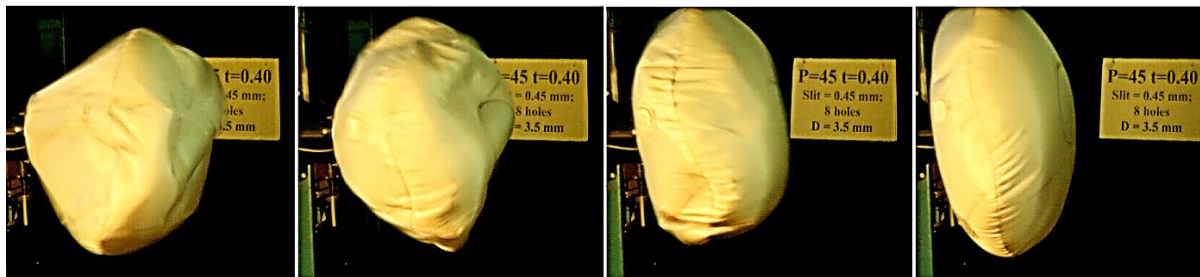


Figure 13. Successive stages of the airbag inflation process:  $d=0.35$  mm;  $P_m = 45$  bar.

Thus, the video-recorded inflation process of an airbag supplemented results of pressure measurements and enabled to recommend optimal sets of parameters for a given inflator design. These recommendations were also confirmed by aspiration ratios measured for various experimental conditions.

### Measurements of the aspiration ratio

Values of aspiration ratio were measured both for the smooth model design of Figure 5, a and the grooved disk #2 surface of Figures 6 and 12. A 200-liter bag was connected to the aspirated inflator and to the flowmeter to enable the air easy filling with further volume measurement. Statistically obtained A values for every case of design and flow parameters are shown in Figure 14 where numerically obtained curves are placed for comparison, the red curve having described the “cold-gas case” comparable with experiments.

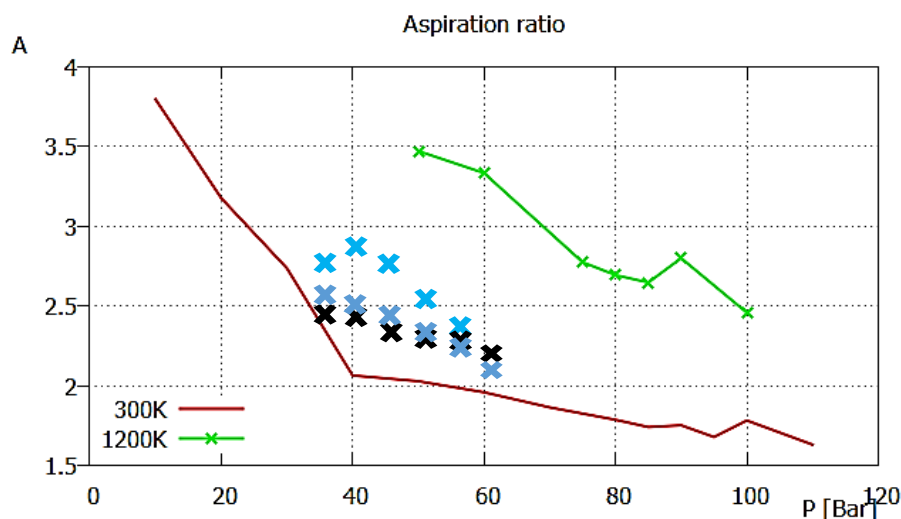


Figure 14. Aspiration ratio for cold (red curve) and hot (green curve) gas found numerically;

✕ - experiment, baseline smooth disk surfaces;

✕ - experiment, grooved surface,  $F=6.7\%$ ;

✕ - experiment, grooved surface,  $F=53.3\%$

All of the experimental aspiration ratio values are higher of the numerical values. Therefore, taking into account 1.5-2 times higher hot gas volume aspiration, one can expect to satisfy the engineering requirement of  $A \geq 4$  in case of the aspirated inflator initiated with a pyrotechnic gas generator. The combination of design and operation parameters play a significant role in the inflator operation which can be optimized using a proper choice of these parameters.

## CONCLUSIONS

The aspirated inflation system is developed for a 50 L driver's airbag with an aspiration ratio,  $A \geq 4$  which can be applicable for airbags of larger sizes. It provides the air entrainment into an airbag from the car passenger compartment due to the realized Prandtl-Meyer supersonic jet flow over a bent nozzle wall. The jet motivating the air entrainment is generated by a small gas generator; its operation is imitated in experiments by a system of high-pressure tanks controlled by a high-speed valve. One of the features built into the design is the 0.2 bar overpressure in the airbag which discontinues the air entrainment that stops airbag deployment on contact with an occupant and thus eliminates out-of-position occupant injuries.

The experimental investigation of the system operation is a multivariate problem where optimal combinations of design geometry and operation parameters are sought. The built experimental facility, appliances, automated measurement complex, and several manufactured and tested models enabled the validation of the numerical approach and results and to show the potential of the developed aspirated inflator.

Various modifications of the design including the circumferential surface regularity over one ring wall of the nozzle can result in noticeable variation of the motive jet behavior. As such, it can be stabilized providing a wider range of acceptable parameters for optimal inflator operation. In its turn, it can be very important in terms of less severe requirements to flatness of pressure curve produced by a pyrotechnic gas generator and thus to the motive gas generator itself.

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