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System of current collectors inertization for safety use in explosive atmosphere-testing and results

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Abstract:

R&D work regarding the innovative mine transportation system, planned to be powered by the three-phase busbar, developed within the RFCS project "Increase of mines efficiency and health protection through the innovative transport system based on BUSDUCT" is discussed. Assumptions regarding the construction of the locomotive and the production of nitrogen from the air for inerting purposes are discussed in the first part, whereas in the second part adapting the current collector's brushes to nitrogen injection, the relevant CFD calculations, the stand for testing the inertization, are presented. Many interesting experiments on the effectiveness of inertization using explosive mixtures of hydrogen and air are illustrated, described and discussed.

Keywords: monorail locomotive, suspended busbar, current collectors, methane atmosphere, brush inertization

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1. Introduction

R&D work based on the "Mid-Term Report" of the project "Increase of mines efficiency and health protection through the innovative transport system based on BUSDUCT" [1] is discussed. The project, led by ITG KOMAG in 2019-2021, was carried out in a consortium of 5 partners, whereas three of them from Poland i.e. KOMAG, BECKER-Warkop and PGG, one from Germany i.e. RWTH Institute and BARTEC company from Slovenia. Completion was expected in 2022, but the project was terminated, as a result of doubts related to market demands for the proposed solution in the context of mine closures. Additionally the experts supervising the project also had doubts about the safe use of the proposed solution in the conditions of methane mines.

The idea of the BUSDUCT project resulted mainly from the situation of the mining industry in Poland, where the transport routes are becoming longer in a result to reach the next coal seams, which are more and more distant from the shaft, whereas building new shafts in terms of the policy of reducing the importance of coal as an energy source is unjustified. An efficient mine transportation system was perceived as very important for the effective functioning of currently operating mines. The commonly used, diesel powered locomotives are onerous due to exhaust gases and heat emission in confined space. Limited speed extends the exposure time of miners to exhaust gases and results in a significant shortening of their effective worktime. The development of the innovative mine transportation system based on a three-phase busbar, for powering the suspended locomotives, complies with the EU Directive [2] ATEX 2014/34/EU [3], standards [4-6] was a project purpose.

According to the Polish legislation, mine workings are divided into three categories: "a", "b" and "c". In mine workings "c", despite active ventilation, the methane concentration may exceed 1%. The main goal of the proposed innovation was the possibility of using such a system in all mine workings even those with the highest risk of methane explosion. The planned transport system offers the following advantages:

– Health protection of miners by elimination of diesel exhaust gases from the underground atmosphere, improvement of work comfort due to limitation of temperature increase in mine workings.
– Higher mine profitability due to increased disposable work time of miners, constant availability of the electrically powered suspended locomotives, with no refueling breaks.
– Up to 65% energy savings and energy recuperation during downhill transportation.
– Possibility of parallel operation in the same time of several locomotives with no danger of exceeding CO concentration in mine workings.

The above advantages could be achieved when the prototype, ready-to-be-produced for the transport system is launched, what was expected as the result of the project, however as mentioned, the project was earlier terminated. Nevertheless, the prototype of the nitrogen generator and the developed dedicated current collector is innovative and technically interesting that the authors decided that it is worth presenting it in the article to share the acquired knowledge in the field of nitrogen separation from air and the method of current collector's brushes inertization.

2. Planned transportation system and its safety case assumptions

Two current collectors (CC) were decided to use for the planned suspended machine. Each current collector has four brushes, working by contacts with the 3-phase busbar at the speed of up to 4 m/s, which results from the assumed maximum speed of the suspended machine. The unavoidable sparking of the brushes creates a huge risk of initiating an explosion. To ensure the safe operation of the current collectors of the planned suspended monorail machine an inertization of brushes contact area was planned. It was also necessary to take into account the maximum speed of air of 8 m/s in the workings.

At the beginning the consortium chose the type of busbar, taking into account the practical aspects, mainly economic, so that for long routes the cost is acceptable to future users. The selected busbar offered by the Conductix company [7] is shown in Fig. 1.

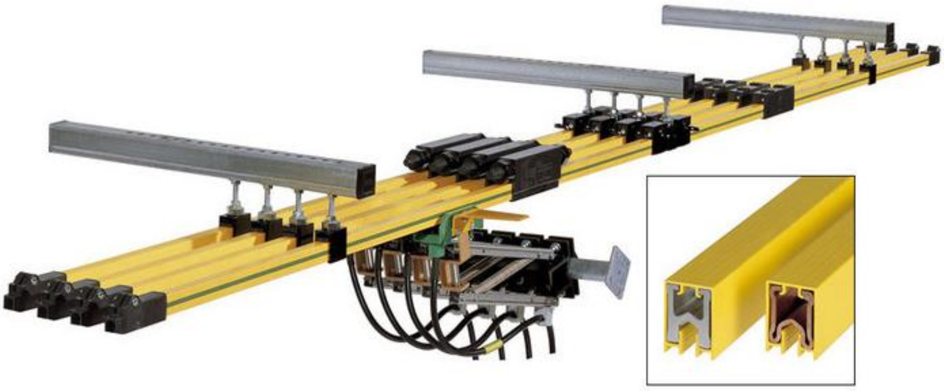

Fig. 1. View of the selected type of busbar [7]

The standard for the explosion protection method “pressurized enclosure” EN-IEC 60079-2 [5] is used as a technical rule, however the standard cannot be applied directly to the mobile devices. Due to possible sparking, the contact zone of the brushes and the busbar lines has to be isolated from the mine atmosphere, which can contain explosive concentration of methane. For that purpose inertization of the current collector working zone, by injecting nitrogen, resulting the overpressure inside the brush collector, separated from the atmosphere by a special aggregate subassembly, were developed. Furthermore, to ensure a safe operation, nitrogen injection to the current collectors should be controlled by a series of sensors. The scheme of the concept of the inertization system is illustrated in Fig. 2.

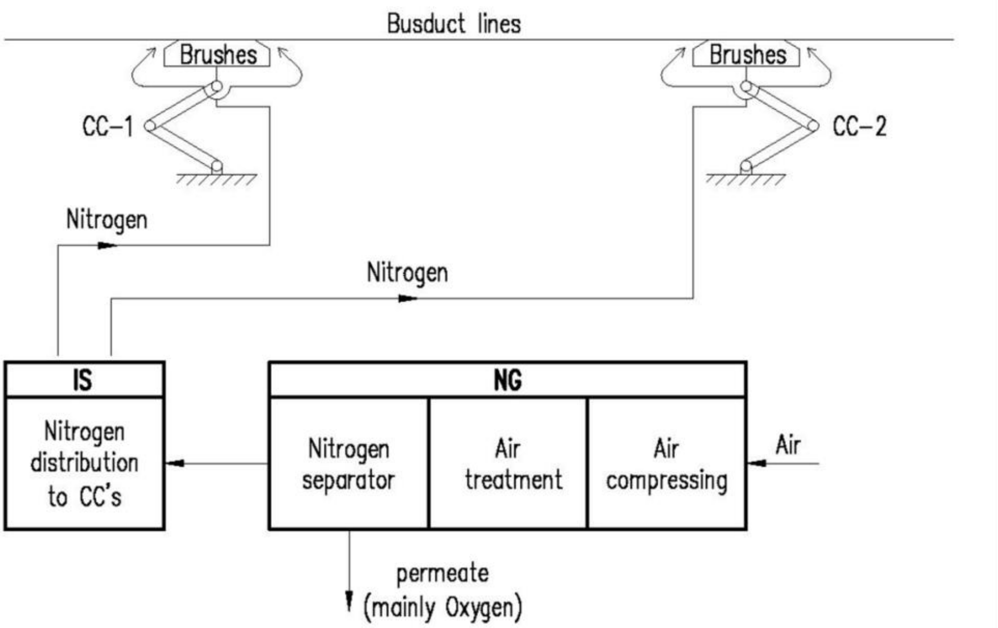

Fig. 2. Block diagram of the brushes inertization [1]

The following sensors were used to control the inertization system:

- Pressure measurement devices to control the minimum overpressure inside the single brush collector,
- Volumetric flowmeters to monitor the nitrogen supply to each brush collectors.

ATEX certification of the type: I M1 Ex ia I Ma is a main requirement for all sensors to be installed in the prototype.

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The scheme in Fig. 2 presents an overview of the blocks of the NG nitrogen generator and the IS inerting system. The NG uses a membrane technology, which was chosen as the most advantageous due to necessity of meeting the requirements of the ATEX directive and the requirement of mobility. As the separation of gases to produce nitrogen takes place at the molecular level [8, 9], the air supplied to the separator must be specially treated. The requirements are related to the content of moisture, solid particles and oil aerosols, that got into the air during its compression. The residual oil content must be below 0.01 mg/m^3. The ambient (atmospheric) air is compressed, carefully filtered, and then passed through a series of separation modules consisting of thousands of membrane fibres. The fibres separate nitrogen from air. The separation follows the principle of selective gas permeability through the membrane walls. Smaller gas molecules (water, carbon dioxide, oxygen and argon), which have high permeability, pass faster through the membrane fibres than the larger, less permeable molecules of gases such as nitrogen and methane. The purity of the nitrogen obtained by this method ranges from 95 to 99.5% but a higher purity results in a lower nitrogen output. According to preliminary calculations, it was possible to design a generator with a separated nitrogen efficiency of approximately 3 l/s in a given size. Since 8 brushes were assumed to be inerted, this efficiency for one brush guaranteed 0.375 l/s of nitrogen.

The nitrogen generator pumps nitrogen to the pressure tank in the inertization system IS consisting of two units, composed of several parts, including pressure reducing valve and pressure sensors. The unit shown in Fig. 3 distributes nitrogen to the four brushes of the one current collector (CC-1) and the same second unit distributes nitrogen to the second current collector (CC-2). Each current collector has 4 brushes. First, nitrogen is directed to the reducing valve, where the pressure is reduced to a constant level (set at the start-up). Nitrogen of the reduced pressure is directed through the flowmeter to the distributor, where it is distributed to each brush of the current collector.

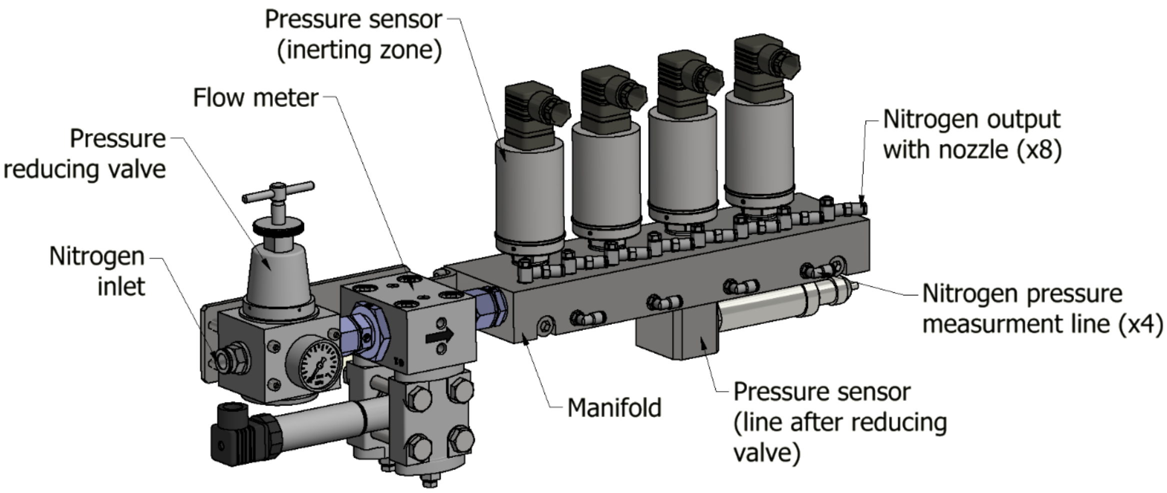

Fig. 3. Nitrogen inertization system unit [1]

3. Testing and results

The initial solution of the inerted brush, is shown in Fig. 4. The main idea was to use sliding scrapers (2) on both sides of the brush (1) due to the bidirectional sliding of the brush on the busbar line (7). The sliding scraper's task was to initially isolate the brush from the atmosphere. The scrapers (2) have channels with nozzles (4) at the end, that supply nitrogen to the brush working zone, delivered from the nitrogen inertization system unit (Fig. 3) through the thin tubes (5). In addition the longitudinal side covers (3) and typical brush cover (6) were taken into consideration.

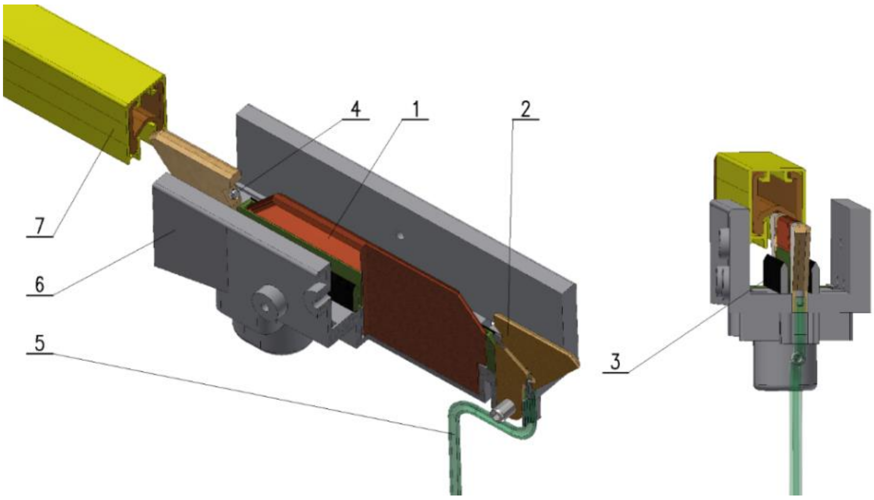

Fig. 4. Model of the solution of inerted brush [1]

Further, a CFD calculation model was developed to determine the assumptions of the nitrogen feed rate regarding the assumed maximum nitrogen efficiency 3l/s i.e. 0,375 l/s per one brush. The simulations, an example of which is illustrated in Fig. 5 show, that building up an overpressure inside the each brush collector is possible with the given seals. However, they also show that it is not yet possible to reach the minimum overpressure at every location inside each brush collector of the present design of the brush collector. That is why the additional sealing was needed.

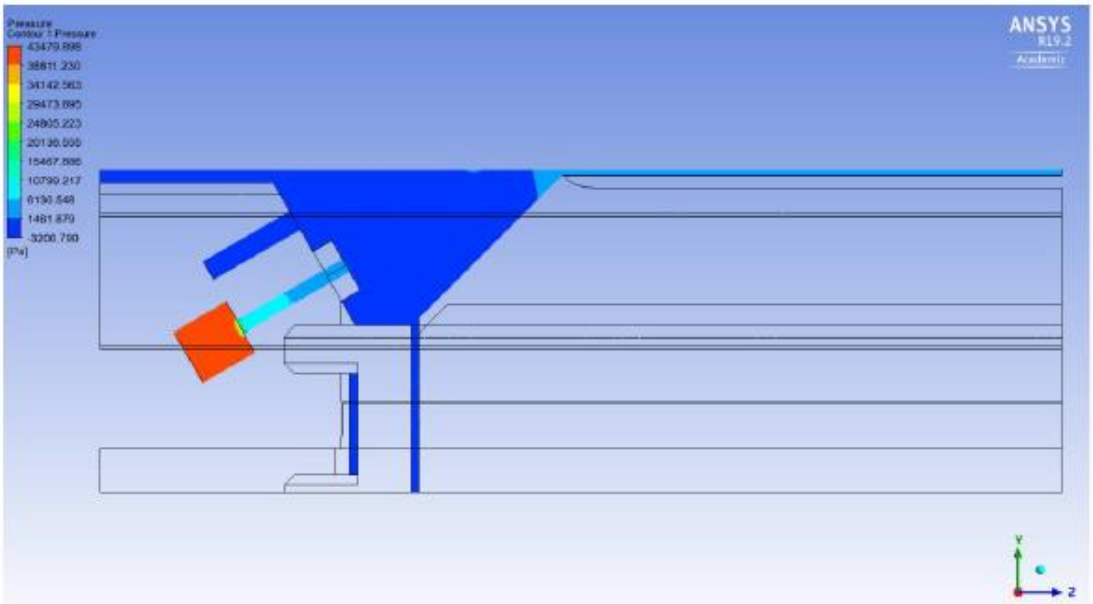

Fig. 5. 2-dimensional overpressure contour result of the CFD simulation on the single brush with using a nitrogen nozzle diameter of 1.0 mm and a 0.15 l/s inlet of nitrogen [1]

The additional wheels with rubber tire, before the scrapers on both sides of the brush, was proposed. The advantage of using the rotating rubber tire is that it better adapts to the shape of the electric track and therefore provides better sealing. As it can be seen in Fig. 6, CFD calculations with such additional rubber tyres give the positive impact. The tire reduces ingress of external atmosphere to the brush to dozen or so percent. The effect of double protection was achieved, which can be compared to the double door windbreak system. As a result the final solution of inerted brush, shown in Fig. 7 has been accepted by the consortium.

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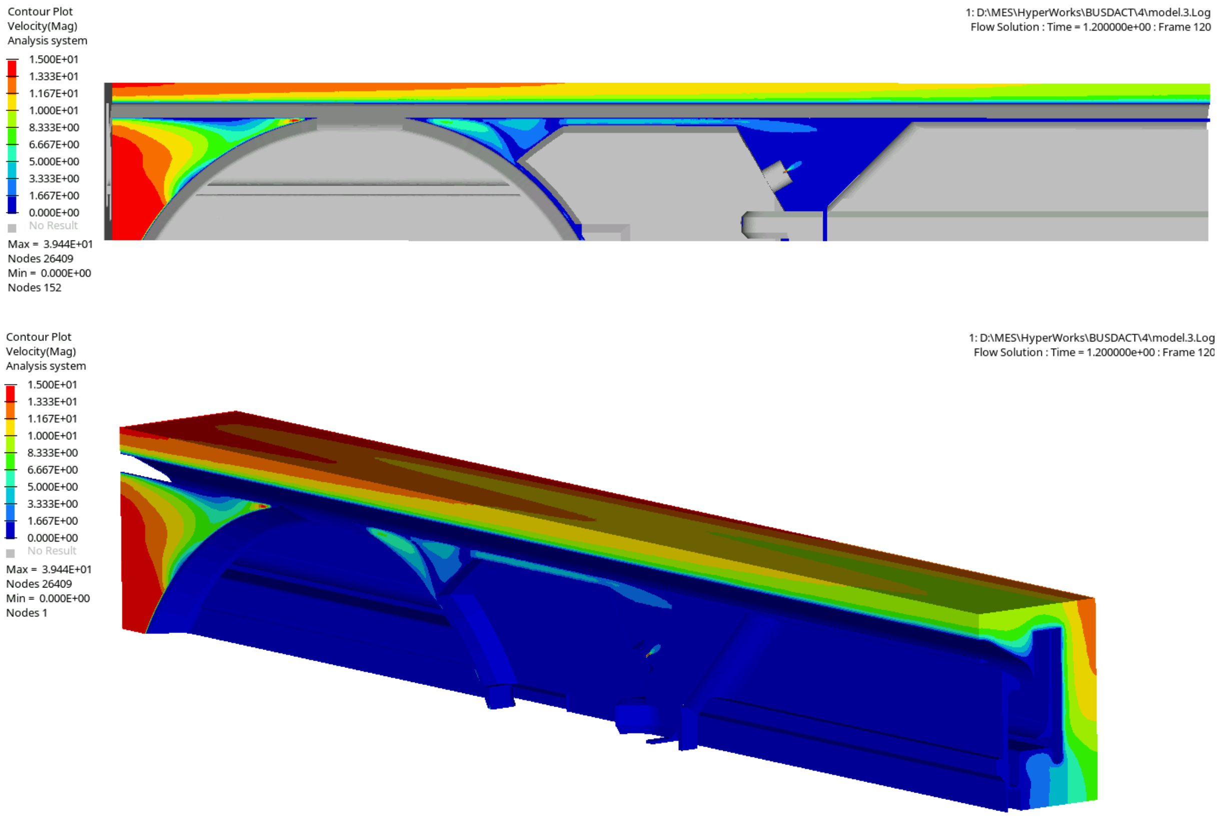

Fig. 6. Illustration of CFD modelling of inertization results- air speed map [1]

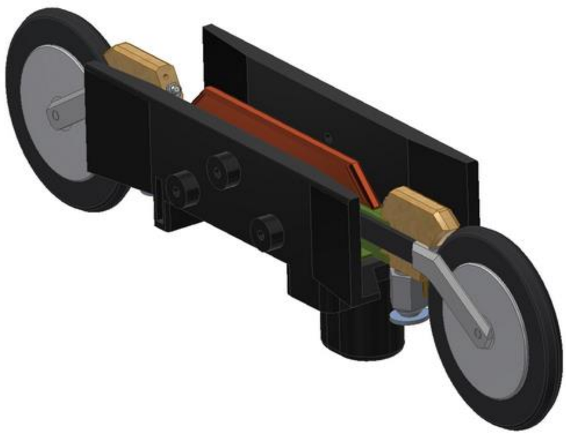

Fig. 7. Model of the final solution of inerted brush retrofitted with additional wheels with rubber tyres on both sides [1]

The next R&D proceeding was to check inertization of the brush efficiency in practice. It was decided to test the brushes during their inertization in the explosive atmosphere. For this purpose it was decided to use a hydrogen mixture, which is reliably explosive at various concentrations, unlike methane mixtures, therefore, the certainty of the experiment was essentially 100%. The special, transparent, two-compartment hydrogen mixture container (HMC) was designed. The hydrogen mixture could move in this container in a closed circuit in the upper and lower compartment thanks to three small fans with adjustable rotational speed up to 20,000 rpm illustrated in Fig. 8 installed inside the upper compartment of the container. The speed of the mixture up to 8m/s was used to reflect the maximum air speed in the mine workings [10].

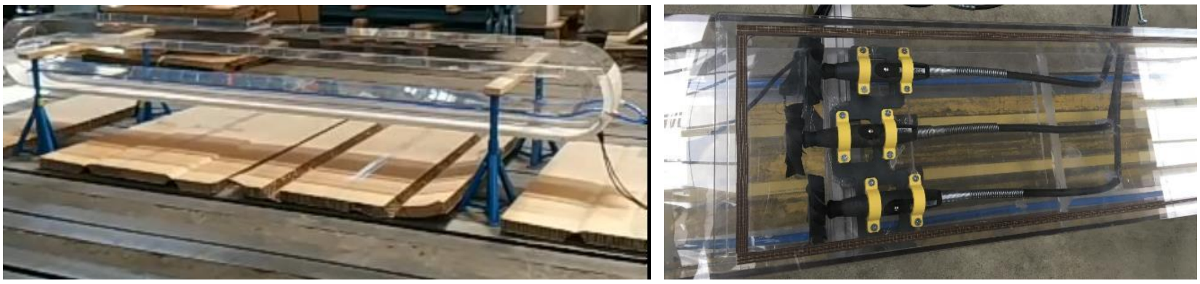

Fig. 8. The transparent two compartment container HMC (on the left), three fans with adjustable speed up to 20,000 rpm installed inside the upper HMC compartment [1]

The trolley equipped with brushes moved along a C-section route placed on the floor. In Fig. 9 it can be seen the route, the trolley equipped with two brushes installation and two busbar lines over the trolley. A speed of the trolley ranging from 0.78 m/s to 4 m/s was used during the tests to reflect the possible speed of the suspended locomotive.

Fig. 9. The trolley with two brushes installation on C-section route on the floor (left), the brushes applied to the busbar lines during nitrogen pressure testing (on the right) [1]

Two busbar lines have been passed through the lower compartment (Fig. 10) Each trolley pass experiment required sealing the lower compartment of the HMC using stretch foil to keep the hydrogen mixture inside before the trolley's pass.

Fig. 10. View of the transparent container, two busbar lines running across, the trolley on the C-section route below [1]

In Fig. 11 the scheme of the test stand is presented. The brushes on the trolley were electrically connected, so the circuit of the 55 kW dyno-motor was closed through the two lines of busbar and brushes on the trolley. Thus assured that the electric current in the busbar and brushes was adequate to the current in the planned system.

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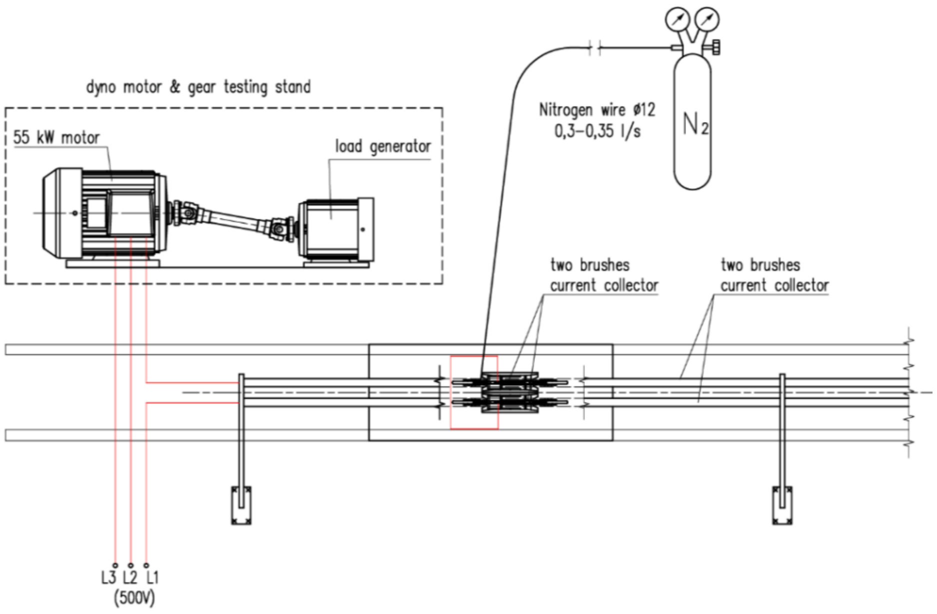

Fig. 11. Scheme of the test stand for inertization efficiency testing [1]

With the help of a high pressure nitrogen cylinder, this gas was fed to the brushes via a 20 m hose. A valve reducer was used to control the nitrogen supply. The first part of the test process dealt with the determination of suitable hydrogen concentrations to enable controlled explosions inside the hydrogen mixture container (HMC). An iterative approach was chosen for determining this concentration. In the experiments, hydrogen-air mixtures with a variable hydrogen content were ignited. Experiments with hydrogen-air mixtures containing 40-50 vol.% of hydrogen lead to explosions that exerted too much mechanical strain on the container, however its loose covers well contributed to dissipation of the explosion energy. The impact of the explosion is given in Fig. 12. The top covers of the HMC were thrown to height of several centimeters.

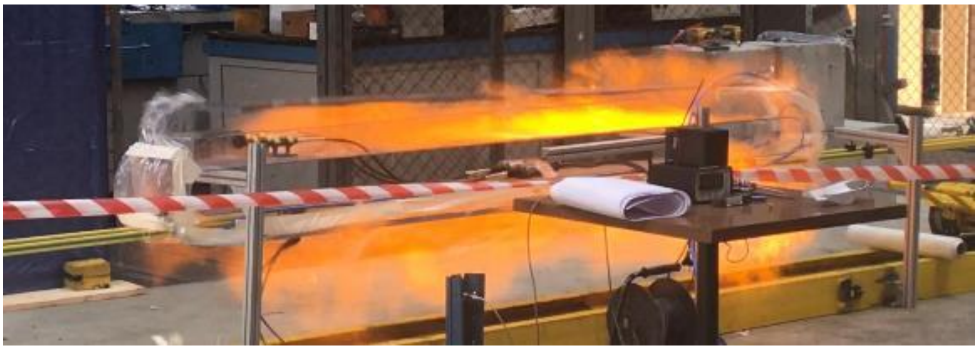

Fig. 12. View of the effect of the explossion, when nitrogen was not used for the brush inertization and the hydrogen concentration was around 30% [1]

Literature analysis [11] and testing the hydrogen mixture concentrations gave the following cognizance. Hydrogen concentration of 20 vol.% proved to be too low as an ignition of the mixture did not reliably occur. A hydrogen-air mixture with 30 vol.% of hydrogen proved to be suitable. No visible damage on the container could have been observed and explosions occurred reliably. The top loose covers of the HMC container were thrown upwards typically by approximately 15 cm, however it happened even by several dozen centimeters, during the explosion.

In the next step, it was decided to test the pressure in the area of the inertized brush in a dynamic way, while the trolley is moving on the test stand. A pressure sensor [8] was installed to one of

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the brushes through a vertical hole drilled in the middle of the brush. The sensor used to measure overpressure gives a feedback voltage which is proportional to the measured pressure. To determine the amount of nitrogen flowing to one inertizated brush, reference was made to the planned capacity of the nitrogen generator i.e. 3 l/s. This amount of nitrogen is designed for two CCs, i.e. 8 brushes, thereby the amount of nitrogen per one brush is 3: 8 = 0.375 l/s, which makes 22.5 l/min. It was also assumed that the actual amount of nitrogen supplied to a single brush may be slightly lower than the nominal one, therefore the inertization efficiency tests were carried out for the flow of 20 l/min and 15 l/min. Two graphs for both amounts of supplied nitrogen are shown below. Graphs of relatively low driving speeds were selected due to the most visible characteristic points of the route. The graphs are shown in the Fig. 13 and Fig. 14.

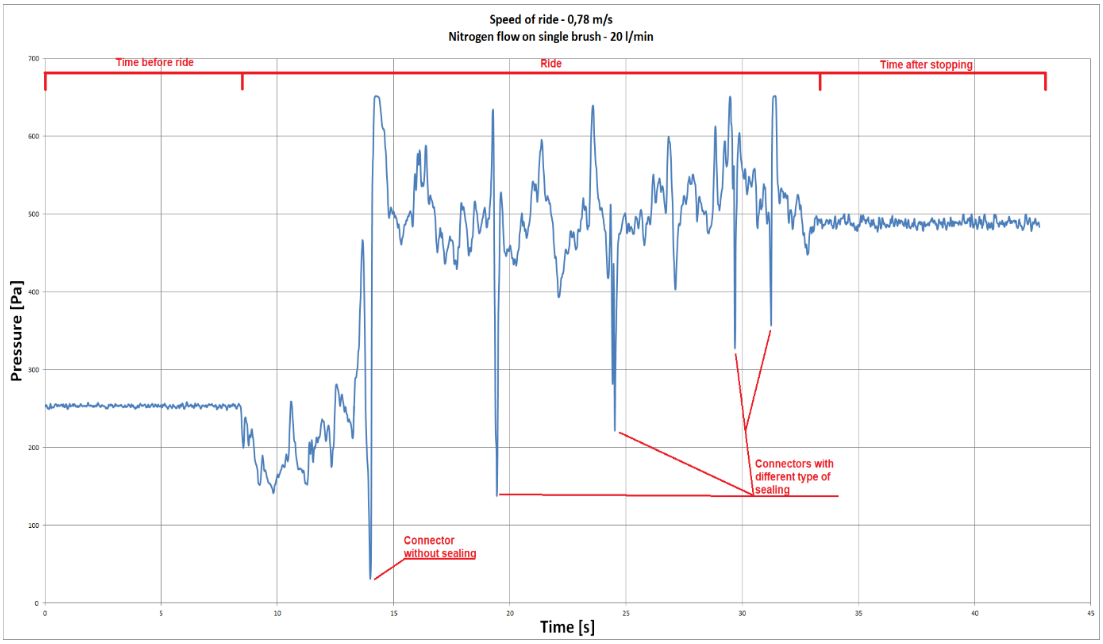

Fig. 13. Graph of pressure of inerting zone – 0,78 m/s & 20 l/min [1]

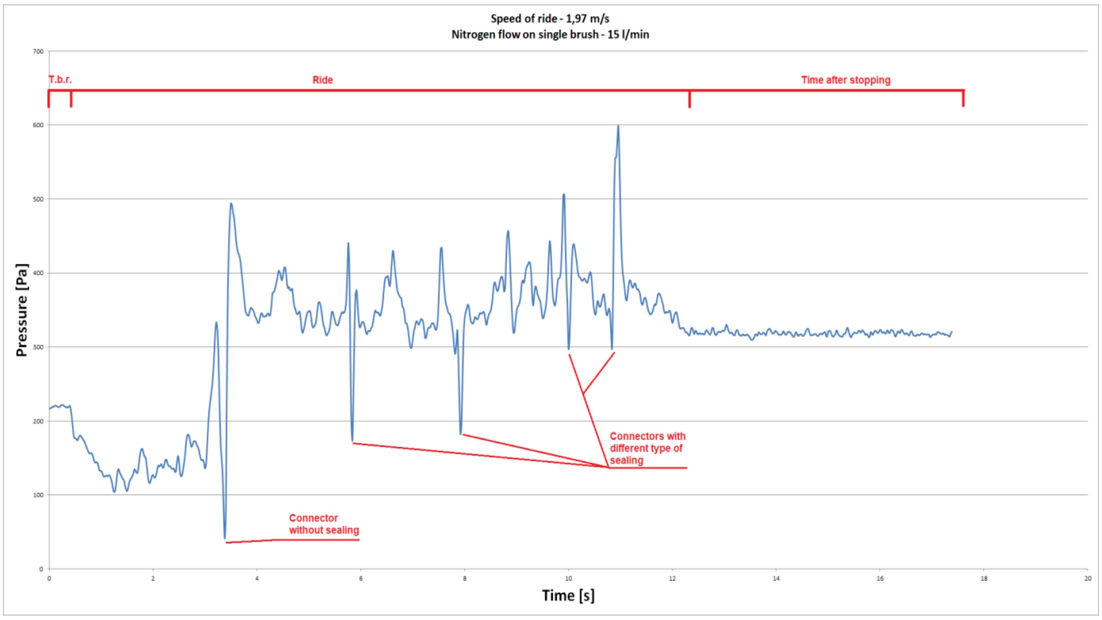

Fig. 14. Graph of pressure of inerting zone – 1,97 m/s & 15 l/min [1]

The graphs show the difference between the pressure at the start and end points of the driving cycle. This is visible in all tests for various speeds. This may be the result of shifts between the busduct lines components. During the driving cycle, the inertization pressure is kept in a relatively stable range. The pressure drops on the busduct connectors are clearly visible. The first - the largest drop is shown by the connector without the use of seals. The next ones present various types of seals, ranging from plastic inserts, through self-adhesive EPDM sponge, ending with the combination of EPDM with polyurethane foam. The tests show that with the use of seals on rail connectors, the inertization pressure remains within satisfactory limits.

Subsequent tests determined the necessity of spark excitation inside the cover for triggering an explosion. The container was filled with a hydrogen-air mixture containing the previously determined 30 vol. % of hydrogen. During the tests, even without inertization, no explosions occurred. This indicated that spark excitation between brushes and busbar lines was necessary. The spark excitation was realised by applying 8 cm long insulating strips to the single busbar lines. The strips cause a temporary loss of electrical contact. When the electrical contact is restored sparks occur as planned.

After preparing the test stand with the mentioned insulating strips, three experiments were conducted without inertization. Every one of the three tests led to an explosion. Another preparatory test was to check if the explosive mixture inside the container stays explosive for the preparation time of the test bench. The preparation time for one test is 30 s. This is the time the testing team needs to be ready for conducting a test.

To check if the explosibility can be ensured after 30 s, 3 tests were conducted with a spark generator. 30 s after the container is filled with the flammable hydrogen-air mixture sparks are generated inside it to trigger an explosion.

During testing the crew of six persons was involved with the following tasks:

1. Operating the dyno test stand to supply 500V voltage and loading to the phase connected to the single bus duct lines,
2. Operating the rope pull device to drive the trolley,
3. Operating the nitrogen supply system,
4. Operating the hydrogen supply,
5. Operating the rotational speed of fans inside the container,
6. Supervising the activities.

Due to the risk of electric shocks and the explosion of the hydrogen mixture, the testing stand was under special supervision. Persons not involved in the tests had no access to the area of the test stand. Every time after passing through the HMC and braking the trolley was retracted manually. During this operation, the power supply of the busbar lines was turned off. The tests were realized for the speed of the CC of 1 m/s, 2 m/s and 4 m/s and for the mixture flow speed of 4 and 8m/s, what makes 3 x 3 = 9 speed variants. The basic assumptions to confirm the efficiency of inertization for each speed variant were as follows:

1. explosion was result in each test when nitrogen for inertization was not used
2. there was not explosion in each test result when nitrogen for inertization was used.

If a positive evaluation for the above is achieved, the inertization system is considered efficient.

The tests were realized with the developed sealing set of the brushes manufactured by KOMAG by using 3D printers of FDM technology. ABS and PLA filaments were used in the manufacturing process. The tests were realized for two variants of CC speed: 1 m/s and 4 m/s. The mixture speed inside the cover was 8 m/s for all experiments. All completed tests confirmed good efficiency of the proposed inertization system as all experiments with inertization resulted in lack of explosion while all experiments without inertization resulted in an explosion.

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4. Conclusions

The tests on the inertization efficiency of the current collector brushes at the KOMAG test stand confirmed the reliability of the inertization system in combination with the brush seals. This means that all tests with use of inertization did not cause an explosion when nitrogen was supplied and all attempts resulted in an explosion when no nitrogen was supplied. This testing procedure gives confidence that the inertization is effective. It should be emphasized here that the explosive mixture was prepared not using the methane but using hydrogen, which strengthens the credibility of the test results and provide the basis for the planned transportation system.

Although the system has not been fully implemented due to the earlier termination of the BUSDUCT project, the use of the inertization system in other solutions for devices operating in potentially explosive atmospheres cannot be ruled out. A nitrogen generator, which is not the subject of this article, with an output of 3 l/s, has also been successfully implemented and can be used in other R&D work.

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