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TECHNOLOGICAL AND SAFETY ASPECTS OF CNG HOME FAST REFUELING UNITS

1. INTRODUCTION

Oil-based products like gasoline account for 95% of all energy used in cars around the world. Mobility has become a necessity in people's everyday life, which led to an addiction to oil. In the search for an answer to the world's addiction to oil, natural gas vehicles (NGVs) are the best available solution:

- Natural gas is less expensive than oil. The cost of natural gas (NG) is 3 to 8 times lower than gasoline.
- NGVs are the cheapest alternative to gasoline cars. Unlike more costly alternatives, NGVs are priced between gasoline and diesel cars.
- NGVs are 'Green' cars. NGVs have 90% lower local emissions of NOx, NO_2 and PM and substantially lower CO_2 emissions.
- Car manufacturers are investing in NGVs. More than 100 models are originally manufactured by most of the OEMs like Mercedes, GM, Fiat, Volkswagen, Volvo and others. NGVs have the same engine with an additional NG storage system and can run either on NG or gasoline. Gasoline cars can be converted to NGV.
- NGVs are safer than gasoline cars. Natural gas (Methane) requires a higher ignition temperature and a precise mixture with air to burn. NG is lighter than air, before and after burning, so it evaporates quickly. NGVs are built with robust fuel systems that are much more durable than the gasoline systems.

2. ANALYSIS OF HRU DESIGN IN VIEW OF ITS TECHNOLOGICAL

The underlying technology is one stage hydraulic compressor (instead of multistage mechanical compressor technology) which provides the possibility to compress low pressure

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gas from residential gas grid to 200 bar for its further usage as a fuel for NGVs. There are two types of the product, Home Refueling Appliance (HRA, refueling time 8–10 hours, Fig. 1), and Home Refueling Station (HRS refueling time 8–10 minutes, Fig. 2).

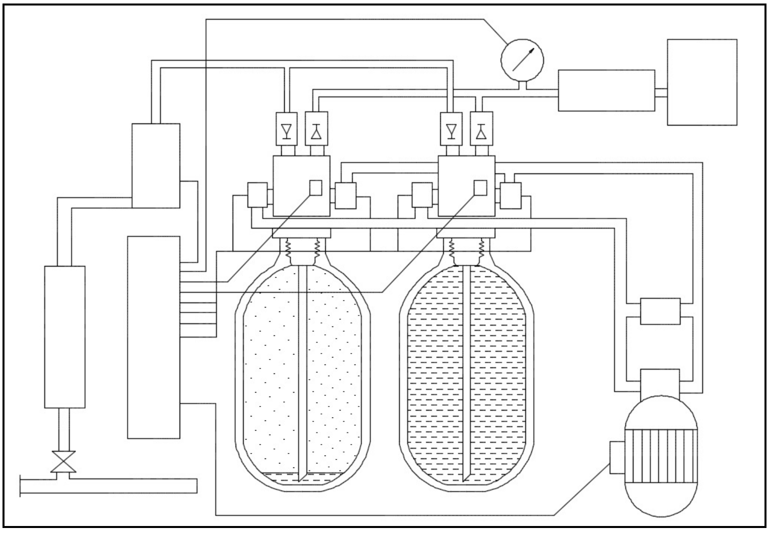

Fig. 1. Technological schematic of HRA [own materials]

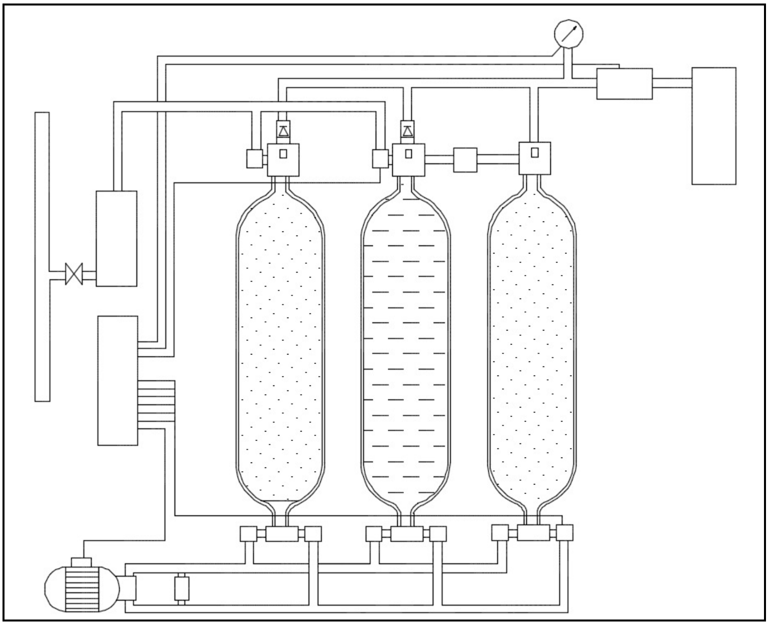

Fig. 2. Technological schematic of HRS [own materials]

The devices consists of the following main components: hydraulic pump, CNG cylinders, pressure sensor, solenoid valve, hydraulic working fluid, pre-compressor, electric motor, refueling hose, filling nozzle, multivalve, high pressure tubes & fittings, digital pressure control, connector, mechanical gas shut-off valve, metal frame, dryer and electronic control unit managing the work of device.

Description of working algorithm: two high pressure cylinders with upper necks connected to low pressure gas source are placed vertically. Initially one of them is filled with liquid and another one – with low pressure gas. During the working process liquid is transferred by means of hydraulic pump from one cylinder to another and back. Working liquid plays a role of pistons inside cylinders. Movement of working liquid inside the cylinders provides simultaneous suction of a portion of low pressure gas into one of the cylinders (where liquid moves down) and forcing out gas of higher pressure from another cylinder (where liquid moves up) to the fuel tank of the vehicle (HRA), or storage tank (HRS). Each cycle of forcing the gas out of the cylinder rises up the pressure of gas in the fuel tank of a vehicle (slow fill appliance with 2 cylinders) or the storage tank (fast fill station with 3–4 cylinders). The process is repeated until the pressure of gas in the fuel tank / storage tank reaches 200 bar [5].

Owing to the fact that the quick refueling installations for natural gas fed vehicles are mounted in garages of residential houses, these appliances should meet the most restrictive safety standards.

Knowing the design of the appliances and understanding their principle one should analyze each of the design elements from the point of view of HRA safety of work.

The most important part of tested Home Refueling Units are cylinders, according to the technological process used by producer. Cylinders are used in very specific working conditions: during the refueling cycle only 10% of the total refueling time cylinders are working under pressure which is close to the Rated Operating Pressure (200 bar). During the full refueling cycle (which is lasting for 10 hours) both of two more intensively operating cylinders alternately fulfill 60 compressing cycles each. Each cycle lasts for 10 minutes. 10% of 60 cycles = 6 cycles (up to approx. 200 bar).

The analysis of Figure 3 reveals that during the whole refueling cycle, which lasts for about 10 hours, the pressure in working cylinders approaches the maximum working value (200 bar) in only 10% of the refueling time, i.e. about 1 hours. The HRS has at least one high-pressure buffer tank, to which the gas is pumped into as first and where it is then stored in high pressure conditions. Natural gas can be stored in this contained for infinitely long when the refueling of the buffer tank has been finished and the moment of refilling tank with gas does not take place for technological or practical reasons (vehicle was not connected to the installation, tank in the vehicle is not empty or other).

Bearing in mind the condition in which natural gas is stored in the buffer tank and the work parameters of operating cylinders we can state that these element are strongly hazardous, and the level of the hazard can be lowered upon a condition that the elements meet all requirements and standards [10].

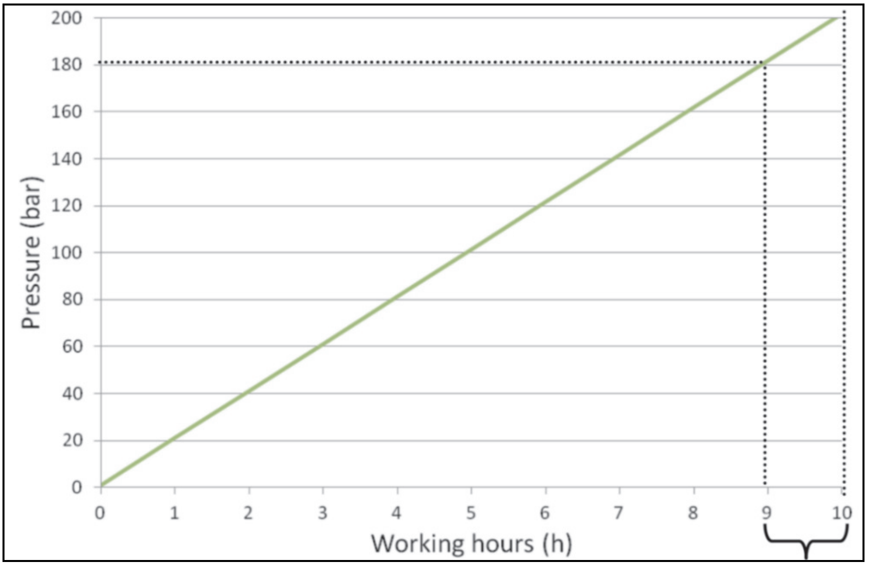

Fig. 3. Working cycle of high-pressure cylinder [own materials]

The second most important element is a hydraulic pomp. Chosen technology provides nonlinear increase of gas and liquid pressure in the operating cylinders of the compressor during the compressing cycles which last for 5 minutes each. During daily refueling cycle device makes 120 compressing cycles. After each compressing cycle pressure in the storage system raises gradually during 10 hours of refueling cycle reaching the pressure of 200 bar at the end of the refueling cycle (Fig. 4). In the framework of the technology hydraulic pump operates in the area of its operating pressure of 100 – 200 bar not longer than 3% of the total 5 minute compressing cycle. Besides that, the pressure in the system raises above 100 bar only after half of the full refueling cycle time (after 5 hours) which lasts totally for 10 hours.

Practically, in the case when gear hydraulic pump works in normal working environment where the risk of contamination of working fluid with abrasive particles persists.

As in our case the liquid is sealed in a closed system without any risk of contamination of the working fluid gear pump. Producers have estimated the lifetime of their gear hydraulic pumps as 10 times longer than the lifetime of the same component working under standard conditions in normal working environment.

Solenoid valves and Multivalve. The only original component of Home Refueling device is multi-valve, which separates the flow of hydraulic working liquid and flow of gas acting as a shut off device. The Multivalve and the solenoid hydraulic valves used in refueling device have only metallic moving closing elements without any rubber seals (which are exposed to wear out). The frequency of operating of these elements in the device is once per 10 minutes. That totals to 60 times per whole 10 hour refueling cycle.

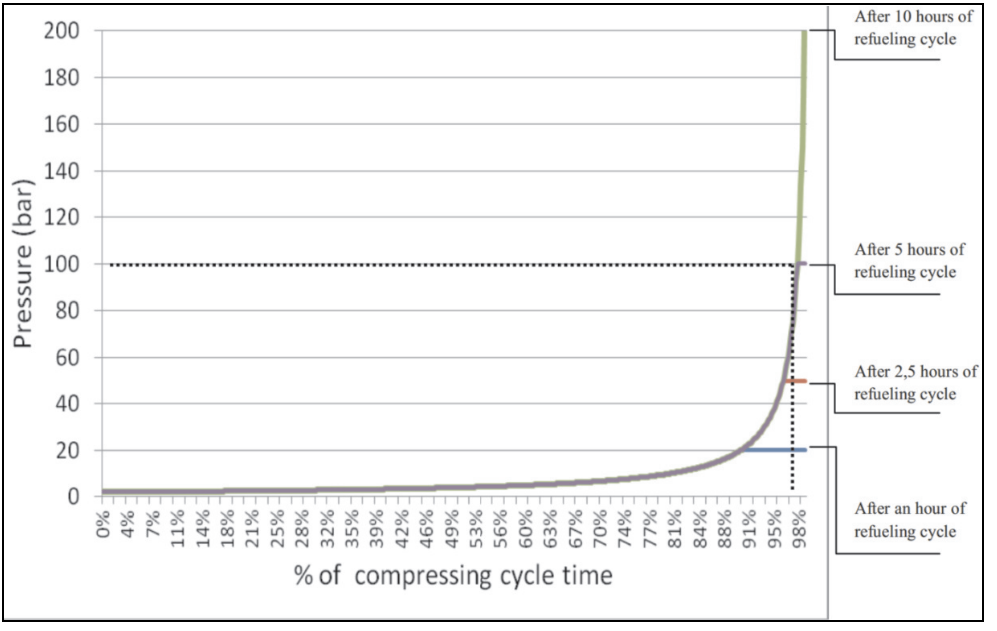

Fig. 4. Nonlinear increase of gas and liquid pressure in the operating cylinders [own materials]

Hydraulic working fluid. In refueling device the synthetic liquid ATF is used as working fluid. Natural gas is inert to ATF, it is slightly soluble in this liquid. During operating cycle of our device the temperature of working fluid is not rising higher than 40–50C and fluid shows continuously stable characteristics. Gas dryer with replaceable cartridge on gas input provides protection from moisture that could be able to change (degrade) the characteristics of ATF. ATF is used in vehicle hydraulic systems for many years working without any degradation of the characteristics even working at high and low temperature regimes [6].

Pre-compressor. In refueling device mechanical mini-compressor in hermetic enclosure is used as a pre-compressor to double the inlet pressure of gas from low pressure gas pipeline that way decreasing the time of refueling cycle by half. It is similar to compressors which are used in ordinary fridges. Such a compressor is designed for 10 bar operating pressure. The task of pre-compressor is to rise the input pressure of hydraulic pump only up to 2 bar.

When assessing the general safety level of analyzed appliances, special attention should be paid to the tightness of all connections. Accounting for the complex design of the system and that HRS should store considerable amounts of natural gas in high pressure conditions, tightness seems to be the most important feature for both HRA and HRS.

The mechanical part of the appliance is scheduled outside, which has advantages and disadvantages. Among advantages we have lower hazard connected with ignition and outburst, because even if the system loses tightness and some amounts of natural gas get to the environment, the probability that an explosive mixture is formed will be definitely lower than in the case of an installation placed in a closed space of a garage [8].

The main disadvantage of this solution lies in the sensibility to atmospheric conditions. A constant exposure to the temperature causes that the temperature of hydraulic fluid and of the entire apparatus will increase, which in the period of summer heat may result in overheating of some HRU elements, change of thermodynamic properties of hydraulic fluid and lowering of strength of seals and refueling hose [9]. Winter temperature equally acts on RHU, lowering the flexibility of seals and other elements of the system, also densifying the hydraulic fluid.

3. EVALUATION OF POTENTIAL HAZARDS RELATING TO HRS/HRA EXPLOITATION AND THE CONSEQUENCES

A process of analyzing HRU design features and use (and misuse) possibilities in order to define a potential incident scenarios and HRU failure modes that might lead to top events with safety implications. To illustrate, a natural gas leak is an example of such a top event, because it might lead to a fire or deflagration if it creates a mixture richer than the lower flammability limit (LFL) that encounters an adequate-energy ignition source [1].

The HRA incident scenarios fell into the six categories discussed in the following subsections.

- **Equipment failure.** Incident scenarios were classified as equipment failures if the initiating event and/or primary contributing event was an HRU component failure. Examples include hose leaks or ruptures, malfunctions of HRU valves or control systems, and failure of the CNG vehicle receptacle reverse-flow check valves. Conceivable failures that might result in air ingress into the HRU so as to create the opportunity for a deflagration inside of the HRU were also considered in this category. All equipment failure scenarios required multiple contributing event failures in order to result in a clearly problematic top event [4].
- **Human errors.** Many incident scenarios had human errors as the primary contributing events. Driving the CNG vehicle away with the refueling nozzle still connected to the receptacle is the classic example, and many of these scenarios involved this error. The HRU must be equipped with breakaway device, and so various other contributing events must occur in conjunction with a connected drive away in order to result in a problematic top event. Debris that affects the ability of the receptacle check valve to seat is another example of human error (e.g., because the user failed to ensure that the coupling was clean) [4].

- **Misuse.** Many incident scenarios classified as misuse were also considered. These included scenarios such as: trying to use the HRA to inflate a tire or swimming pool float, trying to use the HRA to fill a propane tank (e.g., for a gas grill) or to refuel a propane vehicle, or attempting to modify the HRA by adding a buffer tank to provide a fast-fill capability [2].
- **Maliciousness.** Some scenarios had malicious acts as the initiating or primary contributing events. An example is a disgruntled neighbor seeking to shut off the gas or electric supply to the HRA. For all maliciousness scenarios, no credible contributing events were identified that could lead to problematic top events [7].
- **External events.** A few incident scenarios were classified as external events because they involved things like the house catching on fire, an earthquake, or a vehicle striking a wall-mounted HRA. "Disaster" external events were not analyzed in detail because it was judged that the HRA response would be similar to the response of other residential gas appliances [2].

Probable consequences of failure [3]:

- Deflagration.
- Structure Fire.
- Asphyxiation Potential.
- Gas Burns at Vent.
- No Safety Consequences.

4. CONCLUSION

The safety evaluation of Home Refueling Units performed in this article concludes that the the Home Fast Refueling Units really can be a key to solving that problem of refueling infrastructure for Natural Gas Vehicles especially if appliance has a process control approach that incorporates a number of safety features designed to prevent accidental gas releases such that the probability of a gas release is relatively low. Moreover, process control system design and appliance installation specifications that further reduce the predicted frequency of gas releases and the consequences (e.g. fire or deflagration) of a gas release.

The most frequent misuse failure events were the rupture of a LPG bottle or toy being inflated with an HRA with cooling air discharging to the outside and a gas release from a buffer tank added to the HRA with cooling air discharging to the outside. The most serious consequences from the HRA failures evaluated were structure fires or deflagrations. A structure fire might occur if the gas release encounters an ignition source, ignites to form a flame, and in turn ignites combustible material near the gas release. A deflagration would occur if the release resulted in a buildup of methane concentrations to its lower flammability limit (LFL) over a substantial volume, and this volume of high concentration encountered an ignition source.

This safety evaluation concluded that the HRA has a process control system that incorporates a number of safety features designed to prevent accidental gas releases. The vehicle refueling appliance and CNG vehicle user survey noted that gas leaks have been more commonly experienced with aftermarket vehicle fuel system conversions. Aftermarket conversions often incorporate a single fuel tank reverse flow check valve. The analyses suggest that it would be best to place the gas sensor (alarms if gas is detected, and included in the HRA design) along the garage ceiling above where the vehicle fuel tank fill receptacle would be during a typical refueling. However, mounting the detector inside the appliance in the path of the cooling air flow likely provides comparable protection.

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