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Pressures and flow rates occurring in road-tanker/petrol-station systems during the delivery of petrol [1]

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Abstract

To promote the establishment of useful standards in the fields of explosion protection, operator protection, and environmental protection, when underground storage tanks at petrol stations are filled with petrol from road tankers, fundamental investigations were carried out at the Physikalisch–Technische Bundesanstalt in Braunschweig, Germany. Within the scope of a research project, the pressure and temperature conditions in the road tanker and in the storage tanks of petrol-station systems, together with the flow rates in product lines and gas-recovery pipes, were determined during the filling of the underground storage tanks. The parameters influencing the potential release of fuel vapours into the atmosphere were determined under conditions as close as possible to those found in practice. © 1998 Published by Elsevier Science B.V. All rights reserved.

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1. Fundamentals

The storage and transport of flammable liquids and gases involve hazards which, depending on the operational conditions, have to be controlled by suitable safety precautions in order to protect man, the plant, and the environment. As far as the construction and operation of petrol stations are concerned, the aspects of operator protection, explosion protection, and water protection have been regulated in Germany for many years now by the 'Verordnung über Anlagen zur Lagerung, Abfüllung und

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Beförderung brennbarer Flüssigkeiten zu Lande' (VbF) [1], in conjunction with the 'Technischen Regeln für brennbare Flüssigkeiten' in particular TRbF 40 [2]: 'Tankstellen' which has superseded the former TRbF 112 [3]: 'Tankstellen'. These regulations are supplemented by the 'Technische Anleitung zur Reinhaltung der Luft' [4], which require that measures are taken to prevent emissions into the atmosphere. According to these instructions, no hydrocarbons, or only small amounts of them, which, for technical reasons, cannot be avoided, may be released into the atmosphere through vent openings. In refilling processes, displaced vapour/air mixtures must either be returned to the delivery tanker passed or supplied to a vapour recovery unit.

For petrol stations in Germany, these requirements have been laid down in the 20th Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes (Verordnung zur Begrenzung der Kohlenwasserstoffemissionen beim Umfüllen und Lagern von Ottokraftstoffen-20. BlmSchV) [5] and the 21st Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes (Verordnung zur Begrenzung der Kohlenwasserstoffemissionen bei der Betankung von Kraftfahrzeugen-21. BlmSchV) [6]. The 20th BlmSchV prescribes how facilities, from which fuel vapours are displaced during filling, must be installed and operated, according to the state of the art, so that the displaced fuel vapours are collected by a gas recovery system and transferred to the delivering facility. This means for a petrol station that the storage tanks may be filled with petrol from road tankers only if the vapour/air mixtures displaced from the storage tanks are returned to the road-tanker compartments. In addition, the 20th BlmSchV requires among other things that the vapour recovery system and the connected devices do not release fuel vapours into the atmosphere during vapour recovery, except for safety reasons. This requirement has been taken into account in TRbF 40, section 3.3.2, No. 7 [2], according to which two technical solutions are permitted: The vent line must either be provided with a pressure/vacuum (P/V) valve or with a throttle, an opening of 10-mm inner width or a pipe section with a comparable flow resistance being sufficient to ensure the throttling effect.

Both systems have connections between the storage tanks and the atmosphere, which are temporarily or permanently open and allow breathing of the tank when the pressure inside the storage tank increases or decreases. Both systems have a comparatively high resistance to flow and largely prevent release to the atmosphere. It is thus ensured that the vapour/air mixtures displaced from the storage tanks are returned bake to the compartments of the road tankers.

As the throttle with an inner width of 10 mm is an open path to the atmosphere, doubts arose in the past whether this system ensures adequate displacement of the gas into the road tanker. On the other hand, a P/V valve may cause a pressure increase inside the road-tanker system, which results in fuel vapours being released directly into the area where the road-tanker driver works when he is filling the storage tanks.

The investigations were aimed at determining the pressure and temperature conditions and the flow rates during the delivery of petrol to petrol stations, paying particular attention to aspects of operator protection and environmental protection. Influences specific to the petrol station, such as vapour recovery during the refuelling of private cars, and weather-induced influences, such as temperature changes and changes of air pressure were not investigated.

2. Experimental set-up and performance of the test

Fig. 1 shows as an example the experimental set-up in a petrol station. Due to the specific conditions in the petrol stations and road tankers, different types of experimental set-ups were used. The measurements covered the pressures and temperatures in the vapour spaces of the road tanker and storage-tank compartments, the temperatures of the fuel and the filling levels in the storage-tank compartments, the flow rates in the product lines and vapour recovery pipes and the volume escaping into the atmosphere via the vent pipe. The conditions prevailing at the petrol stations were to remain unaffected by the measuring systems used to determine the flow rates and, therefore, had to meet the following requirements:

- pressure loss as low as possible
- flow paths as short as possible
- simple and trouble-free use in practice
- resistant to fuels.

To measure the product flow rate, a modified Prandtl-tube was developed and the flow rate calculated from the static pressure equation. The flow rate in the vapour recovery pipes was determined with the aid of vane-anemometers installed in pipe sections. Both systems were calibrated at the Physikalisch–Technische Bundesanstalt against standard measuring devices. To determine the flow rate of the gas escaping into the atmosphere, a bypass was installed on the vent mast and the flow rate determined with the aid of a gas meter. The pressure loss of the gas meter determined in preliminary

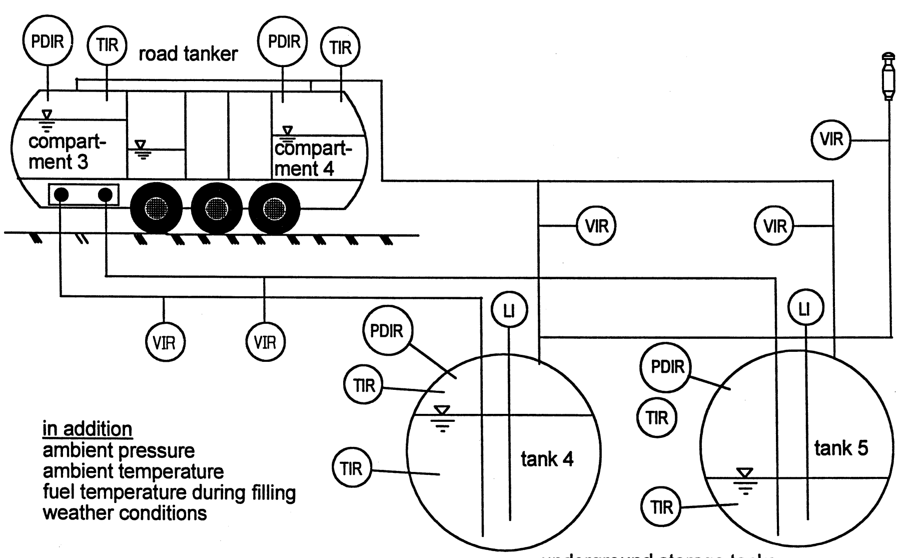

Fig. 1. Example of an experimental set-up in a petrol station (petrol station 3, test 3). PDIR: pressure measurement sensor; TIR: temperature measurement sensor; VIR: flow meter; LI: filling level measurement sensor.

Table 1
Characteristics of the equipment installed at the petrol stations (PS 1–PS 11) investigated

	PS 1	PS 2	PS 3	PS 4	PS 5	PS 6	PS 7	PS 8	PS 9	PS 10	PS 11
Central filling	X	X			X	X	X	X	X	X	X
Direct filling			X	X							
Pipe/hose diameter (in./in.)	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3	3/3
Connections for vapour recovery/hose diameter	3/3	(2×2) /2	2/2 each	2/2 each	(2×2) /2	(2×2) /2	(2×2) /2	4/3	4/3	(2×2) /2	(2×2) /2
Electronic gauge system	X				X	X	X				
Dipstick		X	X	X				X	X	X	X
Vent pipe with type S P/V valve						X					
Vent pipe with type G P/V valve	X	X	X								
Vent pipe with 10-mm throttle					X			X	X	X	X
10-mm Throttles directly installed in the tank compartments				X			X				
Detonation flame arresters in the product lines and vapour recovery pipes									X		
Distance: vent pipe–fill cap (m)	1	20	25	15	1	40	20	3	3	20	2
Vapour collecting line underground	X	X		X	X	X				X	X
Individual pipes up to vent mast			X				X	X	X		
Vapour recovery (stage II)	X	X	X		X	X	X	X	X	X	

tests was compared with the pressure loss of a 10-mm throttle. Both pressure-loss curves show relatively good agreement so that the gas meter in the bypass took over the function of the 10-mm throttle during the measurements.

The investigations were carried out in 11 petrol stations, 4 of them equipped with a P/V valve, and 7 with a 10-mm throttle (cf. Table 1). A total of six different road tankers were used. Table 2 shows the devices with which the road tankers were equipped. The measurements covered the pressures in the road-tanker compartments and in the storage-tank system before the venting system was opened for the first time, the development of pressure, temperature and flow rate during the discharge process and the pressures and amounts released after the end of the discharge process.

3. Results of measurement

3.1. System conditions prior to start of the discharge process

Before the discharge process was started, none of the petrol stations investigated and equipped with a 10-mm throttle in the venting pipe showed an excess pressure in the

Table 2
Characteristics of the devices installed in the road tankers (RT 1–RT 6) used for the measurements

	RT 1	RT 2	RT 3	RT 4	RT 5	RT 6
Number of road-tanker compartments	5	5	8	6	6	7
DN 100 (4 in.) connection for product	X					
DN 80 (3 in.) connection for product		X	X	X	X	X
Direct delivery device	X		X		X	X
Delivery via volume meter		X		X		
Two petrol products in parallel possible	X		X		X	X
Only one petrol product possible		X		X		
Interconnection of various road tanker compartments to one product hose possible		X		X		
DN 80 (3 in.) connection for vapour recovery	X					
DN 50 (2 in.) connection for vapour recovery		X	X	X	X	X
Hose drum, only one for petrol delivering possible		X		X		
Hose drum, two for petrol delivering possible			X		X	
Short direct vapour recovery hoses (m)	2					3
Number of gas collection lines on the road tanker	1	2	2	2	2	3

storage-tank system so that no release occurred when the storage-tank system was opened for the first time. Only at one petrol station, which was equipped with a P/V valve in the vent pipe, was an excess pressure (750 Pa) measured. This resulted in about 450 l of a vapour/air mixture being released when the storage-tank system was opened for the first time.

3.2. Development of flow rate and pressure during discharge

Fig. 2 shows the pressure development in a petrol station equipped with a P/V valve in the venting pipe. The petrol was conveyed from road-tanker compartment 4 into storage tank 5. Immediately before the discharge process was started, the pressure in the storage-tank system had been equalised with ambient pressure by opening the connection pieces for gas displacement and product delivery. Excess pressures possibly existing in the vapour space of the road-tanker compartments escaped into the storage-tank system after the road-tanker valves had been opened; as the volume of the vapour space in the storage tanks was clearly larger, this did not lead to a significant increase of the pressure in the storage-tank system.

Fig. 2 shows that the pressure in the storage tank rises rapidly after the discharge process has been started, stabilizes after a certain period of time (less than 2 min) and then drops slightly while the discharge process is continued. In contrast to this, negative pressure is produced in the road-tanker compartment, where the pressure change takes place even faster than in the storage-tank system. It is significant that the amount of the pressure change in the road-tanker compartment is clearly greater than in the storage-tank system. This is due to the fact that the vapour space in the road-tanker compartment is

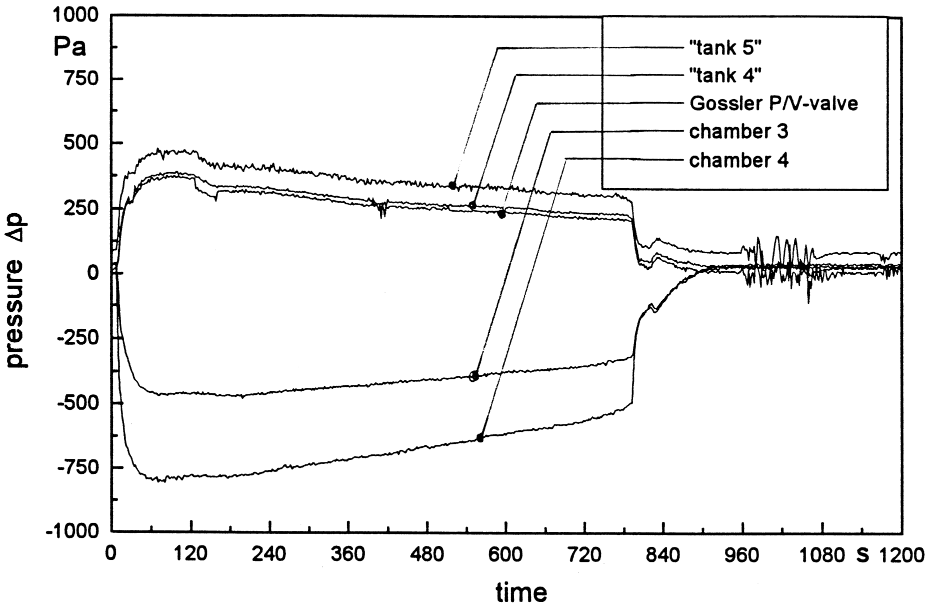

Fig. 2. Pressure development: road-tanker compartment 4 filled into tank 5 (petrol station 3, test 3). $V = 7000$ l, venting system with type Gossler P/V valve.

small at the beginning of the discharge process, whereas the vapour space in the storage-tank system is comparatively large. The greatest pressure difference develops between the road-tanker compartment being emptied (compartment 4) and the storage tank being filled (tank 5). The pressure changes are less in road-tanker compartment 3 and storage tank 4, which are not directly involved in the filling process. An excess pressure of approximately 400 Pa was measured at the vent pipe. As in all petrol stations equipped with P/V valves, this pressure was lower than the opening pressure of the valves used. The valves thus remained closed during the discharge process and no release into the atmosphere through the venting pipe took place.

Fig. 3 shows the respective flow rates for the petrol and for the displaced gas as a function of elapsed time. The maximum product flow rate is quickly reached a few seconds after the road-tanker valves have been opened. As the difference between the liquid levels in the road-tanker compartment and the storage tank is the driving force for the product flow, and as this force decreases during the discharge process because the liquid level in the road tanker compartment drops, the flow rate decreases during the discharge process. It is significant that the gas flow directly follows the liquid flow—except for the start-up phase at the beginning of the discharge process—and assumes identical values. Congruence of the two flow rate curves confirms the above statement that no release via the venting pipe was observed at the petrol stations equipped with P/V valves during the delivery.

At petrol stations equipped with 10-mm throttles in the venting system, the pressure curves determined for the storage tanks and the road-tanker compartments broadly agree

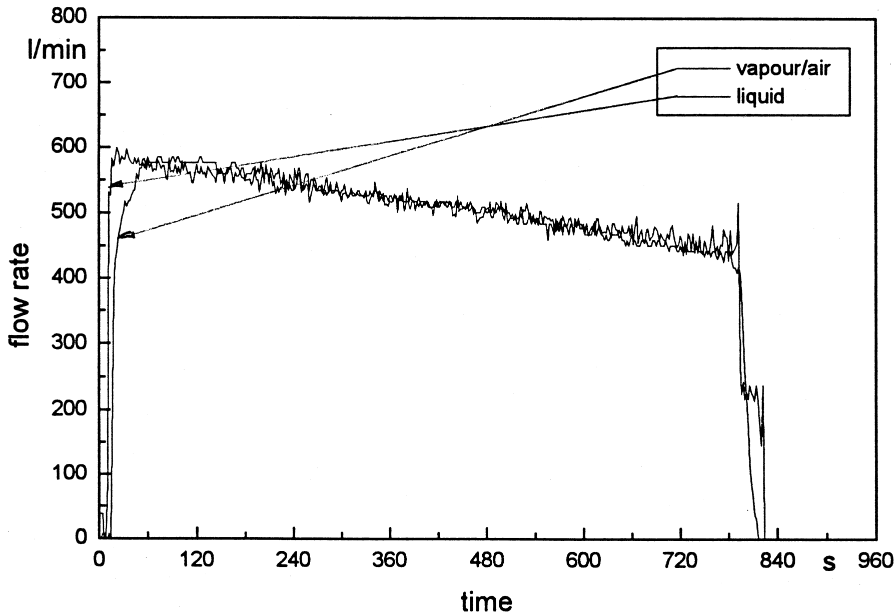

Fig. 3. Flow rate as a function of elapsed time: road-tanker compartment 4, tank 5 (petrol station 3, test 3). $V = 7000$ l, venting system with type Gossler P/V valve.

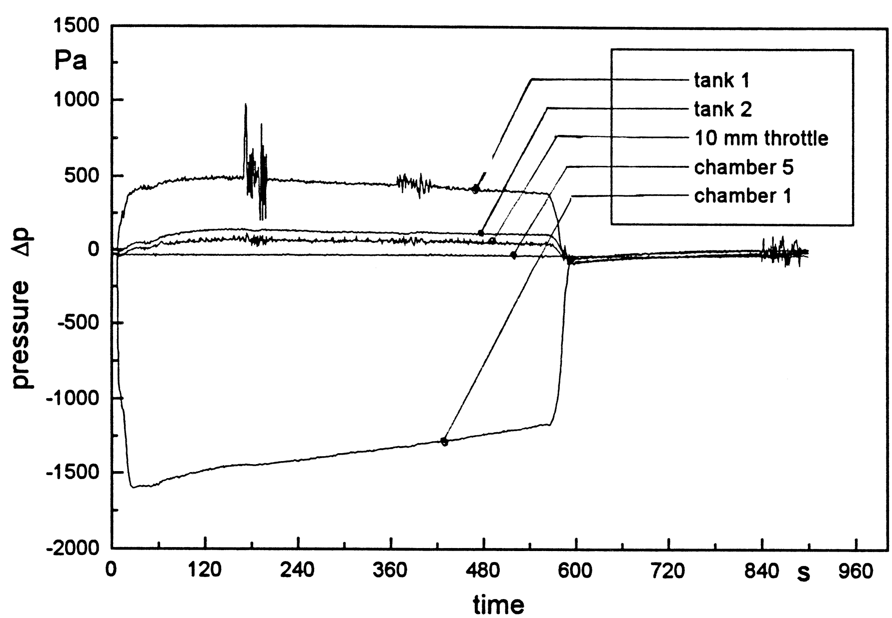

Fig. 4. Pressure development: road-tanker compartment 1, tank 1 (petrol station 8, test 2). $V = 7000$ l, venting system with 10-mm throttle.

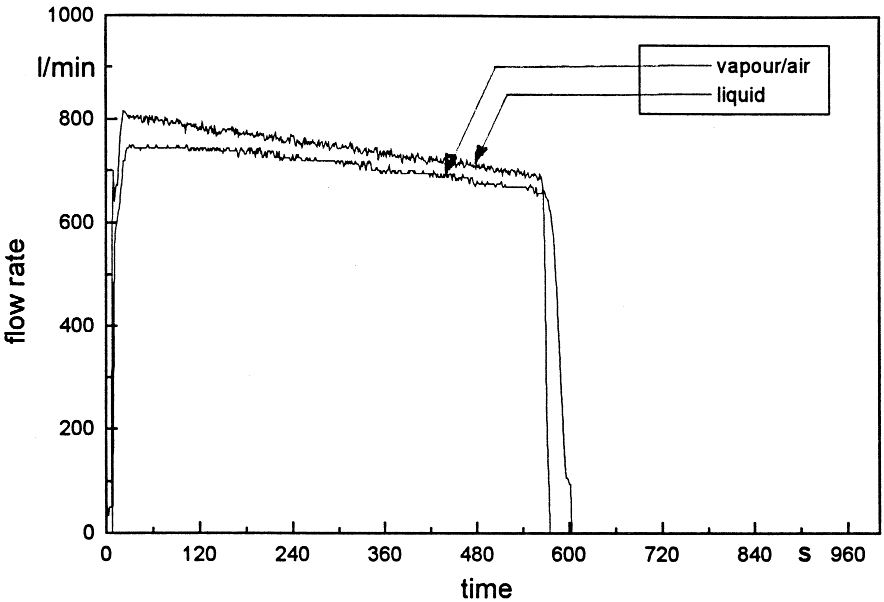

Fig. 5. Flow rate as a function of elapsed time: road-tanker compartment 1, tank 1 (petrol station 8, test 2). $V = 7000$ l, venting system with 10-mm throttle.

with those of the petrol stations equipped with P/V valves (Fig. 4). Likewise, pressures above atmospheric pressure were measured at the venting pipe; their value of 200 Pa maximum was, however, lower than that in petrol stations equipped with P/V valves. As the 10-mm throttle is permanently open to the atmosphere, a release of vapour/air mixture is to be expected when the pressure at the venting pipe is higher than atmospheric pressure. At petrol stations equipped with a 10-mm throttle, the volume of the vapour/air mixture released into the atmosphere via the vent pipe was usually between 0% and 5% of the liquid volume discharged. As 1 m^3 of a petrol vapour/air mixture contains about 1 l of liquid petrol, the quantities released amount to between 0% and 0.005% of the liquid phase, or the loss was 0.05 l of petrol at most for a discharged-liquid volume of 1000 l.

The amounts released via the venting systems are reflected in the flow rate curves, where it can be seen that the rate of the gas flowing from the storage-tank system to the road tanker is lower than the product flow rate (Fig. 5). The difference between both curves corresponds to the volume escaping via the venting system into the atmosphere. The shape of the flow rate curves was not found to differ from that of the flow rate curves measured at the petrol stations equipped with P/V valves.

3.3. System conditions after termination of the discharge process

At the end of the discharge process, a rapid pressure compensation between the road-tanker compartments and the storage-tank system took place at all petrol stations investigated and atmospheric pressure was reached (Figs. 2 and 4). In no case was excess pressure in relation to the atmospheric pressure detected in the system, which would cause a release when the hose connection was opened. In the petrol stations equipped with P/V valves, the gas flow directly followed the liquid flow and dropped to zero immediately after the discharge process had been terminated (Fig. 3). In the petrol station with a 10-mm throttle, however, a follow-up flow of about 20-s duration could be observed.

4. Discussion

The petrol stations investigated can be divided into two groups: (1) petrol stations which are equipped with a 10-mm throttle in the venting system and, thus, have an open connection between the storage tanks and the atmosphere, and (2) petrol stations which are equipped with P/V valves in the venting system and, thus, open only if the opening set pressure has been reached.

The discharge processes were carried out only under the effect of gravity and without the aid of pumps. The equipment currently available (hoses and pipelines, valves, safety and measuring systems) was used for product discharge and vapour recovery in compliance with its intended use.

During discharge, a maximum liquid flow rate of between 450 l/min and 1000 l/min was measured. The flow rate is affected by the following factors.

(1) The pressure difference due to the hydraulic head (≤ 6 m corresponding to approx. 50 000 Pa) between the liquid levels in the road-tanker compartment being emptied and the storage tank of the petrol station being filled.

(2) The flow resistance in the product-carrying pipes of the road tanker (diameter of the pipelines and hoses, volume meter, straight-way valve, dry-break coupler) and of the storage-tank system (lengths and diameters of the pipelines, detonation flame arresters).

In all set-ups investigated, the pressure differences (≤ 4500 Pa) occur in the vapour spaces of the containers involved (road-tanker compartment, storage tank) are small compared with the pressure difference due to the geodetic difference between the liquid levels, and their influence on the liquid flow rate is, therefore, negligible. From this, it follows that the product discharge is not influenced by a properly working gas displacement system.

A few seconds after the valves have been opened, the liquid flow rate reaches a maximum value which slowly decreases (down to approximately 70% of the initial value). This reflects the difference between the liquid levels of the road-tanker compartment and the storage tank which decreases in the course of the discharge process.

The flow rate of the displaced gas determines the pressure difference building up between the gas spaces in the storage tanks and in the road-tanker compartments. During unloading, there can be significant generation of additional vapour caused by warming and evaporation of the existing product by the incoming petrol and evaporation into the air trapped in the fill pipe after being forced through existing product. In the present investigations the temperatures of the products in the road tanker and in the storage tank differed only by 5 K (maximum). There the warming of incoming product had no significant effect. The volume of air in the fill pipe is about 30 l—assuming saturation at 10°C (maximum), this would cause an additional vapour volume of about 10 l, which is also negligible compared to the total gas flow.

Thus, in a good approximation, the gas flow rate in the system is given by the liquid flow rate, as the gas volume displaced from the storage tank being filled is nearly identical with the liquid volume filled in. The pressure difference between the gas spaces in the road-tanker compartment being emptied and the storage tank being filled develops as a result of the flow resistance in the gas displacement system at this given flow rate. Higher flow resistance in the gas displacement pipe, with the other conditions unchanged, do not influence the flow rates; they cause, however, higher pressure differences between the gas spaces involved.

Before the discharge process was started, no excess pressures could be measured in the storage-tank system of those petrol stations where the vent mast was equipped with a 10-mm throttle. During operation of the petrol station, the 10-mm throttle ensures pressure compensation between the vapour spaces of the storage tanks and the environment at any time. Only one of the petrol stations equipped with P/V valves showed excess pressure (750 Pa) built up in the storage-tank system before the discharge process was started.

In the case of the quasi steady-state process of discharging, for a defined moment of observation, the local pressure drop along the path of the displaced gas is an important quantity. This pressure distribution along the path of the displaced gas decides which sections of the path are at high pressure and which are at low pressure compared with the atmosphere. Emissions during gas displacement are possible only if the vent to atmosphere is positioned in the high pressure section of the gas displacement path.

In almost all cases investigated, the vent was found to be positioned in the highest pressure section of the gas displacement path. The reason for this is that the greatest flow resistance in the gas displacement path is found at the road-tanker fittings (venting valves, gas displacement hoses, flame arresters) which prevents the low relative pressure in the road-tanker compartments from equalising throughout the venting system.

The excess pressures built up, during discharge, in the venting systems of petrol stations equipped with P/V valves amounted to 500 Pa at most. The opening pressures of 1350 Pa and 2700 Pa of the P/V valves used in these systems are clearly higher so that no release is to be expected during discharge. On the contrary, a release may take place from venting systems equipped with 10-mm throttles. In the cases investigated the excess pressures were found to be 200 Pa at most. The release of vapour measured at the petrol stations equipped with 10-mm throttles usually amounted to less than 5% of the displaced gas volume.

Before the discharge process was started, no release could be observed at the petrol stations equipped with 10-mm throttles in the venting pipes. The same applies to the majority of the petrol stations equipped with P/V valves, as the pressure in the respective storage-tank systems did not exceed the ambient pressure. In the case of the petrol station where the storage-tank system was at excess pressure, a release of 450 l was measured before the discharge process was started.

After the discharge processes were completed and before the system was reopened again (opening of the product lines and gas displacement hoses), an equalisation to atmospheric pressure had already taken place in all road-tanker compartments and storage tanks involved (no measurable differences to the ambient pressure). No releases were therefore measured when the systems were opened after the discharge process.

5. Conclusions

The measurements have shown that vapour/air mixtures may be released when petrol is delivered to petrol stations. The amount and point of release depend on the following specific plant features.

(1) In petrol stations equipped with P/V valves in the venting systems, in general, no release takes place during the discharge process. It cannot, however, be excluded that an excess pressure possibly prevailing at the connecting piece for the gas displacement pipe will be discharged to the atmosphere when the storage-tank system is opened in order to connect the hoses.

(2) In petrol stations where the venting system is equipped with a 10-mm throttle, there is no excess pressure in the storage-tank system which could be discharged to the atmosphere when the storage-tank system is opened. During the discharge process, however, releases usually take place. The extent depends on the flow resistances in the gas displacement system and the resulting excess pressure in the venting system.

In all the petrol stations, the vent to atmosphere was positioned in the high pressure section of the gas displacement path. The relatively high negative differences from atmospheric pressure in the road-tanker compartments are maintained because the road-tanker fittings offer the greatest restriction to the flow of vapours in the venting system. Positioning the vent in the low pressure section of the gas displacement path, which would clearly lead to lower releases, has not been found in practice.

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