Brimming bubbles?
On an Innovative Piston Design of Dosing Pumps

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Abstract

For delivery, dosing and pressure control of fluids in mobile and stationary applications electromagnetically operated piston pumps are an established solution. The volume per stroke is exactly defined by the geometry. Nevertheless cavitation, more likely with the new fuel blends containing a high proportion of ethanol /1/, deteriorates the dosing precision of the liquid portion.

One important criterion of precise metering is the transport of the liquids through the reciprocating piston pump without transferring bubbles. Especially, pumping in the range of vapour pressure of gasoline fuels implies challenges for precision. The objective of this work is revealing potential sources of reduced cavitation by optimising the design. For doing so, optical investigations have been applied. In addition to this, cavitation can be diminished controlling the piston's travel externally.

The second important item covers pumping of degenerated fluids even without negative effects on the pump's performance. Up to now, wide, inefficient gaps or high force surplus are necessary. A new helix-design /2/ has been investigated and built up in order to reduce the described effort. The effects coming with the helix allow a permanent rinsing of the stressed surfaces, leading to lubrication and lower temperature loads. The results are shown in simulation, fundamental tests and is validated in practical pump operation.

KEYWORDS: metering, dosing pump, fuel, cavitation, automotive

1. Dosing pumps in automotive applications

Automotive dosing pumps have been available on the market for nearly 40 years now. Initially used for fuel fired heaters in mobile systems - trucks, passenger cars, e. g. -, this type of a reasonable compact dosing unit nowadays is applied in many fields of applications. Based on the experience of delivering fuels of any kind, the dosing pump was further developed to deliver and dispense more or less any kind of liquid media /3/.

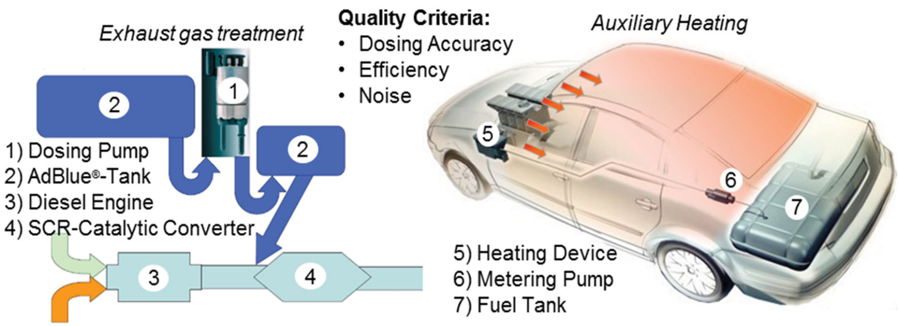

Figure 1: Auxiliary systems with metering pumps in automotive applications

Figure 1 shows the two most common fields of application as there are exhaust treatment systems, like SCR systems reducing NOx, and the regeneration of diesel soot filters and several auxiliary heating systems.

Dosing units have to deliver the exact amount of liquid throughout their entire life in service. Hence, all pump designs were tested in long-term durability tests with different kinds of fuel, even worst-case bio-fuels containing aggressive substances, salt water or ethanol-blends. The global usage of metering units requires a robust design and robust material surfaces as they are in direct contact to the fluids. Therefore, these pumps have to be able to deliver all kind of fuels that are commercially purchasable as they have been tested with worse. Investigations are also performed to fulfil special demands for biomass fuels that potentially may degenerate. As they are designed as electromagnetically actuated piston pumps, the total flow rate is determined by the frequency of the piston´s movement only, which is the basis for easy control to achieve the precise metering ability. Based on relevant test results, the interaction of dosing unit and the individual future fuels is taken into account /3/.

The rising percentage of bio-fuels cause previously unknown interactions with the materials of construction. Rubbers, metals and surfaces, which had been sufficient in the past, have to be replaced by more resistive materials with lower interactions to the fuels, a surrogate for zinc coatings may be stainless steel. Although refined chemical additives and more comprehensive tests on the fuel side should improve fuel quality, more resistant components are necessary. Especially higher temperatures in fuel systems and more and more legal requirements make robust components of exhaust systems and even auxiliary systems essential.

Beside the chemical interactions between fluid and component, especially the two phase fluid flow is an important issue for fuel pumps. Bubbles of fluid vapour and air occur if the pressure is falling below the tank pressure. So it is indispensable to build up pumps which are able to handle and meter high- and low-volatility fluids.

1.1. Generation of gas bubbles

Gas bubbles are generated in areas where pressure drops or temperature rises. In **figure 2** the appearance of air bubbles is illustrated, when the pressure falls below the saturation pressure or the vapour pressure of the specific fluid.

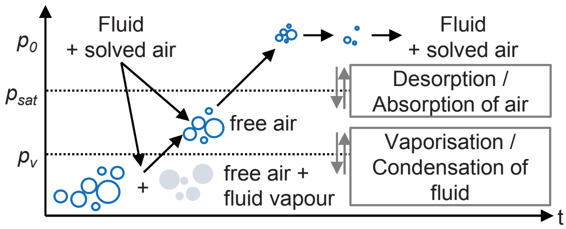

Figure 2: Generation of gas bubbles in fluids

Whereas the vapour pressure p_v depends on fluid and temperature, see **figure 3**, the saturation pressure p_{sat} depends on the history of the fluid – i. e. atmosphere, pressure

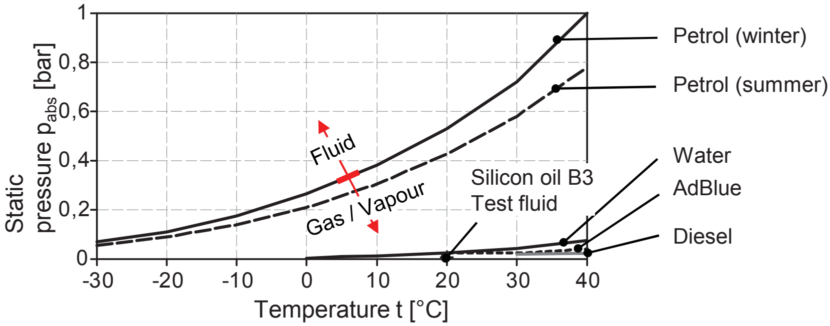

Figure 3: Vapour pressures of fluids at different temperatures

and temperature in the tank for the past time. For example, the saturation volume of air at 1 bar and 20 °C is in diesel: 11 Vol.-% /4/, in gasoline: 21 Vol.-% /4/ and in water: 1.87 Vol.-% /5/. Thus, gasoline is the most critical fluid in vapor pressure and air saturation and there is a significant difference in winter and summer quality. The quantity of gas is a sum of vaporized fuel and air.

1.2. Pump design – one valve pump

There are mainly two different pump designs. The most popular is the “one valve one slot”-principle, see **figure 4**. The fluid flows into the pump where it has to stream around the armature to enter the pump chamber by passing the outer surface of the pump's cylinder, i. e. the bearing of the piston and the metering bore. After that, the fluid fills the exactly defined delivery volume t_1. When the piston overruns the metering bore, the fluid

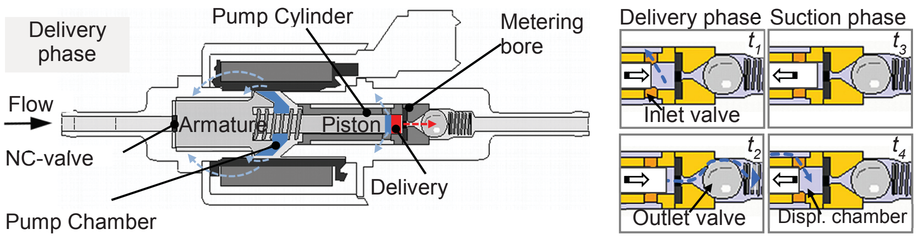

Figure 4: One valve pump

is pushed through the outlet valve t_2. The armature is actuated by energizing the coil by applying a short voltage pulse. The piston travels actuated with 10 to 20 Hz, e. g. during the suction phase t_3, the pressure in the delivery volume decreases to the level of vacuum pressure and bubbles release. The low pressure in the volume remains until new fluid enters the metering bores t_4.

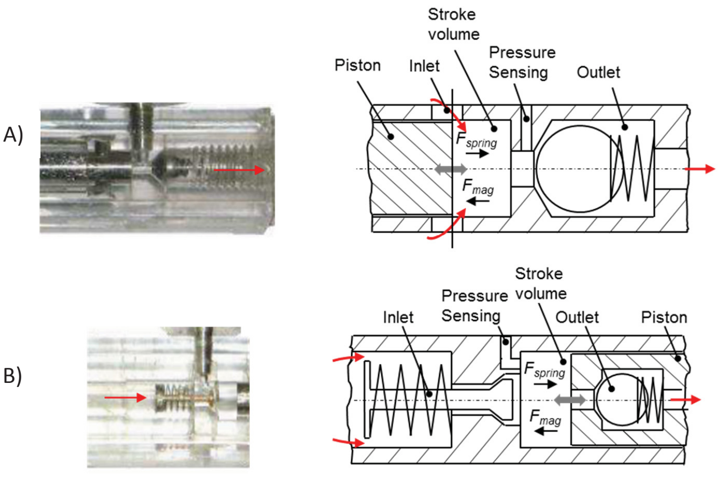

Figure 5: Transparent model of the one valve pump (A) and the two valve pump (B)

To make the effect of bubble release visible, the pump chamber for demonstration with metering bore and outlet valve is built in transparent plastic. The piston is actuated by a separate pump solenoid, see **figure 5**. A pressure sensor measures the pressure inside the displacement volume.

To examine the operation in detail the test bench, see **figure 6**, was build up. A high power LED emits short, triggered pulses of light through a PMMA Model of the displacement chamber and the light is captured by a light-sensitive high speed camera. The one valve design with metering bore shows a lot of air bubbles inside of the delivery chamber at the end of the suction phase.

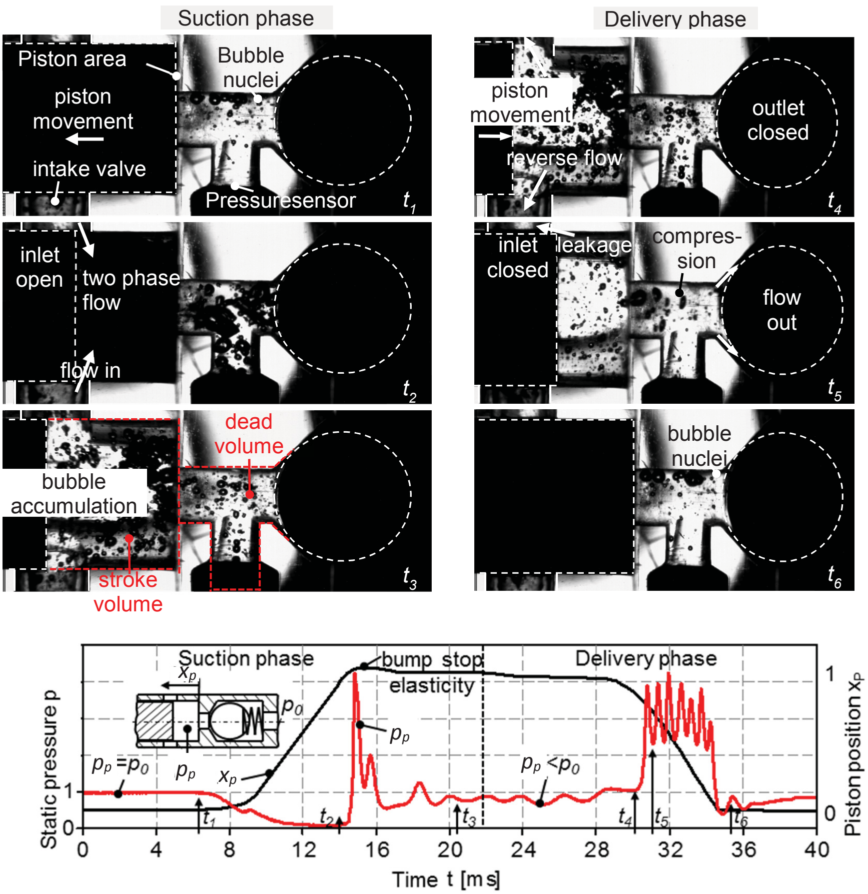

Figure 6: Work Cycle of the one valve pump

In figure 6, the corresponding position and pressure cycle are shown. Between the eleventh and fifteenth micro second, the pressure p_p reaches nearly vacuum ($p_p < p_v$, see figure 2) which explains the high volume of gas inside the delivery volume. This originates not only from free air or air bubbles escaping from the fluid that contained inherent dissolved air, but also from evaporating fuel, see figure 2.

1.3. Pump design – two valve pump

Also the two valve piston pump was investigated with a transparent model, see figure 5. The inlet valve and the piston are original pump parts. The different phases of delivery are shown **figure 7**. Meanwhile the suction phase t_1-t_3, the intake valve opens with low difference pressure and the fluid – here test fluid – can flow in nearly free of bubbles. Even if little bubbles occur at the valve sleeve, see photo bottom left in figure 7, while the flow velocity is at its maximum, no bubble accumulation arises in the stroke volume.

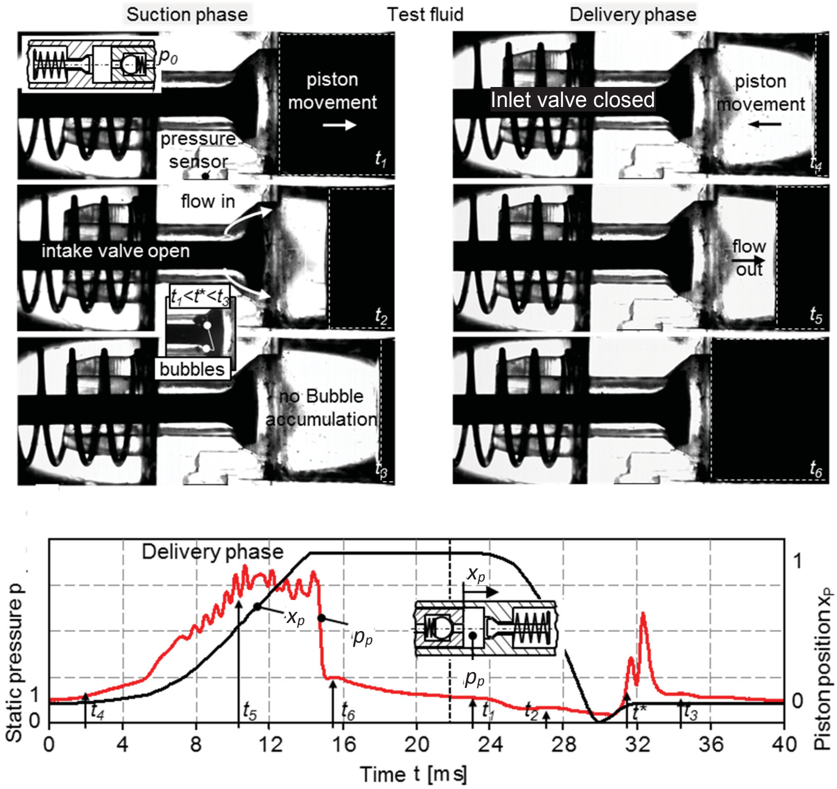

Figure 7: No bubbles in the fluid of the two valve pump during whole work cycle

During the delivery phase t_4-t_6, the pressure in the stroke volume is very high and the fluid is delivered through the piston into the fluid volume around the armature of the pump. In this phase, the volume around the armature and the pressure inside of that volume is almost constant.

1.4. Effect of bubbles for delivery

Low pressures, lower than tank pressure, create the evaporation of the fuel and lead to dissolving of air. Also, stationary air bubbles in the intake and the pump chamber cause a partial filling of the pump chamber. This reduces the efficiency of the delivery and may cause disturbances in the following advices.

To reduce unwanted effects of bubbles, an adequate pump design has to be found, avoiding low pressures in the suction area. That means that low flow resistances, a smooth piston movement and a low pressure input valve generate improvements. Otherwise, using a control bore in combination with a high pressure difference at low pressure level is disadvantageous, especially low boiling fluids have to be metered precisely. This characteristic of the pump and pump control has an increasing effect depending on the physical properties of the fluid. This is shown by a flow rate test with bubble detection, see **figure 8**.

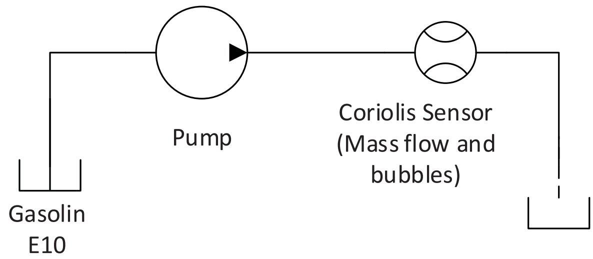

Figure 8: Test rig for pump delivery of mass flow and bubbles

The test rig was built up and operated in a climate chamber with a temperature of 30 °C and gasoline with 22 % Ethanol (E22). The pump has been connected with a short suction line and a 1 m pressure line of 2 mm diameter in effect comparable with automotive applications. The Coriolis sensor measures the volume flow and the fluid density.

Bubbles lead to high frequencies of high amplitudes of the Coriolis signal value shown in **figure 9**. Here also a significant effect of the pump control, voltage e. g., can be observed.

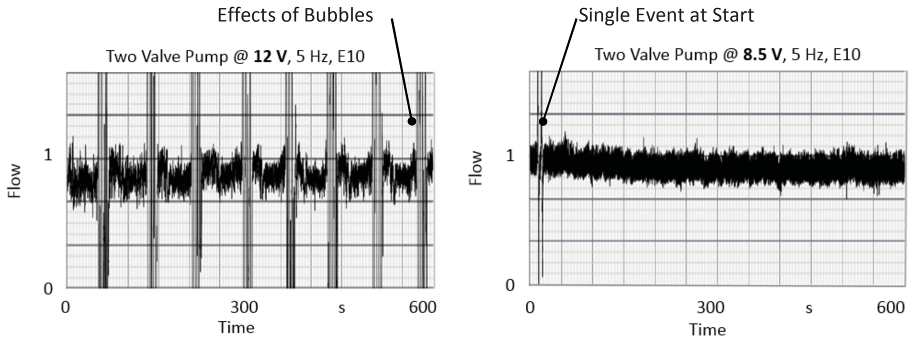

Figure 9: Result with different operating voltages (12 V and 8.5 V)

If the control voltage is unnecessarily high, shown in figure 9 left graph, a lot of bubbles are released and delivered in periodically intervals. The reduction of the voltage to 8.5 V avoids the generation of bubbles. A negligible reduction of the delivery rate is observed.

1.5. Pump design – two valve pump robust against critical fuels

As shown in the chapters before, pumps having two seat valves are to be preferred with respects to the precise delivery of liquids characterized by having low boiling pressures. Hence, the focus in this chapter is set on the pump types with two seat valves as inlet and outlet valve. Modern fuels are typically blends with a certain bio content. Either ethanol for gasoline fuels or biodiesel. Components that are in contact with these fuels have to meet specific requirements. As shown in literature /6/, degenerated biofuels generate deposits or attack surfaces, see also /7/. Thus, more robust pumps have to be designed and brought to market. In addition, ingredients of such bio fuels improperly blended with additives tend to degenerate. For which, an innovative design of the piston is investigated which is characterised by a helix groove in the surface. The intention is to avoid the setting up of deposits respectively layers of them. Inside state-of-the-art pumps liquids are delivered passing dedicated areas besides the gap between piston and cylinder. In **figure 10**, the change of the path of the liquid is illustrated. That gap normally is not wetted by design. With the improved design proposed, this especially dedicated area for the liquids flowing through the pump is just laid in the gap between the piston and the cylinder. This means that the main flow of fuel is passing this helix channel or these helix channels. By doing so, several advantages are won: A flooded gap means that the surfaces are not in direct contact, but are cooled by the liquid. Which then reduces the tribological stress of the surfaces. In case of degenerated fuels, the risk of generating deposits is significantly reduced, as these degenerated fuel contents are pumped through the pump in very little portions and do not settle down to surfaces.

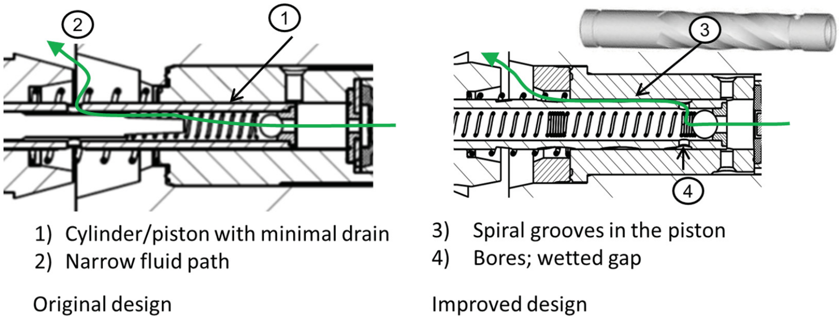

Figure 10: Two-valve pump type with helix grooves (right) at the surface of the piston

Because of the narrow gap ① and the small stroke a cleaning of that gap of a state-of-the-art-pump is not possible, for that reason, the risk of a motionless pump is implied if it is used with not specified fuels. This may be the case if deposits or degenerated fuel trespass the gap and accumulate and built up an adhesive joint between surfaces – ideal to withstand shear loads that are applied when the pump is actuated for further pumping. The improved helix-design leads the fluid from the bores ④ through the grooves of the piston ③. The aim is to rinse residues of fuel and contaminations from the critical areas – especially between piston and bearing. Alternatively, such defined fluid path respectively grooves could be made inside the inner surface of the cylinder. Doing so, no negative effects on the pump's performance even with degenerated fuels were observed. Of course, also these optimized pumps are not designed for pumping honey-like liquids of low viscosity. But this design widens the limits significantly.

As an example of such deposits, in **figure 11** main filters of two test benches positioned centrally are shown that act for a quantity of pumps showing different visual appearances. Both filters have been used in a durability test bench for several months of use. Meanwhile the filter used with proper diesel with a bio content of 20 % looks like new, the filter used with improper bio content is degenerated showing dark deposits.

Figure 11: Example of deposits originating from degenerated biodiesel B20

1.6. Hydraulic effects of the new design

Investigating the new helix design, the main intention is to ensure the performance under relevant conditions compared to the basic design. Therefore, the main functions: tightness, suction and leakage have been tested. All pumps, conventional and innovative helix design, are found to be comparable regarding their basic function. No leakage was observed at all, that's a safety function of course, the flow rate is situated within the specified range and even better with a deviation of approximately 4 %. Also the suction ability was immaculate. Hence, the innovative helix-design of the piston is a superb option for further exploration.

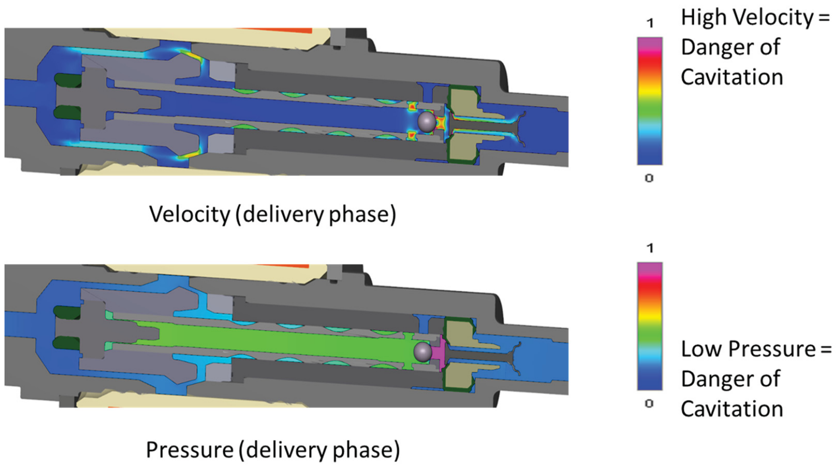

Figure 12: Two-valve principle with helix grooves at the piston

As described, the design has an optimal rinsing around the piston with relative high flow velocity inside of the grooves. The fastest flow occurs in the area of the pump chamber and the outlet valve in an area of high pressure. Here the pump is not able to create bubbles, as can be seen in **figure 12**. A second area of higher flow rates is the cone of the armature, see figure 10 detail ②, where the closing gap between armature and pole in combination with the high volume flow circulating around the armature might be a reason for cavitation. This effect depends on the magnetic force as a consequence of the operating voltage of the pump and refers to the delivery phase.

1.7. Durability test results with critical bio-fuels

As shown, the proposed design is improving the functionality of metering and delivering even bad qualities of bio fuel blends. The question is whether durability of these pumps is affected anyhow. Former studies have shown that properly designed fuel pumps generally are able to pump bio fuels for a long time in service, see /8, 9/. But it is not proven that the benefits of the new helix design, avoiding deposits, e. g., lead to improvements in real systems. In order to investigate into the endurance behaviour of pumps with the new helix design of the piston, a durability test with challenging fuel qualities, both gasoline and diesel, was performed. The improved design showed no failure during an endurance test over lifetime with E22, diesel B20 and B30. Aggressive B20 showed polymerizing of the degenerated fuel. The pumps with the new helix-design worked properly for the full lifetime – even with this challenging fuel, i. e. 70 % longer compared to pumps having original piston design.

While observing deposits inside the gap between piston and cylinder, parts having pumped gasoline blends like E22 showed the most significant result: In **figure 13** pistons are presented after full durability test. At the original pistons without grooves a formation of deposits is visible whereas at the grooved pistons the running surface is absolutely bare and clean. The endurance test with B30 showed no characteristics at any test pump but it shows that pumps with suitable design for challenging biofuels withstand even unrealistically bad fuel qualities.

Figure 13: Effect of helix grooves at the piston (right) after durability test

2. Summary and outlook

By intensive experimental investigations it could be shown that an elaborate pump design with two valves – intake and outlet valve – has essential advantages compared to simpler systems and reduce cavitation effects like the occurrence of gas bubbles.

Considering the questions of metal-fluid interactions a new helix piston design has been proposed and tested successfully which even allows to rinse gaps between piston and cylinder of piston pumps dosing challenging fuel qualities. Even if these effects occur only with age sensitive bio fuels it is an additional safety issue for the robustness of the pumps used for automotive auxiliary heater and exhaust systems, e.g.

3. Acknowledgements

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