

Analysis of the Metering Behavior and the Energy Efficiency of a Dosing Pump

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ABSTRACT

Initially used in motor vehicles to convey a specific volume of fuel from a tank to the burner of an engine-independent heater, the range of applications for electro-magnetically driven dosing pumps has been widely expanded over the past few years, e.g. dosing pumps are part of the emission control system or used to convey a specific volume of fuel from a tank to the burner of an engine-independent heater. Whereas originally only conventional fuel was delivered, nowadays the dosing pumps have to be suitable for any kind of liquid media. As a result of the extensive fields of application, verification and improvement of the design for optimal usage and low energy consumption are needed. The paper presents experimental investigation and computer simulation of the dosing pump in order to examine its metering behavior and the energy consumption. Depending on the aim of the analysis, different simulation tools, namely computational fluid dynamics and system simulation with lumped parameters, are used.

With the help of computational fluid dynamics, which takes the piston motion and the fluid driven check valve into account, a profound understanding of the flow effects in the pump can be achieved. The aim of this work is to investigate the valve kinematics and the interactions with the surrounding fluid by analyzing the fluid-structure interaction. Comparisons are made by experimental testing. Measurements of the pressure inside the displacement volume as well as the valve dynamics are investigated. Noteworthy is a technique based on a laser Doppler vibrometer for examining the dynamics of the piston inside the fluid.

Because the importance of the energy efficiency is growing, this aspect requires further investigation. A system simulation model of the pump is built in order to be able to analyze the energy efficiency in more detail. A general study of the energy conversion process in the pump is presented. Besides mechanics and the hydraulic system, the model also contains a simplified form of the electromagnetic actuator. An energy flow diagram is used to quantify and illustrate energy transformation within the pump. The investigations show the fundamental energy consumer and are the basis for systematic technical improvement.

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INTRODUCTION

Electromagnets are increasingly being used as driving element of mechatronic systems in mobile applications. In automobiles of middle and upper price segment up to 150 solenoid actuators are installed [1]. In addition to the actuation of valves, clutches and brakes, they are driving elements of pumps.

Solenoid-driven dosing pumps, especially the analyzed piston pumps (Figure 1), are characterized as displacement units with a robust design that is not too complex. The pumps are designed to deliver an exact volume per stroke,

independent of the pressure and temperature at the outlet port [2]. Due to their high delivery accuracy, low weight, and dependably long life, solenoid operated pumps have recently been widely used in mobile applications. In motor vehicles, for example, dosing pumps are part of the emission control system or used to convey a specific volume of fuel from a tank to the burner of an engine-independent heater. One of the most innovative operational areas of such compact metering units is fuel cell technology, where dosing pumps are used for metering and conveying fuels for fuel cells and reformers.

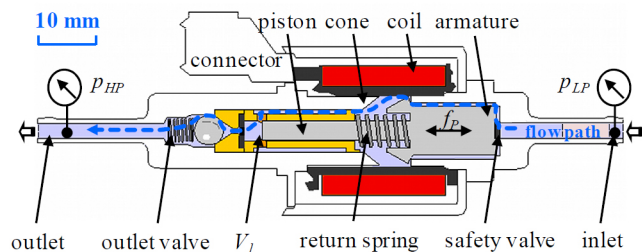


Figure 1. Design of the magnetically driven dosing pump (coil in de-energized state)

To enlarge the fields of its application, noise level and pumping characteristic should be further investigated. Especially under high temperature conditions or with fluids having low boiling temperatures, as gasoline or gasoline-alcohol blends, cavitation may occur due to the working principle and may change the operating behavior of the pump [3]. As a result, both the noise level and metering accuracy are affected. To improve effects caused by cavitation, it is necessary to detect and analyze the critical areas. The experimental investigations of all relevant field variables inside the pump are rarely possible due to the small dimensions of the pump volume. The identification of cavitation zones requires a CFD model, which takes fluid-structure interaction between the outlet valve and the surrounding fluid into account. Hence, with the help of CFD, it is possible to display complex transient flow processes to acquire deep comprehension of significant physical processes and to reduce the number of prototype tests in order to further improve the design for optimal metering behavior.

Moreover, in a variety of applications, such as operation of an auxiliary heater, low energy consumption of the pump is required to conserve vehicle battery power. The determination of the efficiency of the pump results in the ratio of outgoing hydraulic power and incoming electric power, but gives no clear indication about main energy losses. Hence, before setting out to improve the energy efficiency, a detailed overview of the energy consumer in the pump must be carried out. For this purpose, a lumped parameter model is presented. Typically used to analyze the performance of electro-magnetic actuators [4, 5] - due to the multi-domain modeling of the electro-magnetic, mechanical, and fluid subsystems of the pump - the energy flow can also be determined. Model validation is performed by comparing the simulated and measured curves.

OPERATION OF THE DOSING PUMP

A basic advantage of the pump is the simplicity inherent in the method of electric to hydraulic energy conversion. The motion of the piston is realized by an integrated electromagnet. A duty cycle consists of two time intervals (energized duration and de-energized pause). The energized duration is the time between switch on and switch off of a constant supply voltage and summarizes the pull-in time and

the holding time of the armature. During this time, a magnetic field is built up and a magnetic force acts on the armature. The energized duration is followed by the de-energized pause. During this time the magnetic field is removed and the piston is pressed by the return spring force to its initial position.

Most oscillating displacement pumps are equipped with a pressure and suction valve, working in opposite directions during the suction and delivery phases [6]. In the analyzed pump, the suction valve is replaced by cross holes, see Figure 2. In this case, the opening of the inlet is a function of the piston position. An adequate design of the cross holes results in a reduction of moving parts and increases the robustness of the pump with consistent conveying accuracy.

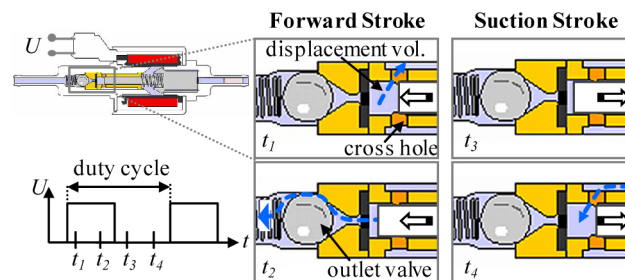


Figure 2. Schematic depiction of the pumping process

In the absence of solenoid excitation, the displacement volume is filled with the fuel to be delivered. After current is applied to the coil, the armature moves the piston against the force of the spring. If the pressure rises above the set pressure, the outlet valve opens and the piston expels the medium from the displacement volume. Meanwhile, the inlet to the displacement volume (cross holes) is closed. Once the supply of electricity is interrupted, the return spring pushes the armature and piston back. At the beginning of the armature's backwards movement, the piston overlaps the cross holes and a partial vacuum is created in the increasing displacement volume. After opening the cross holes, liquid enters the open inlet and a new working cycle begins. If the pump is not running, a safety valve prevents a leakage volume flow through the pump.

The analyzed pump has a fixed displacement volume of $V_1 = 27\text{mm}^3$. With the adjustable stroke frequency $f_p = 0 - 25\text{Hz}$, the average flow rate can be varied continuously.

ANALYSIS OF THE METERING BEHAVIOR

Experimental Investigation

With regard to the delivery accuracy of the pump, the measurements of the pressure inside the displacement volume as well as the piston and ball dynamics are investigated. The final positions of the magnetically driven piston can be determined by the analysis of the current characteristic and the voltage signal. In order to define the dynamics of the

piston very precisely, a laser Doppler vibrometer (Polytec OFV-503; OFV-5000) for non-contact motion analysis is used. Most often, the surrounding medium of the moving object is ambient air. In this work, the laser is used to accurately measure the dynamic of a submerged solid object in fluid.

The investigation undertaken into measuring the movement of an object inside a fluid is useful for examining many hydraulic components, for example the opening characteristics of valves. Often, the moving component must be equipped with additional devices which change the mass, affect the flow path or pressure level, and cause additional friction or leakage.

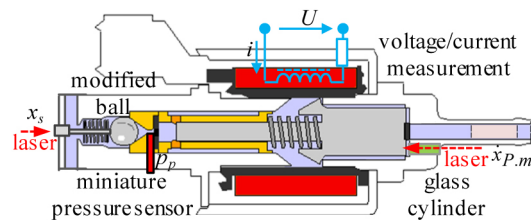


Figure 3. Modified test pump with implemented measurement technology

In Figure 3, the experimental setup is depicted. The piston of the experimental prototype pump is optically accessible through a glass window. Therefore, a transparent and bubble-free fluid is needed. The laser beam is focused on the moving piston and is parallel to the direction of movement. Due to the motion, the Doppler effect causes a change in frequency of the laser beam. The output signal of the vibrometer depends on the optical path difference between the measurement beam and a reference beam. It is a continuous analog voltage and is directly proportional to the velocity $\dot{x}_p$ of the object. If the object moves into a fluid, the index of refraction n_{fluid} must be taken into account by dividing the measured velocity $\dot{x}_{p,m}$ value by this factor [7]. The integration of the velocity $\dot{x}_p$ over time leads to the position of the piston x_p .

Further investigations deal with the highly dynamic motion of the ball seat valve. Although the ball valve is quite small and low-cost, delivery accuracy and noise behavior are highly dependent on their reliability. Furthermore, the valve affects the efficiency factor of the pump. The requirements concerning the valve are: a long service life, a reproducible and reliable behavior, low pressure drop during forward stroke, as well as tightness during suction stroke [8]. The values of the ball diameter $d_s < 5\text{mm}$ and the expected ball valve stroke $x_s < 0,2\text{mm}$ expose the demands on the measurement technique. Due to the inaccessible position of the ball valve, the non-contact vibrometer measurement of the ball motion is difficult to realize. For this reason, the ball is modified by a rod and guided to the outside of the pump, see Figure 3. To measure at almost realistic operating conditions, special attention has been given to maintaining the ball mass and the flow conditions around the ball. By

means of focusing the laser beam on the side surface of the rod, the valve motion is recorded synchronously to the pressure. The pressure is measured by a subminiature pressure sensor (measurement specialties EPIH-17; $p = 0 - 5\text{bar}$), specifically designed for dynamic and high frequency measurements.

The measurements are used for validation of the following simulations and presented when comparing simulation results with real pump behavior.

Numerical Approach by CFD-Simulation

The numerical simulation of the pump is a useful tool for optimizing the flow paths, especially in a product development process. With the help of computational fluid dynamics which takes the piston motion and the fluid-driven ball valve into account, a profound understanding of the flow effects can be achieved. Thus, the dynamic simulation can significantly reduce testing time and costs.

For determination of the real flow conditions, a realistic valve characteristic is essential. The aim of this work is to investigate the ball kinematics and the interactions with the surrounding fluid by analyzing the fluid-structure interaction (FSI). For analyzing the ball motion, the assumption of a 2-way interaction with rigid body motion can be made. The deformations of the ball or the housing are not considered. Furthermore, the approach neglects the leakage gap between the piston and the cylinder. Considering the dominant direction of the ball movement (one degree of freedom), the following equation of motion is determined:

$$m_s \ddot{x}_s = \sum F_{\text{CFD}} + \sum F_{\text{external}} \quad (1)$$

The fluid flow-induced forces F_{CFD} (here: pressure force and force due to the viscous friction) and external forces F_{external} (here: spring force) affect the valve dynamics $m_s \ddot{x}_s$.

To model the solid motion of the piston and the ball, the mesh has to change according to the present position. Due to the symmetrical design of the pump, a numerical quarter section model with two symmetry planes as boundaries can be used to reduce computational effort. The used commercial CFD code provides different approaches to deal with moving/deforming meshes [9]. Thus, at each time step the grid is automatically updated as a function of the new position of the moving parts (Figure 4).

Dynamic layering is used to consider major volume changes of the displacement chamber. In this case, layers of cells adjacent to a moving boundary are added or removed. As the displacement of the ball is small, a spring smoothing approach for the dynamic mesh update is suitable.

Due to the force-dependent motion of the ball, the flow conditions are changing all the time; this is why the fluid flow may be not purely analyzed on the basis of the stationary valve behavior. The calculation takes the dynamic impact of the forces into account, summarized in (1).