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Design and Realization of a Test Stand for Optical Fluid Dynamic Research of Gels

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Abstract

The flow behavior of non-Newtonian fluids is of great interest looking at gel fuels for rocket applications; especially the pressure loss of gel flows wants to be known to design the propellant feeding system. Since a major part of the pressure loss occurs in complex geometries like injectors or valves, a test setup was designed to examine the pressure loss and behaviour of gel flows. The described test setup can be equipped with different test geometries. The measuring sections have an optical access to examine the flow with PIV; furthermore pressure and temperature can be measured on various positions.

1. Introduction and Background

The gels used in this work are viscoelastic fluids as described by Chhabra [1]; this means that the gels have properties of liquids as well as solids. While at rest, they form a solid like structure which makes the gels behave like elastic solids. With shear stress being applied, the gels liquefy and behave like liquids with a shear rate-dependent viscosity. Further the gels used here are shear thinning, and thixotropic, and the breakup of the molecular network in the solid form is reversible. The shear thinning behavior, together with the yield stress is examined by many authors and described by many models within the last decades for example the Herschel-Bulkley model [2], or Bingham-Model as described in [3], or the Herschel-Bulkley-Extended model (HBE) [4]. Since the thixotropic part of the behavior depends strongly on the pre-conditioning of the gel and neither of these approaches reflects this pretreatment like shear or time of rest, the thixotropy of the gel is difficult to grasp and therefor is not represented in the given models.

Due to the partly solid, partly liquid behavior, gels combine the advantages of solid and liquid propellants [5], [6], [7]. They can be handled more easily than liquids, do not spill out of the tank, and do not slosh in the tank, yet a gel rocket motor with variable thrust can be realized, since the amount of gel injected into the combustion chamber can be adjusted. Furthermore, by adding additives to the gel, the propellants properties can be modified, so that, low signature emissions or a higher specific impulse can be realized depending on the added substances. Even hypergolic gel combinations are possible [8].

Nevertheless the flow behavior of gels is difficult to understand because they do not behave like Newtonian fluids and thus the known approaches to predict the pressure loss cannot be used. Since the shear stress changes within the diameter of a pipe, the fluid changes its viscosity and thereby cannot be described by commonly known approaches describing the pressure loss of Newtonian fluids, especially the one described by Bernoulli for example in [9]. Bernoulli's approach is only valid for Newtonian fluids, since the Navier-Stokes equations [10], which Bernoulli's approach can be derived from, are based on a constant viscosity. Therefore it is necessary to do further research on Non-Newtonian fluids.

In the test setup, that is described in this paper, the behavior of gels while flowing through a tapered pipe will be examined and thereby the knowledge in this field is increased. The work focuses on the pressure loss of a flowing gel through a constriction in a pipe. To run the tests, a setup was designed, is currently under construction, and is described in the following chapters.

2. Test setup

The test setup consists of two gel reservoirs which are cylinders with a diameter of 200 mm; these reservoirs, as well as all other parts of the test setup, were designed to conduct tests under pressures up to 35 bar. Due to material incompatibilities, the metal parts of the test setup were coated with a plastic material.
During the test, the gel flows from one of the cylinders to the other as seen in Figure 1. In order to force the gel out of the cylinder a piston is moved within the cylinder, thereby creating pressure in the gel reservoir and a gel movement out of the cylinder into the hydraulically tubing. The force moving the piston is created by a hydraulic system.

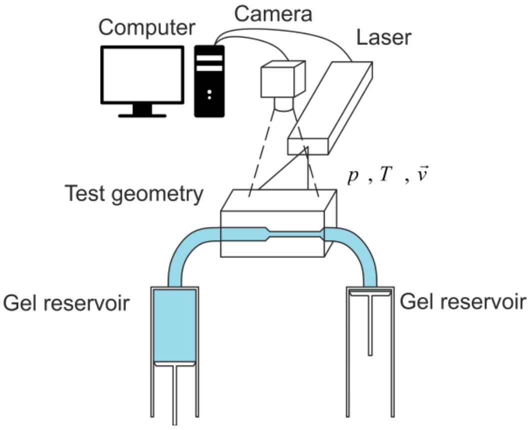

Figure 1: Test setup

While being pushed from one cylinder to the other the gel passes the measurement section or test geometry with the shape of a tapered pipe; in this passage the pressure loss and the temperature as well as the velocity field will be examined. This is schematically shown in Figure 1. The measurement section is made of acrylic glass to have optical access to the flow and be able to examine it with optical measurement techniques.

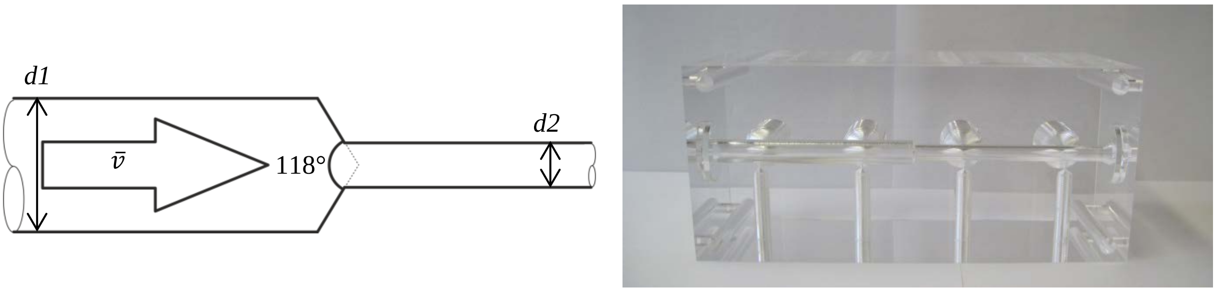

Figure 2: Measurement section

In the test geometry shown in Figure 2 the gel will flow from the left to right. The holes in the lower part of the measurement section are for thermocouples and the larger holes on the rear side are for pressure sensors. The contraction with an angle of 118° fits commonly used manufacturing techniques and the ratios of diameter are based on parameters of the feeding systems of the gel combustion chambers currently used in hot fire tests.
The test setup was designed in a modular way to be flexible with the test to be performed. Therefore, further tests after this campaign can be done with any test geometry of interest by just replacing the section of measurement.

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2.1 Parameters of the test setup

The test parameters which can be changed between the tests are various: By changing the section of measurement, the ratio of diameters in the tapered pipe can be changed. Three different ratios have been chosen, the ratios were selected to be equal to the once of the injectors in the test setup of the combustion chamber for tests with gel propellants. Further, by changing the setup of the hydraulic system, the average velocity $\bar{v}$ can be adjusted up to an average velocity of $\bar{v}$ =14 m/s in the section of measurement.

The last variables are of the gels themselves. By changing the gel, the properties of the fluids can be changed. With the gels being described by the HBE law there are 6 variable parameters:

1. Diameter ratio *d1/d2*
2. Average velocity $\bar{v}$
3. Gel properties
    a) τ_0 (Yield stress)
    b) n (Exponent in HBE model)
    c) K (Factor in HBE model)
    d) η_∞ (Viscosity at high shear rates)

The parameters 3a to 3d depend on the chosen gel and therefore cannot be modified independently which leads to three independently changeable parameters within the test setup. Since three measurement sections were produced, three different diameter ratios *d1/d2,* namely 1:0.3, 1:0.4, and 1:0.7 will be tested.

The geometrical parameters of the test were designed in a way, in which the maximum of velocity should be reached with the given hydraulic system. Nevertheless, since this work is part of the task to develop a prediction model for the pressure loss of gels, no precise prediction of the pressure loss was possible.

2.2 Sensors and measuring techniques

Pressure and temperature are measured each at 14 positions and the measurement position of temperature and pressure on each position is always close together. The two parameters are measured in the two gel reservoirs each with one sensor. Each four probes were placed along the radius before and after the measurement section to check the rotational symmetry of the flow. The last four measurement positions are along the measuring section, two before and two after the reduction of the diameter. With this it is possible to identify the pressure loss caused by the flow in the pipe with constant diameter and which share of the pressure loss is caused by the reduction of the diameter. Since the pressure right at the constriction of the measurement section cannot be measured due to recirculation, the pressure is measured within the straight pipe four times, twice each before and after the constriction. By assuming a linear pressure loss within the part of the pipe with constant diameter, the pressure loss over the constriction can be identified.

The pressure sensors used in this test setup are from STS sensors and Althen, both types with a range of 0 to 35 bar.

Table 1: Pressure sensors

Manufacturer	**Type**	**P_{max} [bar]**	**Accuracy [bar]**	**Operation Temperature [°C]**
STS-Sensors	ATM1ST	35	± 0.175	-25 … 100
Althen	HPSA	35	± 0.088	-20 … 135

For temperature measurement thermocouples of type T are used with a diameter of 1 mm from Electronic Sensors, with the accuracy class 1 (failure: 0.5 °C or 0.5% of measurement). Type T thermocouples were chosen since the temperature range of -40 °C to 350 °C wide enough for the test and the accuracy is higher compared to other thermocouples.

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Further the flow field of the gel flow will be examined in the tapered area by optical methods. It is expected to find recirculation areas just before and after the diameter reduction as it is known from the flow of Newtonian fluids as seen in [11], the influence of the shear rate dependent viscosity, nevertheless, is unknown.

To analyze the flow field close to the contraction, a particle image velocimetry (PIV) system from Dantec Dynamics will be used. The system contains a 15 Hz double pulse laser. Since the laser is, frequency wise, the limiting component of the system a measuring frequency, of the flow field, up to 15 Hz is possible. The lasers pulse energy is 200 mJ, which makes it possible to take images of the gel, even though its transparency is lower than that of water or air.

2.3 Measuring system

All data are recorded by a laptop, with a LabVIEW based software to record the measured data. This software also controls the hydraulic system and triggers the PIV measurement. The digitalization of the data is done by a CompactDAQ System from National Instruments. The components of this system are:

NI 9219: Universal module for cylinder position detection

NI 9472: Relay for hydraulic system control

NI 9220: Voltage measurement module for pressure measurement (via Voltage)

NI 9214: Temperature measurement module (Thermocouple)

NI CDAQ 9178 Chassis

Table 2: Measuring system

Module	**Measured dimension**	**Sampling rate**	**Accuracy (on target dimension)**
NI 9219	Cylinder Position (via Voltage)	100 S/s/Ch	± 1.2 mm
NI 9220	Pressure (via Voltage)	100 S/s/Ch	± 0.074 bar
NI 9214	Temperature	68 S/s	± 0.10 °C

3. Experimental Results

3.1 Pressure Probe Pretest

Since the pressure probes, which are used within this test setup, cannot be placed right in the flow since the diameter of the pressure probes is so large compared to that of the flow channel, a capillary has to connect the pressure probe with the pipe. Gels, unlike Newtonian fluids, have a yield stress, which causes them to only flow if there are stresses applied which are higher than the yield stress. Therefor a pretest was executed to compare the response behavior of a pressure sensor in an area with changing pressure to one which is connected to the same pressurized area via a capillary. The capillary had the same diameter and length as the ones in the final test, which made these pretests comparable to the final tests. This pretest setup is shown in Figure 1.

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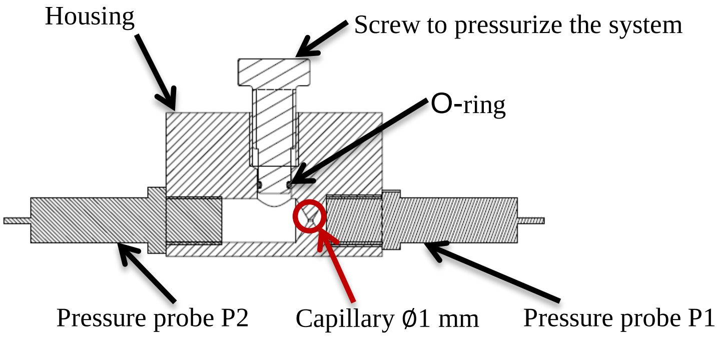

Figure 3: Pressure probe pretest setup

Two different kinds of pressure measuring errors were examined. First the static failure which is caused by the gels yield stress and by the gel being in the capillary. The gel in the capillary can withstand a certain pressure and this pressure will be a failure to the measured pressure even when the pressure in the pressurized area (or the measurement section in the final tests) remains constant for some time. To analyze this behavior, pressure was applied and the difference between the two pressure probes was investgated for 600 seconds. The decrease of the absolute pressurein the system, measured by P1 and P2, which was assumed to be caused by leakage, was neglected. The big pressure drop in the beginning is assumed to be caused by the settling of the o-ring. The negative peak in the beginning of the measurement is caused by a pressure reduction while attaching the wrench to the screw for applying the pressure.

To identify the static pressure failure, the pressure difference P1-P2 (blue curve in Figure 4) at the beginning of the test was compared to the pressure difference at the end of the test; the result of this comparison is the static pressure failure ΔP_{stat}. Due to the little pressure difference between P1 and P2 compared to the absolute pressure, the two pressures appear almost as one line in the graph. The noise of the blue curve is caused by the high resolution of the corresponding scale. As it can be seen in Figure 4, the static pressure failure is below 0.1 bar. Comparing this failure to the pressure sensors' accuracy shown in Table 1 shows, that the static failure is lower than the sensors failure, which is accaptable fo the tests.

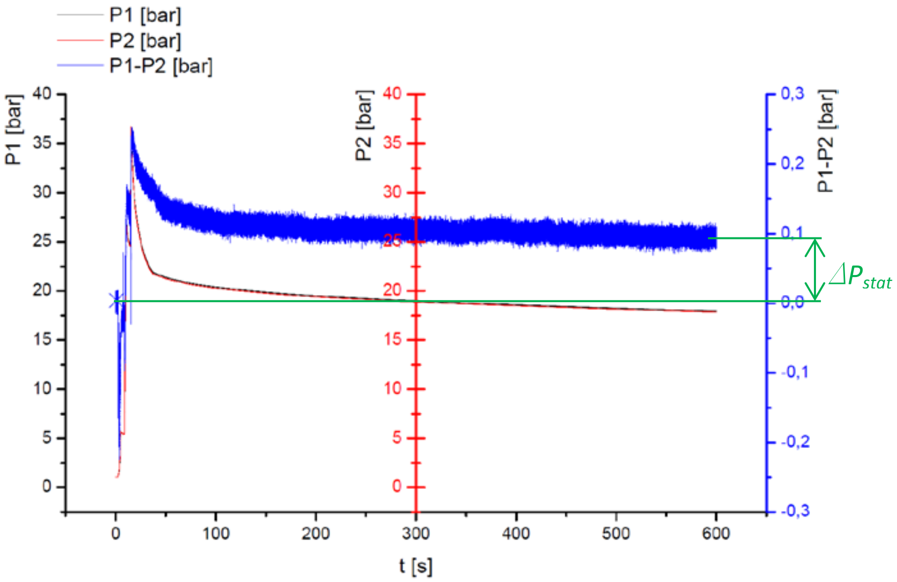

Figure 4: Static pressure failure

The second kind of measuring failure is caused by the gel taking time to move through the capillary. Therefore, a changing pressure was applied to the sytem and again the pressure as well as the pressure difference between the probes was examined. The corresponding graph to this measurement is shown in Figure 5. By knowing the pressure gradient, which was calculated between t_1 and t_2 as well as between t_3 and t_4, and the pressure difference between the pressure sensor before and behind the capillary a time delay can be calculated. The results of the time delay measurement are shown in Table 3.With a time delay of up to 13 ms the time delay is absolutely uncritical for the planned tests.

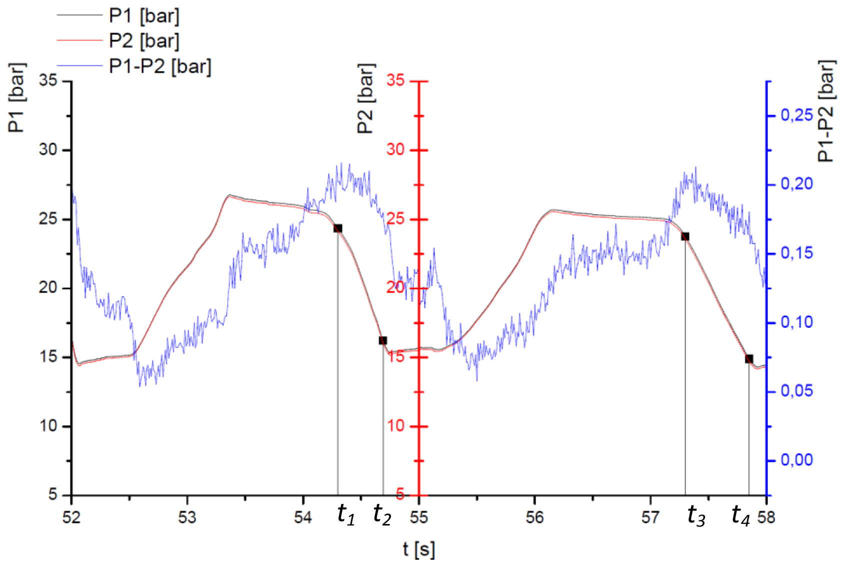

Figure 5: Time delay pressure measurement

Table 3: Time delay of pressure measurement

t	***ΔP* [bar]**	***Δt* [s]**	***P1-P2* [bar]**	**t_{delay} [ms]**
t_1 and t_2	8.12	0.39	0.22	10.6
t_3 and t_4	8.86	0.55	0.21	13.0

3.2 Run-In Tests

The run-in tests will start soon after this conference, and are planned for the mid of July. They will be performed with a water based carbopol gel. Further test will follow with different gels. It is expected to see recirculation areas within the test geometry and to get first data showing the pressure loss.

4. Conclusion

To gain the possibility of predicting the pressure loss of gels in a feeding system and increase the knowledge of gel flow, a test setup to measure the pressure loss through a constriction in a pipe was designed. After this campaign, further test geometries of interest can be examined to the setup. The possibility of getting accurate pressure data with the sensors connected to the flow channel through a capillary was verified.

Acknowledgment

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Nomenclature

d1	Entrance diameter measurement section
d2	Exit diameter measurement section
HBE	Herschel-Bulkley-Extended
K	Factor in HBE model

n	Exponent in HBE model
p	Pressure
$P1$	Pressure after capilary
$P2$	Pressure before capillary
P_{max}	Maximum pressure the pressure sensors can measure
T	Temperature
t_{delay}	Time delay between the pressure sensore P1 and P2
$\bar{v}$	Average velocity
$\vec{v}$	Velocity field
ΔP	Pressure difference between two measuring points
ΔP_{stat}	Static pressure failure
Δt	Time between two measuring points
λ	Wavelength
τ_0	Yield stress
η_∞	Viscosity at high shear rates

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