Development of a Viscosity Model and an Application, for the Filling Process Calculation in Visco-Dampers

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Abstract: The lifetime and thermal management of torsional vibration dampers, working with silicone oils, begin at the design and development phases, of this damping product, with help of properly developed material and CFD simulation models. Dynamic viscosity measurements have been carried out on AK 1 000 000 STAB silicone oil samples, with a high-precision rotational rheometer, to quantify the temperature and shear rate dependence of the mentioned silicone oil's non-Newtonian viscous behavior. Eight commonly used pseudoplastic non-Newtonian viscosity models have been selected for model parameter estimation and comparison, to develop a reliable, accurate and easy-to-implement viscosity model valid in -40°C-200°C temperature and 0 1/s-1000 1/s shear rate ranges, based on the expected operational range of the fluid. The filling process of an existing, small-sized torsional vibration damper has been thoroughly analyzed under eight different filling conditions and filling time comparison. Filling mass characteristics, maximal allowed oil inlet temperatures and maximal oil filling velocities have been determined for each case with help of 3D, transient, multiphase, coupled fluid dynamic and heat transfer calculations.

Keywords: torsional vibration damper; silicone oil; rheology; pseudoplastic viscosity model; multiphase simulation; CFD; Carreau-Yasuda model

1 Introduction

Due to the versatility and favorable physical, chemical and mechanical properties of silicone oils, they are widely used in almost all areas of life, starting from the medical, food and cosmetic industries to instrument technology, production technology and scientific-theoretical research, up to machinery, vehicle and aerospace applications.

Within the vehicle industry, silicone oils play an essential role in damping of harmful torsional oscillations awakening on the crankshaft of high-performance internal combustion engines to extend the engines' lifetime. Viscous torsional vibration dampers (shortly visco-dampers or TVDs) will remain the primary working device in all large-scale internal combustion engines (e.g., ships) where the generation, maintenance and regulation of the electromagnetic field cannot be solved in an efficient and economical way for the application of a fluid-damper operating on the magnetorheological principle [1]. Apart from the vehicle industry utilizations, visco-dampers are preferred not only in the energetic and mining sectors, but they are also applied in the markets of combined heat and power, industrial manufacturing & processing, energy and utilities, landfill, biogas and agriculture.

Since visco-dampers are considered a multi-industry component of high importance from the safety point of view, they have a strong business and economic background. While the internal combustion engine market is estimated to be worth USD 271,508.6 million by 2026 (6.5% Compound Annual Growth Rate from 2018-2026), the visco-damper market is estimated to be USD 2360 million by 2024 (2% average growth rate between 2019 and 2024 [2]).

The durability of a visco-damper is determined by the lifetime of the silicone oil stored in it. The oil's wearing and degradation process occur not only during the operation of the damping device (vibration damping process) due to the high thermal, strong mechanical and long-lasting chemical effects, but it starts at the production phase of the damper when the oil is filled into the damper gap.

The aim of this paper is to investigate the filling process by considering the minimally allowed oil degradation by using fluid flow and thermal calculations for saving cost, time and capacity and to optimize the process also to reach the same goals during the production process. Hence, following the introduction of the visco-dampers and their damping medium as silicone oils, the second step of this report is to present the developments of a reliable and accurate silicone oil material model to be the most suitable for AK 1 000 000 STAB silicone oil in order to apply it in a 3D, transient, multiphase, coupled fluid dynamic and heat transfer calculation suitable for testing and optimizing the filling process of visco-dampers. Eight non-Newtonian viscosity models are used, tested, and compared with each other in terms of best parameter identification and accuracy. By selecting the most appropriate viscosity model, the maximum allowable filling inlet temperature for the mentioned silicone oil is also identified for the different filling inlet overpressure cases (10^5 Pa, 5×10^5 Pa, 10×10^5 Pa and 20×10^5 Pa) calculated numerically, on a small-sized visco-damper gap geometry. The filling time required to push the same amount of oil (25 g) into the damper is calculated, and the highest total temperature are also determined for each investigated filling case.

1.1 Visco-Dampers in the Vehicle Industry

The crankshaft of a high-performance internal combustion engine is loaded with axial, transverse and torsional oscillations. Among these undesirable phenomena, the most dangerous are the torsional vibrations [3], which cannot be absorbed by the crankshaft's support bearings. If the frequency of the harmful torsional oscillations appearing on the crankshaft matches with the natural frequency of the crankshaft and the driven parts, resonance develops, and fatigue fracture occurs.

To avoid the above-mentioned undesirable phenomenon and to reduce the amplitude of harmful torsional oscillations, one possibility is to protect the crankshaft with a torsional vibration damper. This damping device is installed either on the free end of the crankshaft or integrated into the flywheel. There are several types of dampers, such as frictional, spring or rubber, but the viscous version is the simplest in structure and requires the least maintenance. According to Figure 1, the visco-damper is essentially a ring-shaped closed space (housing) in which a solid ring (inertia-ring) can move freely and is guided by slide bearings. The narrow space between the housing and the inertia-ring (oil gap) is filled with high-viscosity silicone oil.

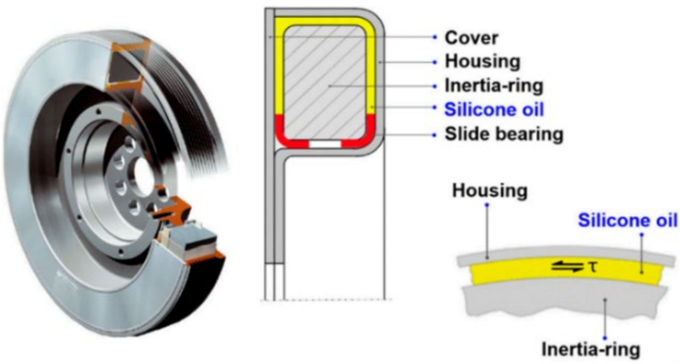

Figure 1
Structure and operation of a visco-damper [4]

The housing is attached to the crankshaft, it rotates together with the shaft, and if even a small torsional oscillation appears on the crankshaft, the housing begins a relative movement to the inertia-ring and the oil in the oil gap is sheared in the tangential direction. The sum of the tangential shear forces on the friction surfaces results in a damping effect, because rotationally the ring is accelerated, and the housing is decelerated. Since silicone oil is a non-Newtonian fluid (see details in subsection 1.2), the tangential shear resulting from the velocity difference between the housing and the inertia-ring and the temperature, during engine operation, have an impact on the viscosity of the silicone oil and on the viscous damping process taking place in the fluid. The torsional oscillations appearing on the crankshaft, are converted into thermal energy (heat) by means of friction and shear in the damper, while the silicone oil suffers from significant mechanical, thermal and chemical wear.

There are several research projects are dealing with modelling and simulating the operational process of the visco-dampers for saving time, cost and capacity in the design and development phases.

In 2017, Pistek et al. [5] focused on the mathematical description of convolute rheological characteristics of the damping fluid of visco-dampers with the application of the traditional fourth-order Maxwell model and with the use of the general rheological model. The optimization program GAMS's CONOPT solver was used to construct a computational tool for calculating the stiffness and damping coefficients of the multi-parameter rheological model. The accuracy of their sophisticated dynamic computational model was validated by tensometric torque measurements at the crank pin.

In 2021, Homik et al. [6] proposed a thermo-hydrodynamic damper model that provides a good approximation of the operating temperature range of a visco-damper. The introduced damper model is able to consider the nature of excitation from the drive unit, geometric parameters, as well as physical, kinematic and dynamic properties of the damper. The input parameters for the model, specifically the angular velocities of the damper parts and the geometry and mass dimensions of the damper were obtained on a test bench using a six-cylinder diesel engine of the Andoria 6C107 equipped with a factory torsional vibration damper. The damper surface operating temperatures used in model verification were measured with a laser pyrometer.

These mathematical models can describe the damping process, but it is hard to investigate the inherent processes of the silicon oils in an arbitrary 3D geometry.

Concerning the silicon oils in the visco-dampers, depending on the degree and length of the fluid's periodical stress, one can talk about a temporary viscosity loss, which is a planned state of the damping process, and one can talk about a permanent viscosity loss, which is called degradation, which should be avoided or delayed, as it results in a significant decreasing in the silicone fluid’s lifetime (and at the same time the entire TVD). The wear and tear process just outlined can start not only during the engine’s operation but also in the last phase of the damper’s production process, when the device is filled with silicone oil (see more details of the filling process in Section 3).

The aspects are mentioned in the paragraph above are the reasons why it is necessary to model and numerically analyze the filling process of a TVD and identify the boundary conditions of the filling, under which the oil suffers minimal degradation from a thermal point of view in the production process. However, the first and most important step of this task is the development of a reliable and accurate silicone oil viscosity model based on rheological measurements (see subsection 2.2). But before solving the task, let us introduce the applied working medium in the next subsection.

1.2 Silicone Oils with Wide Application Ranges

Silicone polymers exist in many different forms in our daily life, such as liquids, greases, rubbers and resins. This article deals only with linear polydimethylsiloxane (PDMS), because the silicone oil (subject of this article) is also made up of this material.

PDMS is a synthetic polymeric organosilicon fluid, which do not exist in nature. Under normal (ambient) conditions, PDMS is a clear, colorless, odorless, pure and viscous liquid without detectable vapor pressure. It is considered physiologically inert, non-toxic, chemically neutral and have no marked harmful impact on living organisms in the environment [7].

Considering the silicone oils' specific viscous character and non-Newtonian behavior, they are primary working fluids in vibration damping applications. Out of the already mentioned applications in vehicle industry, the silicon oils are found in many different dampers widely used for instance in earthquake protection of civil buildings, weapons, spacecraft or in high-precision machinery and instrumentation to avoid impact-vibration damage by absorbing energy of vibrations or shocks and suppress the resonance or alleviate the shock acceleration.

As far as the thermal properties of silicone oils is concerned, they have favorable heat-transfer characteristics with a relatively high thermal stability, so PDMS fluids are perfect thermic lubricants, transformator and hydraulic fluids. They are excellent electrical insulators [8] and, unlike their carbon analogues, are non-flammable. Their temperature stability and good heat-transfer characteristics [9] make them widely used in laboratories for heating baths ('oil baths') placed on top of hotplate stirrers, as well as in freeze-dryers as refrigerants. Silicone oil is also commonly used as the working fluid in dashpots, diffusion pumps and in oil-filled heaters. In electronics they are used as a temperature-resistant, arc-resistant, corona-resistant, anticorrosive, moisture-proof and dustproof insulating medium [10] on electric motors, electrical appliances and electronic instruments. They found to be the best impregnating agent of capacitors and TV scan transformers.

In terms of silicone oils' chemical properties, they are hydrophobic, have relative low surface tension and they wet almost any surface well, thus PDMS is added to many cooking oils (as an antifoaming agent) to prevent oil splatter during the cooking process. PDMS is widely used in anti-dust and anti-oil fluids as additive. In aerospace it is used as aircraft hydraulic oil thanks to its anti-shear properties. They are also used in healthcare as a basic ingredient for consumer products that regulate intestinal gas production or as a substitute for the vitreous in retinal removal surgeries. PDMS is also a popular test material for new rheological theories, and for novel measuring methods and devices. Some rheometer manufacturers (e.g., Anton Paar) use PDMS also as calibration liquids [11].

2 Rheology of Fluids

Rheology is partially related to chemical engineering and partially to solid state physics and aiming to better understand the flow and deformation of liquids and soft solids due to effect of stresses in the material generated by external forces.

The science of rheology is capable of understanding and quantifying the basic nature of the matter, as well as classifying materials with similar behavior and flow-deformation properties. The fundamental relation of rheology, also known as the constitutive or material equation is written in Eq. (1),

$$\tau = \eta \cdot \dot{\gamma} \tag{1}$$

where τ: shear stress [Pa], $\dot{\gamma}$: shear rate [1/s], the velocity gradient associated with the displacement between the adjacent fluid layers, and η: dynamic viscosity [Pas], the resistance of the fluid to deformation, the degree of internal friction between the adjacent fluid layers.

The actual value of viscosity mostly depends on temperature, pressure, shear rate, and time. The most important amongst them is the shear rate in categorization point of view. If the shear stress arising in the fluid depends only on the shear rate at the given time, then one can talk about a simple fluid, while in other cases it is called a viscoelastic fluid. Silicone oil is a viscoelastic and pseudoplastic fluid or shear-thinning fluid where the shear rate increase results in a viscosity decrease according to a given function [12]. Even though silicone oils are viscoelastic fluids [12] and their complex non-Newtonian behavior is usually described both with viscous and elastic terms, considering the filling process of visco-dampers as a relative slow fluid dynamic problem involving small cavities and narrow channels (where the flow times are measured in minutes at room temperature), the authors found the role of elastic terms negligible in this work and focused only on the description of viscous behavior.

1.3 Rheological Measurement Methods

In order to facilitate, and to perform the rheological measurements for determining the basic rheological quantities (shear rate, shear stress, viscosity) and to make the results more reliable and easier to evaluate, simple geometric conditions are chosen for the measurement. Two basic types of rheological measuring devices are used in practice [13]:

- Capillary viscometers – flow in a channel with a simple (usually circular) cross-section
- Rotational viscometers – flow between parallel plates (PP geometry), flow between cone and plate (CP geometry) or flow between concentric cylinders (CC geometry)

The great advantage of rotational viscometer is that it can be used to determine the forces acting perpendicular to the flow direction, i.e., the normal stresses. Based on these, the flexibility of the fluid can be quantitatively characterized.

In case of PP geometry, the sample is located between two parallel plates at an adjustable distance from each other. The bottom plate is fixed while the top plate rotates. During measurement, a steady, laminar and isothermal flow is formed, however, the shear rate in the fluid is not constant. The advantage of this arrangement is the simplicity of sample loading, the possibility to easily adjust the size of the gap between the plates and the possibility to measure shear stresses in the normal direction.

In order to develop a silicone oil material model suitable for calculating the filling process of visco-dampers, rheological analyses have to be carried out, which include temperature- and shear rate-dependent viscosity measurements of a pseudoplastic, high-viscosity liquid. The purpose of the measurements is to determine the basic rheological quantities of silicone oil in a known and prescribed temperature and shear range. Instead of describing the complex viscoelastic behavior of the oil, it is enough only to model the viscous behavior of the silicon oil for the filling process analysis. This requires a rotational viscometer and is suitable for performing constant shear test and simple shear test. Constant shear rate test means that one part of the equipment rotates at a constant, relatively low speed. This method is used to determine the basic rheological quantities, such as shear rate and shear stress and the viscosity can be calculated from them. In case of simple shear test, the shear rate or the shear stress is increased while the other quantity is measured. During the filling process of a TVD, the silicone oil is exposed to static and short-term (few minutes long) stress, so it is unnecessary to carry out oscillation and creep tests. Kőkuti's work [12] reveals the fact, that the necessary time required for this type of silicone oil to test its thixotropy can be measured in hours, so the time dependence analysis of silicone oil's viscosity is out of scope in this work.

1.4 Rheological Measurement Results of AK 1 000 000 STAB Silicone Oil

The rheological measurement results of AK 1 000 000 STAB silicone oil, presented in the current section, are valid at atmospheric pressure. The reason behind the lack of pressure-dependent viscosity analysis is that it has negligible effect, the recently investigated filling process operates at ambient pressure and the pressure-viscosity diagram available in the silicone oil's product brochure [14] that provides enough information about the pressure dependence of the viscosity. According to this diagram, all types of silicone oil react in the same way to pressure changes. Even though the viscosity of the silicone oil increases as pressure increases, silicone oils are much less sensitive to pressure changes than mineral oils. In fact, their viscosity experienced under ambient conditions (10^5 Pa) is doubled at 450×10^5 Pa [14].

The rheological measurements of the AK 1 000 000 STAB silicone oil, chosen as the subject of the study, were carried out by an Anton Paar Physica MCR 302 rotational rheometer. In order to minimize the loss of friction and resulting inaccuracy during the rotation of the measuring head, the instrument is equipped with a fine porous carbon coated air bearing; with an active temperature-controlled, electronically commutated permanent magnet synchronous motor (EC-motor), with an integrated normal force sensor and with a high-resolution optical encoder. This modular compact rheometer (MCR) is a "shear stress-controlled rheometer", which means, that the rheometer calculates the shear stress applied to the fluid sample from the instantaneous value of the electric motor's current that moves the rotating part of the measuring geometry, and at the same time, this current is controlled in such a way, that the prescribed time-dependent shearing is realized in the fluid sample based on the data of the optical angular rotation sensor mounted on the same axis as the motor. The torque range that can be applied with the instrument is 0.5 nNm-230 mNm; which has an angular velocity range of 0-314 rad/s (3000 RPM) and the target temperature range of the fluid sample is -40°C to 200°C.

The main components of the measuring system are displayed in Figure 2:

- MCR 302 rheometer (1) with cooling/heating air volume flow rate regulator, air- and fluid circulated Peltier system (2) and PP25 measuring head geometry (3);
- Compressor (4) to keep the volume flow rate of the cooling/heating air guided to the air-circulated Peltier element at a constant value;
- Thermostat and heat exchanger (5) filled with hydraulic fluid to control the temperature of cooling/heating air and cooling/heating fluid;
- Hydraulic pump (6) for circulating the cooling/heating fluid in the measuring system;
- Desktop computer (7) for controlling the measuring instrument via RheoCompass software;
- Additional components (8) such as calibration fluid, sample dispenser, sample handling and removal spoons, acetone cleaning agent, wipes.

Based on a private communication with the Anton Paar Support Team, in case of high-viscosity samples (e.g., silicone oil with an initial viscosity of around 1000 Pas), measurements above the shear rate of 1000 1/s are laden with greater error than measurements below this threshold value. Furthermore, in the high shear rate range (1000 1/s already falls within this range), simple shear tests are proved to be more accurate than oscillation tests. The accuracy of the instrument is claimed to be 1.5% for CC geometry and 3% for PP and CP geometries.

The theoretical considerations written in subsection 2.1 and 2.2 were taken into considerations as well as the properties and limitations of the available measuring instrument. According to this background, the authors prepared and implemented the following measurement plan.

Figure 2
Measuring system with the main components used in the rheological measurements

The goal of the rheological analysis is to measure the dynamic viscosity curves of the AK 1 000 000 STAB silicone oil with the Anton Paar Physica MCR 302 rotational rheometer at 100 points in the shear rate range of 0 1/s and 1000 1/s; between -40°C and 200°C at 14 different temperatures; at atmospheric pressure; applying a PP25 measuring head geometry (according to the standard protocols, one has to work with a fluid sample amount of 0.5 ml for each measurement).

Main steps of the measurement plan:

I. The first step of the rheological analysis is to determine the accuracy and precision of the measuring instrument with a given measurement gap, and to determine the minimum required number of measurements for a given measurement case (in other words: how many times the viscosity measurement must be repeated at a given temperature and shear rate) on a suitably chosen confidence level.

II. The second step of the rheological analysis is to determine the time required for the entire silicone oil sample placed on the measuring plate to reach the desired target temperature through cooling or heating. The initial viscosity at the prescribed 14 different test temperatures is also recorded.

III. The third step of the rheological analysis is to carry out the dynamic viscosity measurements in the shear rate range of 0 1/s and 1000 1/s at all 14 different temperatures repeated the required number of times.

Details of the measurement steps:

In the first step, constant shear rate tests were repeated 30 times at a shear rate of 0.1 1/s, at 25°C and with a gap size of h = 0.2 mm. This gap size provided the most accurate results for the initial dynamic viscosity of the samples at 25°C according to the product brochure [14]. The absolute value of the deviation of the arithmetic mean of the 30 measured and recorded viscosity values from the exact (catalogue) value gives the accuracy of the measuring instrument (A = 39 Pas). The corrected empirical standard deviation of the measured values from the mean indicates the precision of the measuring instrument (P = 12.65 Pas). If the confidence level is chosen to be 95% (this means that in 95% of the performed measurements the measured result must fall within the accuracy range of the measuring instrument, i.e., within the error limit of the instrument), the confidence factor (k) can be found from the standard normal distribution table for the 95% confidence level (in this case k = 1.96). The minimum required number of measurements (n) is given by Eq. (2) based on the measurement techniques [15].

$$n = \left(k \cdot \frac{P}{A}\right)^2 = \left(1.96 \cdot \frac{12.65\ Pas}{39\ Pas}\right)^2 = 0.404 \tag{2}$$

Rounding up n = 1 is gained, therefore it is theoretically sufficient to measure only once in each measurement case with the high-precision measuring instrument presented at the beginning of the subsection. Regardless of the gained number, each measurement was performed 5 times based on 'one measurement is not a measurement' principle.

In the second step, after different cooling/warming waiting times, constant shear rate measurements were carried out at a shear rate of 0.1 1/s with a gap size of h = 0.2 mm for 5 minutes at each investigated temperature. The viscosity-shear rate diagrams were selected, on which the viscosity of the sample remained almost constant during the 5 minutes of the measurement. During the measurements, the farther the measurement temperature was from 25°C room temperature, more time was needed for all regions of the sample to reach the target temperature and for the initial viscosity value to remain unchanged during the measurement. Finally, 15 minutes is proved to be the necessary minimum waiting time, which ensures that all regions of the sample will take the target temperature in all investigated temperature cases. The initial viscosity values measured at each investigated temperature are listed in Table 1.

In the third step, simple shear tests were performed at all 14 investigated temperatures with a gap size of h = 0.2 mm, with a cooling or heating waiting time of 15 minutes, repeated 5 times, in the shear rate range of 0 1/s and 1000 1/s (logarithmically increasing value distribution in $N = 100$ points) and with a shearing time interval between 10 s and 0.01 s (with a logarithmically decreasing value distribution). In this step, a total of 7000 pieces of measured viscosity data were stored and evaluated. The following quantities were recorded: Elapsed time of measurement [s], Temperature [°C], Dynamic viscosity [Pas], Shear rate [1/s], Shear stress [Pa], Shear strain [%], Torque [Nm], and Normal force [N].

At each investigated temperature, the shear stress and dynamic viscosity values recorded at the same shear rate (measured 5 times) were averaged. Figure 3 depicts the measured points of the rheological curves obtained by averaging the results and present well the non-Newtonian behavior of the analyzed silicone oil.

Table 1
Measured initial dynamic viscosity values of AK 1 000 000 STAB silicone oil

Temperature [°C]	**Dynamic viscosity [Pas] at 0.1 1/s shear rate**	**Temperature [°C]**	**Dynamic viscosity [Pas] at 0.1 1/s shear rate**
-40	5968.995	80	459.890
-20	2842.767	100	377.767
0	1652.900	120	302.737
20	1102.225	140	244.270
25	1005.600	160	203.750
40	786.670	180	178.753
60	590.630	200	131.145

The rheological measurement results clearly reveal the pseudoplastic nature of the silicone oil. The shear stress generated in the fluid increases with the increasing shear rate, but its actual dynamic viscosity decreases (see Figure 3). The measurement results also confirm the fact that silicone oil is a thermorheological simple fluid (fulfils the Time Temperature Superposition rule) since its rheological characteristics behave in the same way at all temperatures, the rheological characteristic curves are only shifted in the vertical direction based on the temperature.

1.5 Commonly Used Viscosity Models for Pseudoplastic Fluids

Based on the literature, eight most used pseudoplastic viscosity models were selected for comparison. These are the Carreau, Carreau-Yasuda, Cross, Johnson, Meter, Münstedt, Powell-Eyring and Power-Law [16]. The formula of each investigated viscosity model is presented by Eqs. (3)-(10) in Table 2. Nonlinear regressions were applied for each model separately, in order to identify the unknown parameters. Table 4 compares the fitting accuracy of each model to the measurement data based on several aspects. A viscosity model is then highlighted by the authors that is found to be the most appropriate for CFD calculation of the visco-damper's filling process based on evaluating aspects.

The formulas of the viscosity models are considered as a fitting function and the averaged measured dynamic viscosity values presented in Figure 3 are used to perform the model parameter identification by applying least squares method based nonlinear quasi-Newtonian regression tracing back the solution into an extremum search in iterative way. The functional minimum is gained by making the partial derivatives of the functional equal to zero.

Table 2
Investigated non-Newtonian viscosity models

Model	Formula	Eq.
Carreau	$\eta(T,\dot{\gamma}) = \eta_\infty(T) + \frac{\eta_0(T) - \eta_\infty(T)}{[1 + (\lambda(T) \cdot \dot{\gamma})^2]^{\frac{1-n(T)}{2}}}$	(3)
Carreau-Yasuda	$\eta(T,\dot{\gamma}) = \eta_\infty(T) + \frac{\eta_0(T) - \eta_\infty(T)}{[1 + (\lambda(T) \cdot \dot{\gamma})^{a(T)}]^{\frac{1-n(T)}{a(T)}}}$	(4)
Cross	$\eta(T,\dot{\gamma}) = \eta_\infty(T) + \frac{\eta_0(T) - \eta_\infty(T)}{1 + (\lambda(T) \cdot \dot{\gamma})^{1-n(T)}}$	(5)
Johnson	$\eta(T,\dot{\gamma}) = \eta_\infty(T) \cdot e^{\left(\frac{1}{\frac{1}{ln\eta_0(T) - ln\eta_\infty(T)} + \lambda(T)\cdot\dot{\gamma}}\right)}$	(6)
Meter	$\eta(T,\dot{\gamma}) = \eta_\infty(T) + \frac{\eta_0(T) - \eta_\infty(T)}{1 + \left(\frac{\dot{\gamma}}{\dot{\gamma}_{1/2}(T)}\right)^{1-n(T)}}$	(7)
Münstedt	$log\eta(T,\dot{\gamma}) = A(T) + B(T) \cdot log\dot{\gamma} + C(T) \cdot (log\dot{\gamma})^2 + D(T) \cdot (log\dot{\gamma})^3 + E(T) \cdot (log\dot{\gamma})^4$	(8)
Powell-Eyring	$\eta(T,\dot{\gamma}) = \eta_\infty(T) + \left(\eta_0(T) - \eta_\infty(T)\right) \cdot \left(\frac{sinh^{-1}(\lambda(T) \cdot \dot{\gamma})}{\lambda(T) \cdot \dot{\gamma}}\right)$	(9)
Power-Law	$\eta(T,\dot{\gamma}) = K(T) \cdot \dot{\gamma}^{n(T)-1}$	(10)

The model parameters $P(T)$ in each viscosity model formula depends on the temperature, thus a model parameter can be approximated by an eight-order polynomial.

The correct value of the parameter coefficients c_i in each polynomial for each viscosity model is gained by polynomial regression. To enhance the convergence during the iteration, the unknown model parameters are set to be only non-negative values. As a result, in case of the Carreau-Yasuda model, the polynomials for the temperature dependent model parameters are shown in the Table 3, which satisfied the sign constraint and provided the least squares deviation in the measured shear rate range.

Based on Table 4, from the highest absolute difference's point of view, the Carreau-Yasuda viscosity model is found to be the most reliable. In terms of highest relative difference, the Cross model works better. Considering the average of relative differences, the Münstedt model provides smaller differences to the measured viscosity values.

It is also important to investigate how does each viscosity model behave above the measured shear rate region (above 1000 1/s). If the calculated viscosity values diverge to infinite or fluctuate, they can cause numerical error during the CFD specific limiters.

Table 3

Identified model parameter polynomials for the selected viscosity model

Model	Polynomials of the temperature-dependent model parameters
Carreau-Yasuda	$\eta_\infty(T) \cong 0$ $\eta_0(T) = 3.55208E\text{-}14 \cdot T^8 - 3.04511E\text{-}11 \cdot T^7 + 1.06686E\text{-}08 \cdot T^6 - 1.98312E\text{-}06 \cdot T^5 + 2.15475E\text{-}04 \cdot T^4 - 1.48606E\text{-}02 \cdot T^3 + 0.77383 \cdot T^2 - 38.54805 \cdot T + 1662.14402$ $\lambda(T) = 2.97570E\text{-}19 \cdot T^8 - 3.44028E\text{-}16 \cdot T^7 + 1.49141E\text{-}13 \cdot T^6 - 3.26433E\text{-}11 \cdot T^5 + 4.06031E\text{-}09 \cdot T^4 - 3.17045E\text{-}07 \cdot T^3 + 1.84093E\text{-}05 \cdot T^2 - 9.51978E\text{-}04 \cdot T + 3.99458E\text{-}02$ $a(T) = 1.20867E\text{-}08 \cdot T^3 - 5.12543E\text{-}06 \cdot T^2 + 7.77623E\text{-}04 \cdot T + 0.84655$ $n(T) = 5.18491E\text{-}06 \cdot T^2 - 1.19737E\text{-}04 \cdot T - 6.35822E\text{-}03$

Because of this fact, Münstedt model is excluded from the selection as the model would result divergence and numerical error at higher shear rates. As far as Cross model is concerned, not only the highest absolute difference but also the average of relative differences is higher compared to Carreau-Yasuda model, thus Carreau-Yasuda viscosity model is selected for the most reliable and accurate viscosity model for the CFD calculations that can be implemented into ANSYS FLUENT environment without limiters in form of a user-defined function.

Figure 3 shows not only the averaged measured dynamic viscosity values (dots) but also the dynamic viscosity curves (lines) calculated by the Carreau-Yasuda model for AK 1 000 000 STAB silicone oil at each measured temperature above the investigated shear rate range.

Table 4

Comparison of the investigated viscosity models based on different aspects

Model	**Highest absolute difference to the measurement**	**Highest relative difference to the measurement**	**Average of relative differences (deviation)**	**Model behavior at higher shear rates (above 1000 1/s)**
Carreau	815.659 Pas	15.702%	4.913% (3.365%)	viscosity monotonically decreases to zero
Carreau-Yasuda	62.483 Pas	10.757%	1.105% (1.381%)	viscosity monotonically decreases to zero
Cross	195.9 Pas	6.399%	1.167% (1.033%)	viscosity monotonically decreases to zero
Johnson	1110.325 Pas	34.207%	4.137% (4.603%)	viscosity converges to a value between 18 and 55 Pas
Meter	125.326 Pas	7%	1.383% (1.101%)	viscosity monotonically decreases to zero

Münstedt	179.377 Pas	7.723%	1.082% (1.079%)	viscosity diverges to ± ∞
Powell-Eyring	357.276 Pas	32.66%	5.436% (5.017%)	viscosity monotonically decreases to zero
Power-Law	2818.624 Pas	88.675%	10.962% (15.928%)	viscosity monotonically decreases to zero

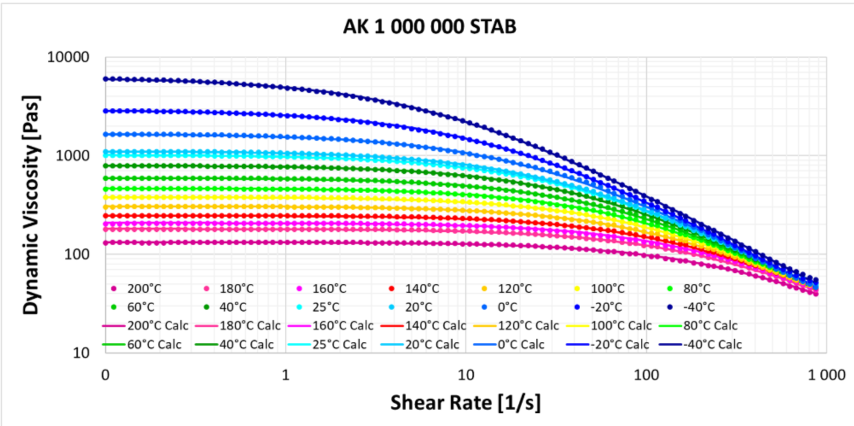

Figure 3

Measured (dots) and Carreau-Yasuda calculated (lines) dynamic viscosity values

3 Computational Fluid Dynamic Analysis of the Filling Process of a Visco-Damper

In design and development phases of TVDs the estimation and calculation of fluid flow, the thermal control of silicone oil, the reduction of filling time and the management of silicone oil's degradation level are important aspects for increasing the lifetime of the product and increasing the revenue. Hence, a simplified, small-sized, narrow damper gap geometry has been used to investigate the filling process at different discharge pressures.

The filling is carried out on a special filling bench, which is capable of creating a near-vacuum condition in the damper gap (around 100 Pa remaining absolute pressure in the gap) as a first step, and then injecting a pre-programmed amount of oil into the damper gap on a constant high pressure as a second step. As the third and last step, the plug is welded into the filling hole. The oil in the visco-damper is allowed to undergo minimal degradation from thermal point of view to provide maximum service life under operating conditions. For this reason, it is necessary to know the maximum oil temperature value recommended by the oil manufacturer, at which the oil still can be used safely under operation.

AK 1 000 000 STAB thermally stabilized silicone oil is used for high-performance visco-dampers manufactured by Wacker Chemie AG which is a German company headquartered in Munich and is the market leader among many manufacturers producing silicone oils. According to the manufacturer's technical data sheet [17], AK 1 000 000 STAB silicone oil can be used at operating temperatures higher than 150°C. According to the Wacker Chemie AG product brochure of the AK series silicone [14], this type of oils shows excellent long-term heat resistance up to 150°C in the presence of air. Above 150°C, however, permanent viscosity change occurs due to the oxidation in the fluid.

Based on the items above, the task is to examine the filling process on the damper gap geometry of a small-sized visco-damper by using a reliable and accurate temperature- and shear rate- dependent viscosity model developed in subsection 2.3 and using a temperature-dependent density model found in the product brochure [14] with specific heat, thermal conductivity and surface tension. The filling process is calculated at four different filling inlet overpressures (10^5 Pa, 5×10^5 Pa, 10×10^5 Pa and 20×10^5 Pa) and the maximum allowed filling inlet temperature of the oil is determined for all pressure cases, so that during the filling process the oil's temperature will not exceed in any point of the fluid the 150°C and the minimal degradation of the oil is ensured.

The authors were intended to perform 'works-case analysis' to gain highest possible oil temperatures from the filling process. Because of this fact, in each investigated filling case the heat transfer on the walls must be considered adiabatic by allowing no cooling effect on the damper housing.

The above-mentioned analyses were completed by CFD calculations based on the finite volume method. 3D, transient, multiphase, coupled flow and thermal simulation model is developed in the ANSYS FLUENT software environment to analyze the filling process of the damper.

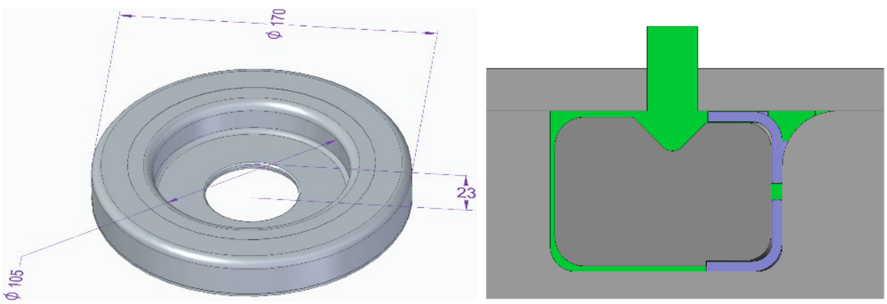

Figure 4

Main dimensions (left) and the cross-section of the investigated visco-damper with the damper gap highlighted (right)

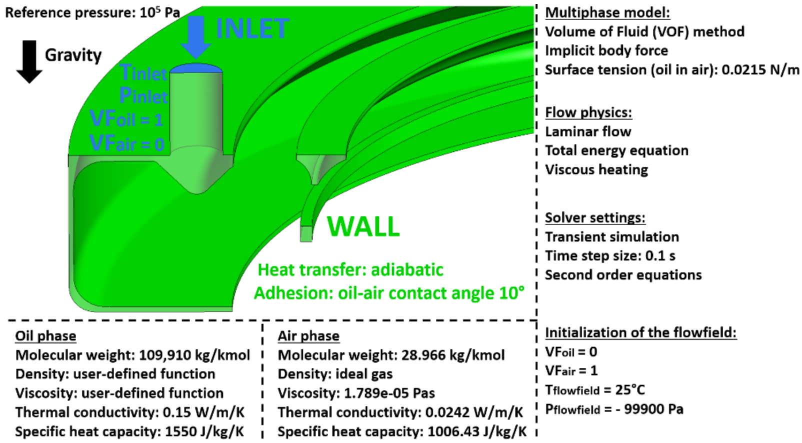

Figure 5

CFD simulation model with main boundary conditions and applied settings

1.6 Geometry and the Boundary Conditions for the Filling Simulation

A small-sized visco-damper has been selected for the CFD analysis that is shown on the left side of Figure 4 with its main dimensions in mm. The silicone oil's flow field (damper gap) is highlighted by green on the right side. The CFD simulation setup of the damper's filling process with the boundary conditions and applied models are depicted in Figure 5. In each case, the filling process is performed as long as 25 g amount of silicone oil is filled into the damper gap domain.

1.7 Numerical Results and Discussion

The main outcomes of the numerical calculations for each investigated filling case are collected in Table 5, and a qualitative result about the test case at 20×10^5 Pa inlet pressure and at 102°C inlet temperature is shown in Figure 7. The highest allowable oil inlet temperature values for each investigated filling case are highlighted by the pressure-case's color in 'Oil inlet temperature' row of Table 5.

There is a temperature increase in the silicone oil during the filling process in each investigated simulation case. The reason behind this temperature development is explained as follows. On the one hand, while the oil is filled into the narrow damper gap on a relative high filling pressure, internal friction occurs among the fluid layers. This mechanical energy is converted into heat and increases the oil's total temperature. On the other hand, as the oil spreads in the gap the volume of the gap-air reduces and its temperature increases (suffers from compression).

Table 5
CFD simulation results of the investigated filling cases

Oil inlet overpressure [Pa]	10^5		5×10^5		10×10^5		20×10^5	
Oil inlet temperature [°C]	25	**119.4**	25	**107.7**	25	**104**	25	**102**
Oil peak temperature [°C]	25.4	150	29.5	150	54.2	150	86.6	150
Maximal oil velocity [m/s]	0.06	0.12	0.29	0.6	0.95	1.65	7.35	9.8
Filled amount of oil [g]	25	25	25	25	25	25	25	25
Filling time required [s]	325	124.9	96.4	41.9	44.2	21.6	23.2	18.4

A part of the additional thermal energy originated from the compression of the gap-air transfers into the silicone oil through the oil-air interfaces.

The filling process is found to be the slowest in case the inlet overpressure is selected for 10^5 Pa and the oil inlet temperature is set to room temperature (25°C). In this case, 325 s is needed to fill 25 g oil into the gap and the silicone oil suffers only 0.4°C total temperature increases during the filling process. If the inlet overpressure is set to 20×10^5 Pa and the filling temperature is set to 102°C, the shortest filling time (18.4 s) can be reached for the same amount of silicone oil to be filled in such a way that the oil's total temperature does not exceed the maximal allowed 150°C value in any point of the oil phase domain (oil's total temperature increase is 48°C) during the filling process.

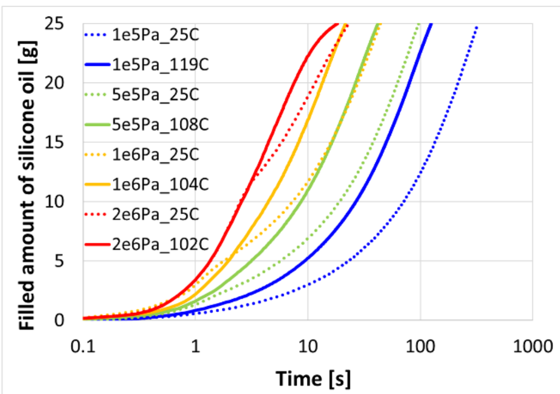

Figure 6
Filling mass characteristics

Figure 6 displays the filled amount of silicone oil's mass increase over time considered as the filling mass characteristics of the visco-damper (related to AK 1 000 000 STAB silicone oil and 25 g target mass). Figure 7 depicts the calculated filling process for 20×10^5 Pa oil inlet overpressure and 102°C oil inlet temperature simulation case in two different timesteps by coloring the oil phase domain according to the oil's total temperature distribution. The t = 3.5 s means the moment when exactly the half of the 25 g amount of oil is entered into the damper gap while t = 18.4 s is the last moment of the filling process when exactly 25 g amount of oil is pushed into the damper gap. As the time passes during the filling process, the pressure difference between the gap-air and the inlet decreases while the high-pressure zone is spreading in the oil and the oil slows down gradually, it is exposed to lesser shear, thus the dynamic viscosity of the oil shows a gradual increase to its maximum (initial) value (in case of 102°C this initial value is close to 380 Pas based on Table 1). At the end of the filling process, the majority of the oil phase domain reaches the minimal velocity (below 0.1 m/s) and its dynamic viscosity is increased back to the initial viscosity value. The oil temperature increase can be observed mainly along the oil-air interfaces (additional heat transferred from the compressed gap-air) and along the walls of the inertia-ring which region is well insulated by the oil cover.

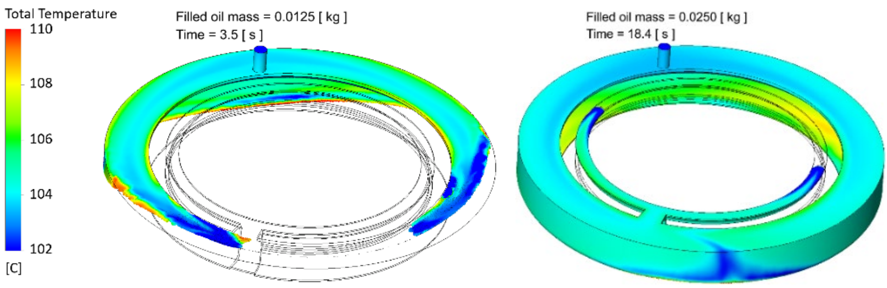

Figure 7
Total temperature distribution in the silicone oil at the inlet total pressure 20×10^5 Pa, at the inlet total temperature 102°C, and at t = 3.5 s (left) and at t = 18.4 s (right)

Conclusions

Dynamic viscosity measurements have been carried out on AK 1 000 000 STAB silicone oil samples, in the form of simple shear tests, using a high-precision rotational rheometer, to quantify the temperature and shear rate dependence of the mentioned silicone oil's non-Newtonian viscous behavior. Eight commonly used pseudoplastic non-Newtonian viscosity model have been selected for model parameter estimation and comparison to develop a reliable, accurate and easy-to-implement viscosity model valid in -40°C to 200°C temperature and 0 1/s to 1000 1/s shear rate ranges, for CFD calculations to analyze the filling process of an existing, small-sized visco-damper under eight different filling conditions. Carreau-Yasuda viscosity model is found to be the most appropriate for describing the viscous behavior of the analyzed high-viscosity silicone oil in CFD simulations.

The outcome of the numerical analysis shows that in case the silicone oil is filled into the damper gap, at highest allowed temperature (instead of 25°C), the filling time can be shortened:

- at 10^5 Pa inlet overpressure by 61.6%
- at $5×10^5$ Pa inlet overpressure by 56.5% (by 87.1% related to 10^5 Pa – 25°C)
- at $10×10^5$ Pa inlet overpressure by 51.1% (by 93.4% related to 10^5 Pa – 25°C)
- at $20×10^5$ Pa inlet overpressure by 20.7% (by 94.3% related to 10^5 Pa – 25°C)

In the above presented cases, the oil's total temperature increase remains under the allowed 150°C and no permanent thermal degradation of the silicone oil occurs. The next step of this work is to introduce filling process calculation method, by neutron radiography measurements, to investigate the impact of different damper assembly configurations (changing the position of bearing gap and the orientation of the inertia-ring) on the filling time, drawing more filling mass characteristics and filling velocity characteristics, for different assembly configurations and to optimize the filling process, for additional filling time reductions, with minimal oil degradation.

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