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TESTING THE CRITICAL VELOCITY OF A MAGNETIC FLUID SEAL WORKING IN A WATER ENVIRONMENT

BADANIA PRĘDKOŚCI KRYTYCZNEJ USZCZELNIENIA Z CIECZĄ MAGNETYCZNĄ PRACUJĄCEGO W ŚRODOWISKU WODY

Key words: ferrofluid, magnetic fluid, magnetic fluids seal, measuring method, critical velocity, ferrofluid properties.

Abstract: Magnetic fluid seals are used in many applications, primarily in gas and vacuum environments. The unique properties of this type of seal are very low torque friction, high tightness, and almost unlimited durability. These parameters are also expected for seals that operate in a water environment. This article presents the results of a magnetic fluid seal's maximum (critical) velocity operating in a water environment. The scope of the investigation included an analysis of parameters such as the pressure of the sealed water and the properties of the magnetic fluid. Two independent parameters, such as the pressure change and the torque change of the seal, were used to determine the leakage. The results showed that the best performance was obtained for the fluid with the lowest dynamic viscosity. In addition, the water pressure had a significant effect. Furthermore, pressure change has been shown to be a better indicator of leakage occurrence at high speeds than measuring torque. The results indicate a different leakage mechanism at low and high pressures.

Słowa kluczowe: ferrociecz, ciecz magnetyczna, uszczelnienia z cieczą magnetyczną, metody pomiarowe, ciśnienie krytyczne, właściwości cieczy magnetycznych.

Streszczenie: Uszczelnienia z cieczą magnetyczną z powodzeniem znalazły zastosowanie w szeregu aplikacji, przede wszystkim w środowisku gazowym i próżni. Unikatowe właściwości tego typu uszczelnień, wśród których można wymienić: bardzo niskie opory ruchu, wysoką szczelność i omal nieograniczoną trwałość są oczekiwanymi parametrami także dla uszczelnień pracujących w środowisku wody. W pracy przedstawiono wyniki badań dopuszczalnej (krytycznej) prędkości uszczelnienia z cieczą magnetyczną pracującego w środowisku wody, przy której następuje jego trwałe uszkodzenie. Zakres badań obejmował analizę wpływu takich parametrów jak ciśnienie uszczelnianej wody oraz właściwości cieczy magnetycznej. Do wyznaczenia przecieku wykorzystano dwa niezależne parametry: zmianę ciśnienia oraz zmianę momentu tarcia uszczelnienia. Wyniki badań wykazały, że najlepsze rezultaty uzyskano w przypadku zastosowania cieczy charakteryzującej się najmniejszą wartością lepkości dynamicznej, a ciśnienie wody ma istotny wpływ. Ponadto wykazano, że pomiar zmiany ciśnienia jest lepszym wskaźnikiem wystąpienia utraty szczelności przy wysokich prędkościach niż pomiar momentu obrotowego. Wyniki wskazują również na odmienny mechanizm przecieku przy niskim i wysokim ciśnieniu.

INTRODUCTION

Magnetic fluids, also known as ferrofluids, are substances consisting of particles with magnetic properties, usually around 10 nm in diameter. They are placed in a carrier fluid with nonmagnetic properties, usually mineral or synthetic oil, and less frequently in water. Additionally, the particles are coated with a surface-active agent to prevent aggregation and sedimentation. Ferrofluids belong to the broader group of smart materials that are magnetic fluids. Another example of magnetically

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active fluids are magnetorheological fluids, whose rheological properties can be altered under the influence of the magnetic field **[L. 1]**. Ferrofluids may be used in loudspeakers **[L. 2]**. There are also efforts to use it in medicine **[L. 3]**. However, seals are one of the main areas of application for this type of substance. They are used in vacuum technology **[L. 4]** or in high-speed equipment **[L. 5]** in both rotary and reciprocating motion **[L. 6]**. Seals of this type are characterised by very low movement resistance, high tightness, and almost unlimited service life. In an air environment, this type of seal can operate for more than ten years without the need for maintenance or regular repairs.

Magnetic fluid seals operating in fluid-water contact still create scientific and engineering challenges, and some aspects of their operation are not yet fully understood. It is known that ferrofluid and water can mix during operation, and the leakage mechanism under such operating conditions is different from that of gas seals. When working in a water environment, there is difficulty in ensuring a long service life, and this problem is particularly evident when operating at high rotational speeds.

Among the main factors affecting the service life of seals in the water one can include the viscosity of the ferrofluid. The lower the viscosity, the longer the seal can operate **[L. 7]**. This can be explained as the result of friction at the interfacial interface in the region where magnetic fluid is gradually removed from the seal gap. Due to the operating conditions, the rotational speed significantly influences the seal operating time. A decreased rotational speed results in an approximately exponential increase in seal durability **[L. 8, 9]**. Water pressure is also important, and an increase can significantly reduce seal life. This leads to the conclusion that for low velocity, the main factor responsible for maintaining seal tightness is the ability of the magnetic fluid to not mix with the sealing medium. So, a high hydrophobicity of ferrofluid is desirable.

Combination seals (hybrid) are often used to increase seal performance, especially when operating in challenging conditions **[L. 10]**. Research in this area has led to the design of seals with an additional shield that reduces the contact area between the magnetic fluid and the sealing medium **[L. 11, 12]**. A six-fold reduction in the contact area between water and ferrofluid resulted in a 40-fold increase in sealing operating time **[L. 13]**. Water, as a substance with a lower density and dynamic viscosity and higher surface tension than ferrofluid, can penetrate the seal as a so-called "wall leak" under pressure. This phenomenon was described in work **[L. 14]**.

The issue of using ferrofluid seals in the water environment is still relevant because, for this type of application, seals with a low friction moment and tightness are also sought **[L. 15]**. This paper focuses on investigating the critical velocity of a magnetic fluid seal working in a water environment with overpressure on the water side. To the present, there are relatively few studies of this parameter. Most research in this area focuses on investigating the durability or leakage mechanism but at constant velocity **[L. 16]**.

In this study, the pressure measurement was used to assess the operating condition of the tested seal at high rotational speeds. An alternative test method was also proposed: the observation of seal torque changes as an indicator of leakage.

THE CRITICAL VELOCITY OF THE SEAL

The basic parameters characterising a magnetic fluid seal include the maximum pressure determined for static conditions, the so-called critical pressure (p_{kr}). In these circumstances, the continuity of the sealing ring formed by the magnetic fluid is lost, and leakage occurs. The value of this static pressure (with some model simplifications **[L. 2]**) can be expressed as a function of the magnetic properties of the ferrofluid and the magnetic field value in the seal gap.

$$p_{kr} = M_s \Delta B_{max-min} \tag{1}$$

where:

Ms – the saturation magnetisation of ferrofluid,

$\Delta B_{max-min}$ – a difference between the maximum and minimum magnetic induction values in the sealing stage region.

Equation (1) indicates that, from the point of view of maximising the critical pressure value, it is advantageous to increase the difference in magnetic induction or to use a fluid with a high saturation magnetisation. Determination of the expected critical pressure value for dynamic conditions (p_{krd}) in the air environment requires consideration of the centrifugal force acting on the ferrofluid:

$$p_{krd} = p_{kr} - \frac{\rho_F v_r h}{D} \tag{2}$$

where:
v_r- linear velocity,
ρ_F- ferrofluid density,
h, D- characteristic seal dimensions such as nominal diameter and seal gap height.

The consideration of the seal velocity is particularly important above 10 m/s. Because up to this velocity, the critical pressure value is approximately constant, while beyond, there is a clear decreasing trend. When $p_{krd} = 0$ Pa, the seal is destroyed by centrifugal forces. Hence, the maximum operating velocity of a magnetic fluid seal (v_{max}) can be determined as follows:

$$v_{max} = \sqrt{\frac{p_{kr} D}{\rho_F h}} \tag{3}$$

The mechanism of failure and loss of the seal tightness of the rotating seal operating in water is not fully understood. There is no clear description of this phenomenon in world literature. Some authors consider the formation of the Kelvin-Helmholtz instability at the water-ferrofluid interfacial boundary as the main mechanism. This phenomenon occurs as a result of the velocity difference between the two fluids (v_{KH}), the value of which, in the case of magnetic fluid seal, can be determined as:

$$v_{KH} > \sqrt{\frac{\rho_F + \rho_w}{\rho_F \rho_w} \left(2\left[g\left(\rho_F - \rho_w\right)\sigma_{W-F}\right]^{\frac{1}{2}}\right)} \tag{4}$$

g – gravitational acceleration,
σ_{W-F} – interfacial surface tension,
ρ_W – water density.

According to this equation, the value of the critical velocity of the two fluids increases as the interfacial tension σ_{W-F} increases and the difference in the fluid density increases.

THE MAGNETIC FLUIDS USED

Four magnetic fluids were selected for the study. Their properties are shown in **Table 1**. Parameters such as (M_s) and (ρ) were obtained from the information received from the manufacturer. The dynamic viscosity (η) and the surface tension value are parameters received from our own research.

The fluids are characterised by different saturation magnetisation values, density, and viscosity. Differences in dynamic viscosity are particularly important, and this parameter affects the durability of seals when operating in a water environment.

The viscosity values are given without a magnetic field and for a magnetic induction of 0.3 T. The value of 0.3 T corresponds to the magnetic saturation conditions of the ferrofluids, so this is the highest viscosity value for each of them. Further magnetic induction increase does not change the viscosity.

The pair of fluids 1 and 2 and fluids 3 and 4 have similar densities. Since their carrier base is synthetic oil, all fluids are characterised by similar surface tension.

In order to evaluate the suitability of each ferrofluid for high-speed operation, the following were determined:

- for static conditions: the value of static critical pressure p_{kr},
- for rotating seal operation in the air: critical velocity parameter v_{max},

Table 1. Physical properties of examined ferrofluids
Tabela 1. Właściwości fizyczne badanych cieczy ferromagnetycznych

Des.	Saturation magnetisation M_s	Density ρ_F	Surface tension σ	Viscosity η (B = 0 T, t = 25°C)	Viscosity η B = 0.3 T, t = 25°C
	kA/m	g/ml	mN/m	Pa·s	Pa·s
FF1	40	1.309	28.1	0.265	0.547
FF2	36	1.345	30.9	0.579	1.23
FF3	44	1.573	29.0	0.675	1.499
FF4	47	1.513	33.0	2.025	3.9

- for seal operation in a water environment: the parameter of the critical velocity difference in the case of Kelvin-Helmholtz instability v_{KH}.

The results are shown in Figure 1. The highest values of v_{max} were obtained for fluid FF1 and the lowest for FF2, but the difference is not greater than 10.9%. Regarding the velocity v_{KH} parameter, the smallest values were obtained for fluids FF1 and FF2, while the highest values were obtained for fluids FF3 and FF4, which is related to their higher density. The highest and lowest velocity difference, in this case, is less than 11.4%.

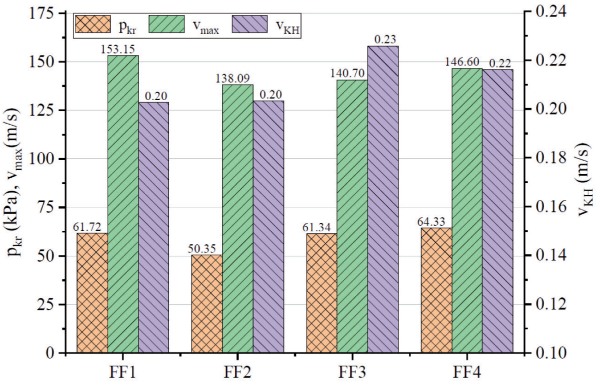


Fig. 1. Values of the seal limiting parameters
Rys. 1. Wartości parametrów granicznych uszczelnienia

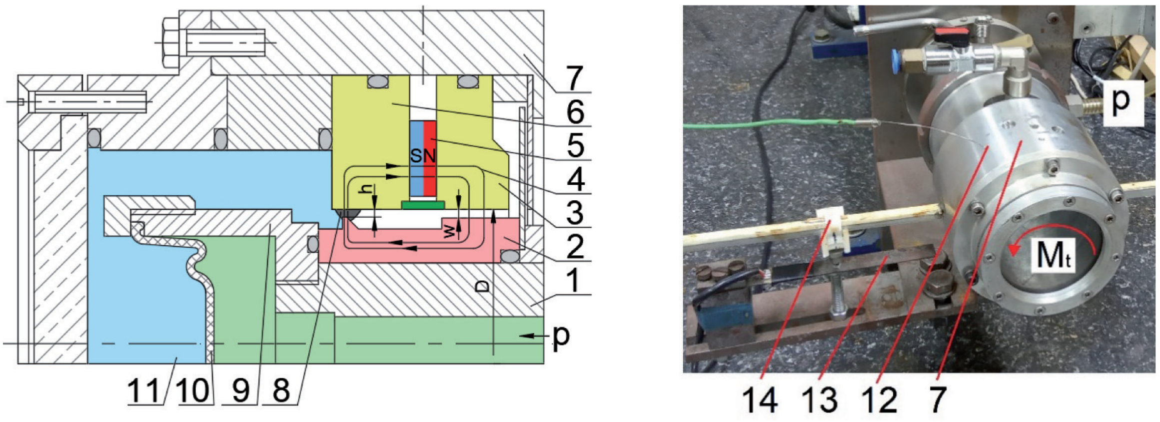
RESEARCH METHOD

The tests were carried out on the test stand, the design of which is described in detail in work **[L. 8]**. A schematic illustration of the test stand is shown in **Fig. 2a**. In the housing (7), there is a permanent magnet (5) combined with two pole pieces (3, 6). Whereas a bush (2) is mounted on a hollow, rotating shaft (1). This creates a closed magnetic circuit (4). Ferrofluid (8) is placed in the region between the stage made in the bush (2) and the pole piece (6). This forms a liquid ring, which is a sealing barrier.

A chamber housing is attached to the housing (7), which is closed by a transparent plate. The space is filled with water (11). At the threaded end of the shaft (1), a rubber membrane (10) and a holder (9) are mounted. The purpose of this is to separate the water from the compressed air supplied by a channel in the shaft.

During the tests, air pressure (p) was measured. The second parameter was the seal torque friction (M_t), the measurement principle of which is shown in **Fig. 2b**. This was achieved using a swivelling housing (7), which is mounted on two ball bearings. As a result of the torque, the housing rotated along the shaft axis, causing the element (14) mounted on the arm to contact the strain gauge beam (13). When a leak occurred, a decrease in the torque was observed, or there were oscillations of change in its value. During the tests, the temperature was measured using a thermocouple (12), which was placed in a hole made in the pole piece (6) and body (7).

The main geometric parameters of the seal are: nominal diameter D = 50 mm, seal gap height h = 0.1 mm, and gap height w = 0.2 mm (**Fig. 2a**). The source of the magnetic field is a neodymium magnet (N38), whose volume was 13.25 cm^3. FEM simulations were used to determine the value of magnetic induction in the seal gap. The maximum value is 2 T, ensuring the magnetic saturation state of the ferrofluid.



a) b)

Fig. 2. The test stand, a) diagram, b) photography of measuring cell
Rys. 2. Stanowisko badawcze, a) schemat, b) fotografia komory

The research plan included a one-stage magnetic fluid seal under constant water pressure and increasing rotational speed. The purpose of the tests was to determine the critical velocity of the seal using two methods; based on pressure changes and based on torque changes. Rotating speed was linearly increased n = 0–5400 rpm, and three pressure values were p = 12.5, 25 or 37.5 kPa.

The pressure value was, therefore, approximately 25 to about 75% of the static critical pressure (depending on the ferrofluid). The change in rotational speed in the mentioned range corresponds to a change in the circumferential velocity of the seal in the range of v = 0–14.1 m/s. The tests were carried out at room temperature (approximately 25°C), and each measurement was repeated at least three times.

RESULTS

Fig. 3 shows a sample test result of pressure changes in the test stand during the test for 12.5, 25 or 37.5 kPa pressure. The critical velocity is the value at which there was a change in the trend of the pressure curve. Depending on the starting pressure, a different trend was observed. At the highest pressure (p = 37.5 kPa), a significant value decline was observed when the critical velocity occurred. At lower pressures (p = 12.5 kPa and 25 kPa), a monotonic pressure increase occurs during the first phase of the test, which then changes to a steady-state value or a slow decline. The increase in pressure is mainly due to the water temperature increase.

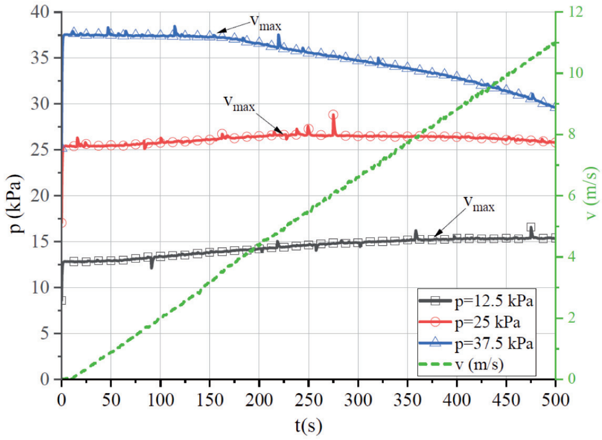


Fig. 3. Sample test results of determining the critical velocity of the seal by measuring pressure changes

Rys. 3. Przykładowe wyniki wyznaczania prędkości krytycznej uszczelnienia poprzez pomiar zmian ciśnienia

The result of a torque measurement sample test for FF3 fluid and three values of pressure is shown in **Fig. 4**. During the initial phase of the test (t = 0–100 s), an increase in torque is observed, and the trend is close to a linear character. Above time t = 100 s, due to the change in the dynamic viscosity of the ferrofluid with increasing temperature, the torque increase rate begins to decrease. Further increase in the rotational velocity leads to a step decrease in the torque value. The rotational speed at which this phenomenon occurs is the critical velocity.

This torque decrease is because the water destroys the ferrofluid sealing barrier, and the water washes out the ferrofluid and mixes with it.

However, it should be noted that variations in the torque trend for pressures of 25 kPa and 37.5 kPa often had the character of oscillatory changes without an evident step change. This probably indicates a different mechanism of seal failure at high and low pressure. It can be assumed that at low pressure, a gradual mixing of the two fluids occurs, and consequently, the viscosity of the fluid mixture is lower. On the other hand, at high pressure, water penetrates the ferrofluid faster without a phase of mixing.

In **Fig. 5**, the critical velocity determined from the measurements of pressure changes is shown. In this case, the pressure increase causes a significant decrease in the critical velocity value.

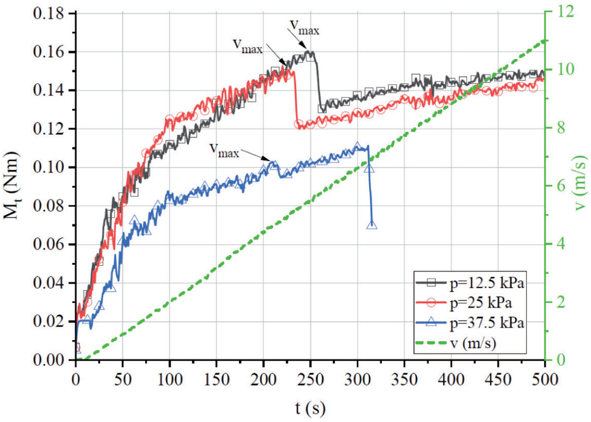


Fig. 4. Sample results of determining the critical velocity of the seal by measuring torque changes

Rys. 4. Przykładowe wyniki pomiaru prędkości krytycznej uszczelnienia poprzez pomiar zmian momentu obrotowego

For pressures p=25 kPa and 37.5 kPa, the highest critical velocity was obtained for fluids with lower dynamic viscosity, which is the expected trend. Comparing the results obtained for the fluids with the lowest viscosity (FF1) and the highest viscosity (FF4), it can be seen that the decrease in critical velocity for pressure 12.5 kPa and 37.5 kPa is: 35 and 12%, respectively.

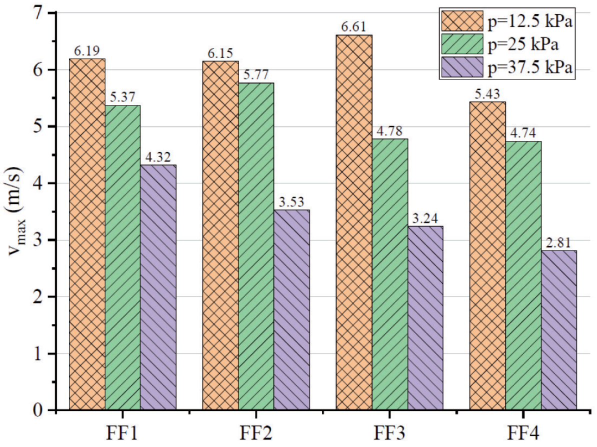


Fig. 5. Critical velocity values obtained from measuring the pressure change in the test cell

Rys. 5. Wartości prędkości krytycznej otrzymanych na podstawie pomiaru zmiany ciśnienia w komorze badawczej

When considering various magnetic fluids, significant differences can be observed in the change in critical velocity due to pressure increase. When comparing the results between p = 12.5 and 37.5 kPa, a 20% decrease in the value is observed for the FF1 fluid; for FF2 and FF3, it is 39 and 32%, respectively, while for FF4, it is 41%. These variations are greater than the proportional differences in the fluid properties; hence, it can be concluded that the pressure mainly influences the value of the critical velocity.

By approximating results with an exponential function, a relationship describing the correlation between the critical velocity, the dynamic viscosity of the magnetic fluid at saturation state (η, Pa·s), and the pressure (p, kPa) was proposed:

$$v_{max}(\eta, p) = (-0.028\eta - 0.08)p + 0.534\eta + 7.224 \tag{5}$$

This equation indicates that the pressure influences the critical velocity more than the dynamic viscosity of the ferrofluid. While increasing each of these parameters reduces the velocity at which the seal can maintain its tightness.

Fig. 6 shows the critical velocity values determined from measurements of torque. In this case, only the pressure 12.5 kPa are similar values compared to those obtained from the measurements of pressure change.

At the same time, for the fluids FF1, FF2, and FF4, the leakage determined by this method occurred at a higher velocity. The critical velocity values are about 2.1 m/s (832 rpm) higher. It is noteworthy that the critical velocity for the other two pressures is significantly lower than that for the pressure change measurement. This probably indicates a small leakage value that could not be measured using the first method. However, it should be emphasised that verifying this hypothesis requires additional research.

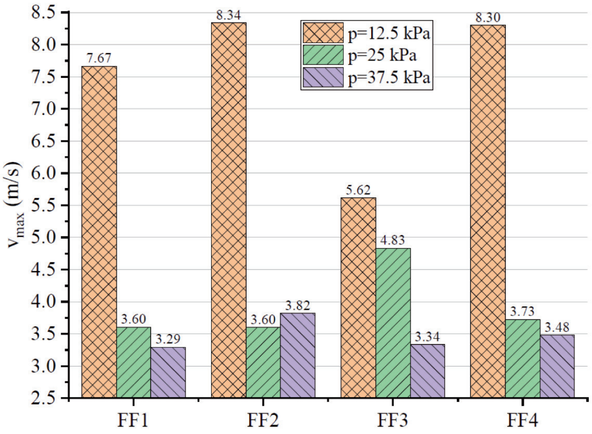


Fig. 6. Critical velocity values obtained from measuring the torque changes

Rys. 6. Wartości prędkości krytycznej otrzymanych na podstawie pomiaru zmiany momentu tarcia uszczelnienia

CONCLUSIONS

The leakage mechanism of a ferrofluid seal operating in a water environment at high speeds is a complex issue to study because of the influence of many parameters. Based on the studies, it can be concluded that:

- Measurements obtained by the pressure change can be considered as the results that allowed us to determine the actual critical velocity value of the seal, and this is because these values indicate permanent seal failure.
- The results from the torque measurement indicate that there may have been a so-called "wall leakage" during the rotational speed increase of the seal.
- The important parameters influencing the critical velocity are the dynamic viscosity and the operating pressure. The smaller the

values of these parameters, the higher the critical velocity. Less important is the value of saturation magnetisation and ferrofluid density. The best results were obtained for the fluids FF1 and FF2, i.e., with a viscosity lower than those of the FF3 and FF4.

- The value of the critical velocity based on calculation in the air environment (v_{max}) and the Kelvin-Helmholtz instability (v_{KH}) did not agree with the results obtained for the parameter (v_{max}) in the case of the seal in a water environment. It indicates that the Kelvin-Helmholtz instability did not significantly influence the results.
- When a leakage occurred, a decrease or oscillation in torque was observed. This phenomenon could be the result of mixing the ferrofluid with water, which causes a change in the effective viscosity.

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