

Thessaloniki, November 12th, 2013

Our Reference Code: **Hydromx02/20072013**

Contract No : ....

Report : **HYDROMX PROPERTIES INVESTIGATION**

Tasks : **1. DENSITY MEASUREMENTS**  
**2. MASS TRANSFER**  
2.1 Viscosity measurements  
**3. HEAT TRANSFER**  
3.1 Conduction - Thermal conductivity  
measurement  
3.2 Convection - Experiment  
**4. CONCLUSION**

Sample : **Hydromx (50% v/v diluted with distilled water)**

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# 1. DENSITY MEASUREMENTS

## 1.1. RESULTS

Technique : The density was measured by filling a glass volumetric flask of known volume (100 mL), and placing it in a temperature controlled bath. Every time a temperature stability was achieved, the extra liquid Hydromx was removed and the remaining 100 mL were weighted very accurately.

Results : The measurements of the density of Hydromx are shown in Table 1.1.

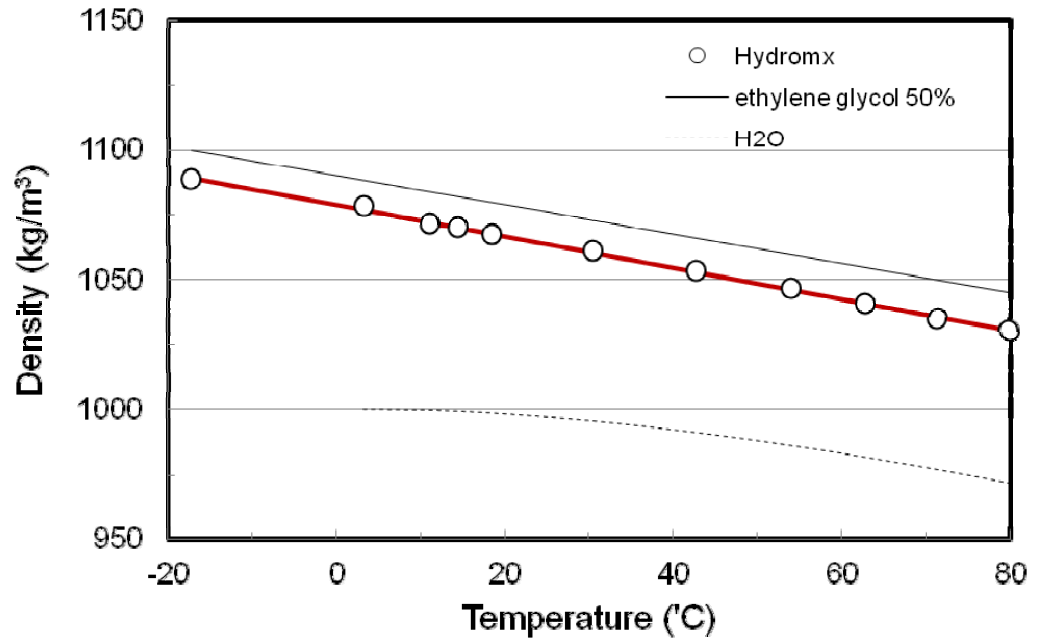
**Table 1.1.** Measurements of the Density as a function of temperature.

Temperature		Density (kg m <sup>-3</sup> )		Deviations (%)
(°C)	(K)	measured	fitted	
-17.30	255.85	1088.5	1089.1	-0.06
3.20	276.35	1078.3	1076.7	0.14
11.00	284.15	1071.3	1072.0	-0.07
14.40	287.55	1070.2	1070.0	0.02
18.40	291.55	1067.4	1067.6	-0.02
30.40	303.55	1061.1	1060.4	0.07
42.60	315.75	1053.4	1053.0	0.04
53.90	327.05	1046.7	1046.2	0.05
62.70	335.85	1040.8	1040.9	-0.01
71.30	344.45	1035.1	1035.7	-0.06
79.80	352.95	1030.5	1030.6	-0.01

The measurements were fitted to the equation

$$\rho = 1243.3 - 0.6027T \quad (1.1)$$

In the above equation,  $\rho$  (kg m<sup>-3</sup>), is the density, and  $T$  (K), is the temperature. In Table 2.1, values calculated by this equation are also shown. The percentage deviations of using this equation are less than 0.2%. In Figure 1.1, the measured densities of Hydromx are shown. For comparison reason, typical literature values for the density of water and ethylene glycol 50%, is also shown.



**Figure 1.1.** Measurements of the density of Hydromx as a function of temperature.

In Table 1.2, recommended values of the density of Hydromx, calculated by Eq.(1.1) are shown. The uncertainty of these values is  $\pm 1\%$ .

**Table 1.2.** Recommended values of the Density as a function of temperature.

Temperature		Density (kg m <sup>-3</sup> )
(°C)	(K)	
-20.0	253.15	1090.7
0.0	273.15	1078.7
20.0	293.15	1066.6
40.0	313.15	1054.6
60.0	333.15	1042.5
80.0	353.15	1030.5

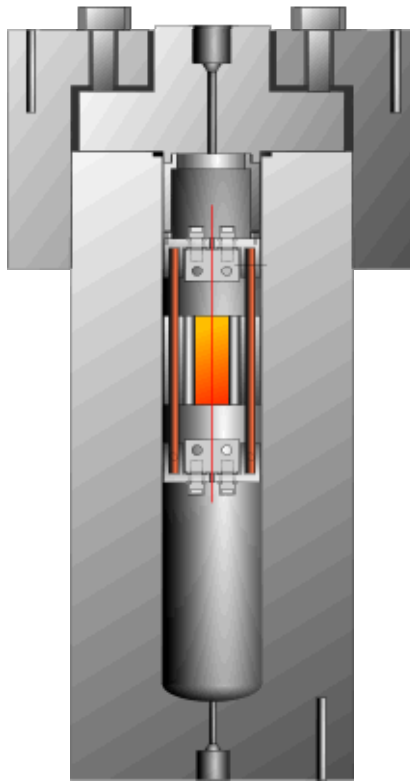
## 2. MASS TRANSFER

### 2.1 Viscosity Measurements

#### 2.1.1. TECHNIQUE EMPLOYED

Technique : Vibrating-Wire Viscometer, employing a 150- $\mu\text{m}$  diameter tungsten wire. The method is characterized by high precision, the availability of a full theoretical background in interpreting the results, and an uncertainty of better than  $\pm 1\%$ .

Instrument :



The tungsten wire, stretched between two stainless steel supports held apart by two tungsten rods, is placed in a 1 T homogeneous field provided by two samarium-cobalt magnets placed in a magnetic steel shell. The wire motion is excited by the application of two pulses of opposite sign to the wire, inducing a symmetric oscillation. Thus, the wire performs a damped oscillating motion in the liquid.

The emf produced by the oscillatory motion of the wire in the magnetic field, about 300  $\mu\text{V}$ , is amplified about 28,000 times to approach the level of 5 - 10 V that is easily detectable by the A/D converter. The frequency of sampling is 50 kHz, with a resolution of 12 bits.

The viscosity of the liquid is obtained from the fitting of the decay of the transverse vibrations, which conform to a damped sinusoidal oscillation, as a function of the logarithmic decrement and frequency of oscillation in the gas and the corresponding logarithmic decrement in vacuum. For every oscillation 3,000 points are obtained.

The viscometer is placed in a pressure vessel made of stainless steel and held just over the atmospheric pressure, to ensure that no evaporation takes place. The pressure vessel is consequently placed in an ethylene glycol bath, externally regulated by a Julabo PID F81-MV circulator. In this way, the temperature in the bath is very stable and the temperature gradients are kept within a tolerable level.

- The temperature is measured by two platinum resistance thermometers embedded along the pressure vessel wall, calibrated vs. a Tinsley Class 1 NPL thermometer, to an uncertainty of better than  $\pm 20$  mK.
- The pressure in the vessel, is measured with a Druck PTX 520 pressure transducer with an uncertainty of  $\pm 0.005$  MPa.

To ensure the continuing good operation of the instrument 1-MNP was measured before and after the Hydromx measurements, in 2 different temperatures. The viscosity of 1-MNP is known<sup>1</sup>.

## 2.1.2. RESULTS

In Table 2.1, the actual measurements of the viscosity of Hydromx as a function of the temperature are shown. Some temperatures are taken twice to ensure repeatability. Densities employed were obtained from the equation developed in Section 2.

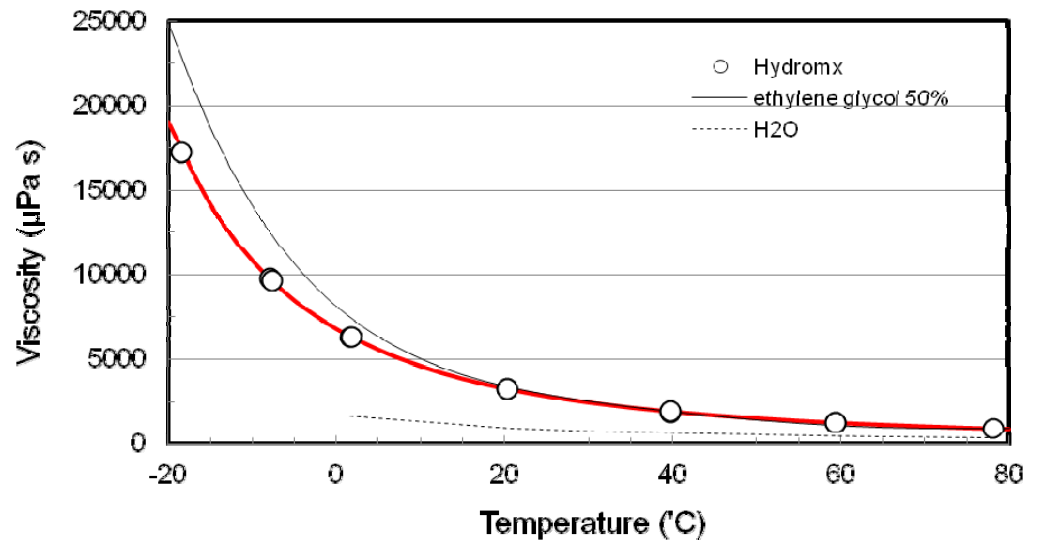
**Table 2.1.** Measurements of the Viscosity as a function of temperature.

Temperature		Density (kg m <sup>-3</sup> )	Viscosity (μPa s)		Deviation s (%)
('C)	(K)		measured	fitted	
-18.52	254.63	1089.8	17250.2	17357.3	-0.62
-7.91	265.24	1083.4	9752.5	9728.7	0.24
-7.71	265.44	1083.3	9669.6	9633.6	0.37
1.57	274.72	1077.7	6320.4	6358.0	-0.59
1.75	274.90	1077.6	6307.0	6311.2	-0.07
20.22	293.37	1066.5	3303.7	3291.4	0.37
20.25	293.40	1066.5	3284.6	3287.8	-0.10
39.71	312.86	1054.7	1958.9	1966.8	-0.40
39.71	312.86	1054.7	1969.1	1966.8	0.12
59.27	332.42	1043.0	1316.5	1320.3	-0.28
59.25	332.40	1043.0	1326.5	1320.9	0.42
78.12	351.27	1031.6	969.2	971.9	-0.28

The measurements were fitted to the equation

$$\eta = 60.4 \exp\left(\frac{527.26}{T-161.49}\right). \quad (2.1)$$

In the above equation,  $\eta$  (μPa s), is the viscosity, and  $T$  (K), is the temperature. In Table 2.1, values calculated by this equation are also shown. The percentage deviations of using this equation are less than 0.7%. In Figure 2.1, the measured viscosities of Hydromx are shown. For comparison reason, typical literature values for the viscosity of water and ethylene glycol 50%, is also shown.



**Figure 2.1.** Measurements of the viscosity of Hydromx as a function of temperature.

In Table 2.2, recommended values of the viscosity of Hydromx, calculated by Eq.(2.1) are shown. The uncertainty of these values is  $\pm 1\%$ .

**Table 2.2.** Recommended values of the Viscosity as a function of temperature.

Temperature		Viscosity ( $\mu\text{Pa s}$ )
( $^{\circ}\text{C}$ )	(K)	
-20.0	253.15	19018.5
0.0	273.15	6787.9
20.0	293.15	3313.1
40.0	313.15	1953.8
60.0	333.15	1303.1
80.0	353.15	945.8

### 3. HEAT TRANSFER

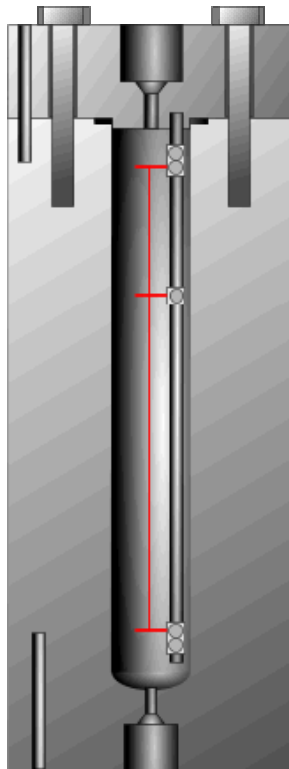
Heat transfer is characterized by two types of transfer, conduction and convection (radiation is negligible in this case). Conduction is characterized by the thermal conductivity and hence this property is measured in Section 3.1. To investigate convection a simple experiment is carried out in Section 3.2, as proper investigation would require a full type of heat-exchanger experiment.

## 3.1 Conduction – Thermal Conductivity Measurements

### 3.1.1. TECHNIQUE EMPLOYED

Technique : Transient Hot-Wire, employing two anodized 25- $\mu\text{m}$  diameter tantalum wires. The method is characterized by high precision, the availability of a full theoretical background in interpreting the results, and an uncertainty of better than  $\pm 1\%$ .

Instrument :



According to the Transient Hot-Wire technique, the thermal conductivity of the fluid is determined by observing the rate at which the temperature of a very thin metallic wire increases with time after a step change in voltage has been applied to it, thus creating in the fluid a line source of essentially constant heat flux per unit length. This has the effect of producing throughout the fluid a temperature field which increases with time. The temperature increase at the metallic wire itself is described by the solution of the Fourier equation.

In an actual instrument (see left), the cell employs two 25  $\mu\text{m}$ -diameter tantalum-wire heat sources, differing only in length. All electrical connections are also made out of thick tantalum wire. The resistance change of the tantalum wires as a function of time is observed by the use of a fully-automated Wheatstone-type bridge coupled to a micro-computer. This arrangement allows sampling of temperature rise vs time sets in a time scale from 20 microseconds to seconds.

A full FEM analysis for the exact geometry employed, produces the value of the thermal conductivity of the fluid.

The transient hot-wire is placed in a pressure vessel made of stainless steel and held just over the atmospheric pressure, to ensure that no evaporation takes place. The pressure vessel is consequently placed in an ethylene glycol bath, externally regulated by a Julabo PID F81-MV circulator. In this way, the temperature in the bath is very stable and the temperature gradients are kept within a tolerable level.

- The temperature is measured by two platinum resistance thermometers embedded along the pressure vessel wall, calibrated vs. a Tinsley Class 1 NPL thermometer, to an uncertainty of better than  $\pm 20$  mK.

- The pressure in the vessel, is measured with a Druck PTX 520 pressure transducer with an uncertainty of  $\pm 0.005$  MPa.

To ensure the continuing good operation of the instrument water was measured before and after the Hydromx measurements, in 2 different temperatures. The thermal conductivity of water is known to a very low uncertainty.

The precision is 0.1%, while the absolute uncertainty is about 1%.

For further information, please see published literature on the instrument<sup>2</sup>.

### 3.1.2. RESULTS

In Table 3.1, the actual measurements of the thermal conductivity of Hydromx as a function of the temperature are shown. Some temperatures are taken twice to ensure repeatability.

**Table 3.1.** Measurements of the Thermal Conduvctivity as a function of temperature.

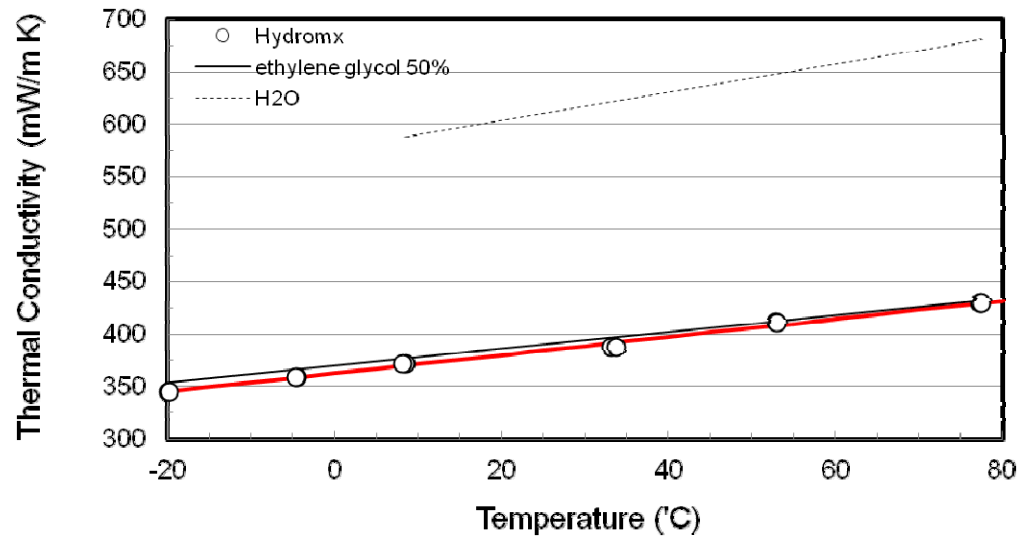
Temperature		Thermal Conductivity ( $\text{mW m}^{-1}\text{K}^{-1}$ )		Deviations (%)
(°C)	(K)	measured	fitted	
-19.92	253.23	345.0	344.9	0.04
-19.80	253.35	345.1	345.0	0.04
-4.52	268.63	358.2	358.3	-0.03
-4.61	268.54	358.7	358.2	0.14
8.63	281.78	371.1	369.8	0.37
8.20	281.35	371.4	369.4	0.53
33.25	306.40	387.0	391.3	-1.09
33.85	307.00	387.4	391.8	-1.12
52.91	326.06	412.1	408.4	0.90
53.12	326.27	411.2	408.6	0.64
77.50	350.65	429.8	429.9	-0.02
77.62	350.77	429.8	430.0	-0.03

The measurements were fitted to the equation

$$\lambda = 123.93 + 0.8725 T . \quad (3.1)$$

In the above equation,  $\lambda$  ( $\text{mW m}^{-1}\text{K}^{-1}$ ), is the thermal conductivity, and  $T$  (K), is the temperature. In Table 3.1, values calculated by this equation are also shown. The percentage deviations of using this equation are less than 1.1%. In Figure 3.1, the measured thermal conductivities of Hydromx are shown. For comparison reason, our previously<sup>3</sup> measured values of the thermal conductivity of water and ethylene glycol 50%, are also shown.





**Figure 3.1.** Measurements of the thermal conductivity of Hydromx as a function of temperature.

In Table 3.2, recommended values of the thermal conductivity of Hydromx, calculated by Eq.(3.1) are shown. The uncertainty of these values is  $\pm 2\%$ .

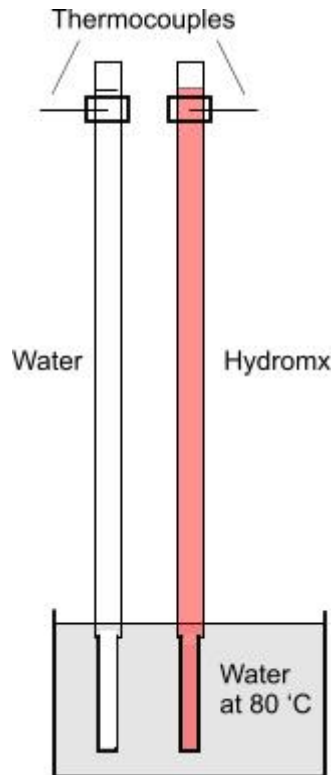
**Table 3.2.** Recommended values of the Thermal Conductivity as a function of temperature.

Temperature (°C)	Temperature (K)	Thermal Conductivity (mW m <sup>-1</sup> K <sup>-1</sup> )
-20.0	253.15	344.8
0.0	273.15	362.3
20.0	293.15	379.7
40.0	313.15	397.2
60.0	333.15	414.6
80.0	353.15	432.1

## 3.2 Convection - Experiment

### 3.2.1. EXPERIMENT EMPLOYED

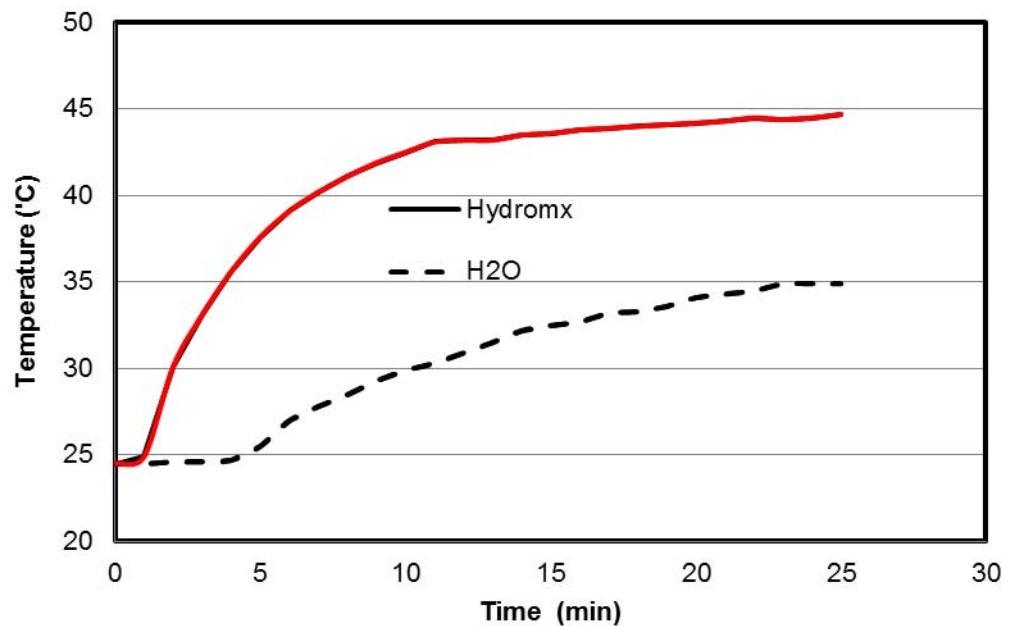
Instrument :



Two identical transparent plastic tubes, 1 cm diameter and about 1 m length, were employed. In the bottom of each tube a copper tube was attached to enhance heat transfer. At each top end of the plastic tube, a thermocouple was attached to record the temperature.

One tube was filled with water and the other with Hydromx, and both tubes were simultaneously placed in a vessel of water at 80 °C. The temperatures recorded in each tube are shown as a function of time in Figure 3.2.

Since in both cases the fluid is equally heated from the bottom, the temperatures recorded at the top thermocouples are characteristic of the heat transferred mainly by convection.



**Figure 3.1.** Temperature measurement at the top of each plastic tube, as a function of time.

## 4. CONCLUSIONS

### a) Temperature range higher than 0°C - Comparison with water

Hydromx is about 8% heavier than water (Figure 1.1) and more viscous than water (Figure 2.1). Its thermal conductivity is also just over half of that of water (Figure 3.1).

However, in the simple convective experiment, its heat transfer is considerably higher, resulting in an almost double temperature difference. This can only be explained by the special composition of Hydromx and the enhancement of the heat transfer attributed to the nanoparticles in Hydromx.

Heating from below produces convective currents which in turn result in additional heat transfer mechanisms attributed to the movement of the nanoparticles, and consequently the total heat flux transferred is increased regardless of its lower thermal conductivity.

Thus, Hydromx is expected to carry heat much better in real applications than water, because of this convective mechanism.

It is also expected that this nanoparticle-enhancement will be increased in the presence of flow.

### b) Temperature range lower than 0°C - Comparison with ethylene glycol+water 50%

Hydromx is about 2% lighter than ethylene glycol+water (Figure 1.1) and considerably less viscous than ethylene glycol+water 50%(Figure 2.1) – almost 70% less viscous at -20 °C. Its thermal conductivity is very similar to ethylene glycol+water 50% (Figure 3.1).

Furthermore, at these low temperatures the effect of nanoparticles in heat transfer is expected to be much lower.

Thus, Hydromx is expected to carry heat better in real applications than ethylene glycol+water, because it is less viscous (either because of its special composition or because of the presence of nanoparticles).

### c) Sedimentation of nanoparticles in Hydromx

It is worthwhile pointing out also, that the nanoparticles in Hydromx are exceptionally stable. Over the four months that we tested Hydromx, there was no sedimentation and the suspension remained homogeneous.

Finally, it would be useful in the future to measure the heat capacity of Hydromx, although it might be difficult to find appropriate method because of the presence of nanoparticles.

## 5. REFERENCES

1. Assael M.J., and Mylona S.K, "A Novel Vibrating-Wire Instrument for the Measurement of the Viscosity of High-Viscosity Fluids", *J. Chem. Engin. Data* **58**:993-1000 (2013)
2. Assael M.J., Chen C.-F., Metaxa I., and Wakeham W.A., "Thermal Conductivity of Suspensions of Carbon Nanotube in Water", *Int. J. Thermophys.* **25**:971-985 (2004).
3. Assael M.J., Charitidou E., Avgoustiniatos S., and Wakeham W.A., "Absolute Measurements of the Thermal Conductivity of Mixtures of Alkene-Glycols with Water", *Int. J. Thermophys.* **10**:1127-1140 (1989)



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