Thermal Conductivity Measurement

Application Note for the SLF3C-1300F Liquid Flow Sensor

Summary

This application note describes how to use the SLF3C-1300F liquid flow sensor to measure the thermal conductivity of the liquid inside the flow channel. This measurement can for example be used to qualitatively identify which medium (out of a selection) is present inside the sensor or to quantitatively determine the concentration of a binary mixture of liquids.

Contents

1 Introduction

1.1 Thermal Conductivity Measurement

The Sensirion liquid flow sensors SLF3C-1300F can be operated in a special mode to measure the thermal conductivity of the liquid (or more general: the medium) inside the sensor.

At zero flow, the thermal conductivity of the medium determines the heat transport away from the sensor's microheater. A higher thermal conductivity leads to a stronger cooling and hence to a lower heater temperature. This is illustrated in Figure 1 below.

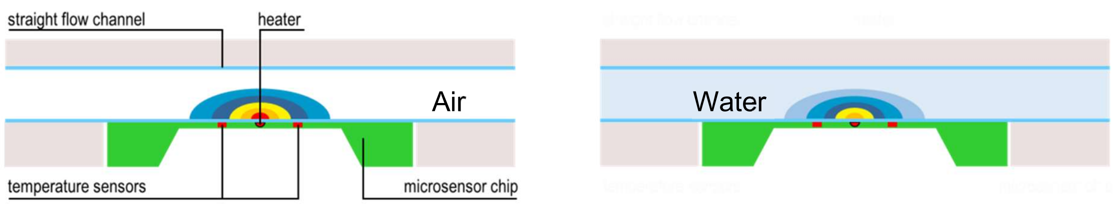


Figure 1: Thermal conductivity measurement at zero flow. Left: Air has a low thermal conductivity, leading to a higher heater temperature. Right: Water has a high thermal conductivity, leading to a lower heater temperature.

The SLF3C-1300F sensors provide the result of the thermal conductivity measurement in arbitrary units, which are scaled such that the output for air is 100 and the output for water is 10'000. These arbitrary units can be used as an approximate measure for the thermal conductivity of the medium. For reference, the thermal conductivity of some common liquids as well as air are listed in Table 1 below.

Medium	Thermal conductivity (W/m K)	Sensor output (arbitrary units)
Water	0.607	10'000
Glycerol	0.292	↓
Ethanol	0.169	
Isopropyl alcohol	0.135	
Diesel fuel	0.13	
Air	0.026	100

Table 1: Thermal conductivity of selected media (all at 25°C, 1 bar abs.)

The following two sections describe two possible applications of the thermal conductivity measurement.

1.2 Use Case 1: Media Recognition

Complex fluidic systems increase the risks for errors during service intervals and thus even highly trained technical personnel can potentially mix up connections between fluidic lines or replenish reagent reservoirs in the wrong order. A thermal conductivity measurement in the fluid line allows the instrument to check that the correct liquid has been connected to the respective line and to raise an alarm if a liquid with unexpected thermal conductivity is detected.

1.3 Use Case 2: Concentration Measurement

Many liquids are binary mixtures of two main components. Examples include:

- Milk (milk fat in water)
- Engine coolant (antifreeze in water)
- Diesel exhaust fluid (urea in water)

The concentration of a test liquid can be determined if the thermal conductivity (in arbitrary units) is measured and the calibration curve from arbitrary units to concentration is known. For a given combination of two constituents, the calibration curve can readily be obtained by measuring the sensor output (in arbitrary units) for a handful of samples with known concentrations of the mixture.

1.4 Temperature Compensation

The thermal conductivity of every liquid changes with its temperature. If the measurement is not always done at the same temperature, this effect needs to be considered. As the temperature dependency of every liquid is different (see Fig. 2) it is not possible to offer a universal temperature compensation. This must be done by the customer by using the temperature-output of the sensor.

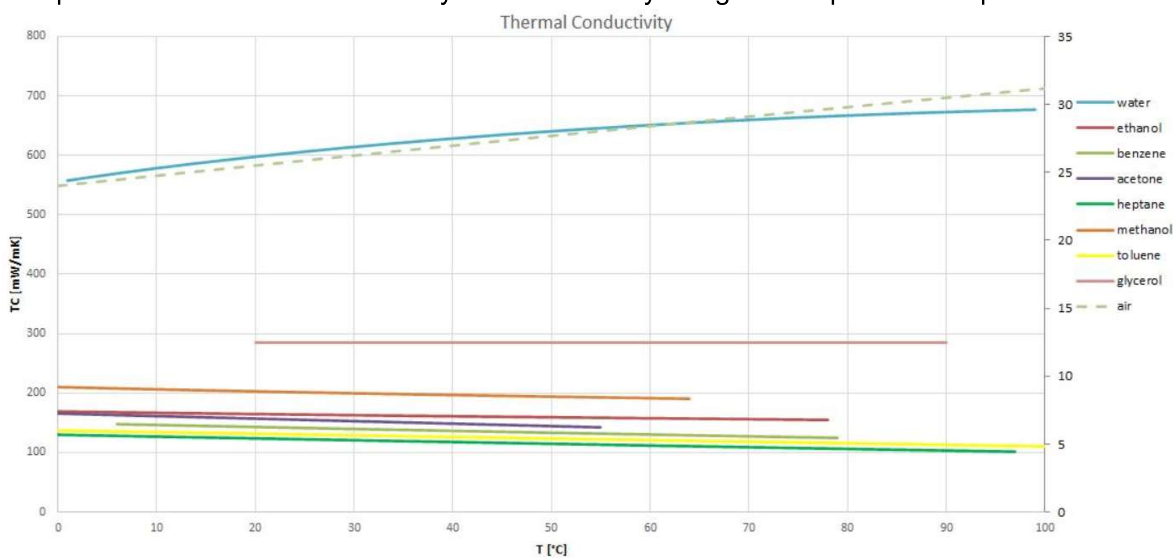


Figure 2: Behavior of thermal conductivity with respect to the temperature of different liquids.

A correction factor that is a good starting point for oil in water mixtures (single digit percentage of oil in water) is $TC_{compensated} = TC_{raw} / (1+1.35e\text{-}3*(T-25°C))$

2 Measurement Sequence

For a precise thermal conductivity measurement using the SLF3C-1300F sensor, the following recipe should be followed:

Priming

1. Completely fill the sensor with the liquid to be measured
   ⇨ If several different liquids shall be measured one after each other, flush thoroughly with the new liquid to avoid carry-over of the previous liquids to consecutive measurements.
2. Completely halt the flow (stop the pump, close the valve)

Zero-flow confirmation

For a precise thermal conductivity measurement, it is necessary that the medium is standing still inside the sensor. This can be verified by measuring the flow rate and confirming that there is no flow. As is pointed out in the SLF3x sensor datasheets, after starting the measurement it takes a short time before the flow measurement reaches the best accuracy. Therefore, the first measurement should be discarded.

3. Start the flow measurement (start continuous measurement, I^{2}C command 0x3608; see the SLF3x sensor datasheets for details)
4. Wait 100 milliseconds
5. Read out the first flow measurement and discard it (send I^{2}C read header; see the SLF3x sensor datasheets
   for details)
6. Wait 100 milliseconds.
7. Read out the flow measurement again (send I^{2}C read header; see the SLF3x sensor datasheets for details.)
   ⇨ Only proceed if the flow rate is zero (within the experimental uncertainty, see the SLF3x sensor datasheets for details on the sensors' offset). Otherwise, repeat steps 6 and 7 to continue reading the flow rate every 100 milliseconds until the flow has come to a full stop.
8. Stop the flow measurement (stop continuous measurement, I^{2}C command 0x3FF9; see the SLF3x sensor datasheets for details.)
9. Wait 0.5 milliseconds for the flow measurement to terminate.

Thermal conductivity measurement

The thermal conductivity measurement itself is triggered by a single command, after which the result can be read out exactly once. If another thermal conductivity measurement shall be performed, the concentration measurement command needs to be sent again.

10. Trigger the concentration measurement (I^{2}C command 0x3646; see section 4 below)
11. Wait 2.3 seconds for the measurement to complete

12. Read out the thermal conductivity measurement result as well as the temperature and the delta-temperature signals (send I²C read header; see section 4 below)
    ⇨ Check that the delta-temperature signal (see section 4.3 below) is low (below ±0.02 °C). If there is a larger delta-temperature, this is a sign that the liquid temperature and the sensor temperature have not yet reached the equilibrium. In this case, repeat the concentration measurement from step 10. Otherwise use the measurement result depending on the application, for example as described in the next section.

3 Output Interpretation

3.1 Media Recognition

The thermal conductivity measurement may be used to distinguish and identify different liquids, provided that they have different thermal conductivity values.

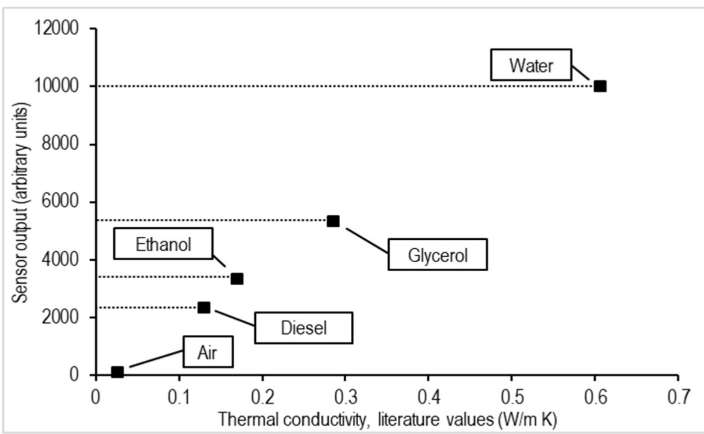


Figure 3: Thermal conductivity for selected fluids. Sensor output in arbitrary units and literature values in W/m K.

As can be seen from Figure 3 above, different liquids such as e.g. Ethanol, Glycerol or Water can clearly be qualitatively distinguished – and hence identified – based on the sensor's thermal conductivity measurement.

3.2 Concentration Measurement

In binary mixtures of two constituents with different thermal conductivity, the concentration of the two components can be quantitatively determined by measuring the thermal conductivity of the mixture.

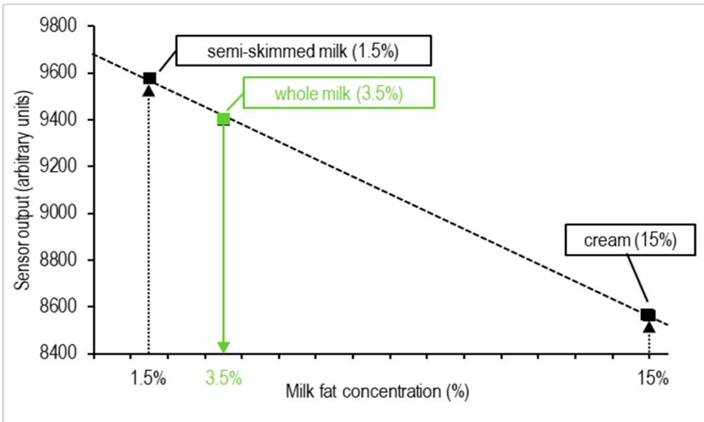


Figure 4: Sensor output vs. milk fat concentration. The dashed black line determined by measuring two anchor points (1.5% semi-skimmed milk and 15% cream, black squares) can be used to determine the fat concentration of other types of milk, e.g. 3.5% whole milk (green square).

For such a quantitative measurement, first the calibration curve for the mixture needs to be determined. In the present example, two corner points are used to establish the calibration curve (dashed line): 1.5% semi-skimmed milk and 15% cream (black squares). Using this calibration curve, the concentration of milk with an intermediate fat concentration can be determined. In this example, we measure 3.5% whole milk and effectively obtain a 3.5% fat concentration (green square).

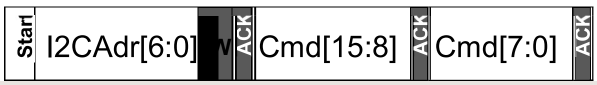
4 Digital Interface Description

The sensor's digital interface is compatible with the I²C protocol. This chapter describes the extended command set which is needed to run the thermal conductivity measurement. For general information on the SLF3x liquid flow sensors and basic commands, see the sensors' datasheets on www.sensirion.com/slf3x.

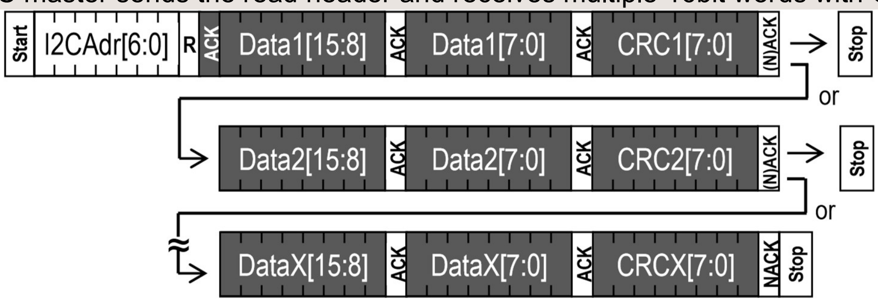
4.1 I²C Sequence

The commands are 16 bits long. Data is read from the sensor in multiples of 16-bit words, each followed by an 8-bit checksum to ensure communication reliability.

I²C master sends the write header and writes a 16 bit command



I²C master sends the read header and receives multiple 16bit words with CRC byte.



Dark areas with white text indicate that the sensor controls the SDA (Data) line.

The I²C read sequences can be aborted with a NACK and STOP condition.

4.2 I²C Command

The thermal conductivity measurement itself is triggered by a single, specific I²C command. The remaining commands needed for the entire measurement sequence are described in the sensors' datasheets.

4.3 Perform Thermal Conductivity Measurement

The sensor measures the thermal conductivity, the sensor temperature and the delta-temperature (a measure for the temperature difference between the liquid and the sensor). All three signals can be read simultaneously.

Command	Command code (Hex)	Description
Trigger single thermal conductivity measurement	0x3646	This command starts the thermal conductivity measurement. The measurement takes approx. 2.3 seconds. After completion, the heater is switched off and the sensor enters idle mode.

Table 2: I²C command to perform the thermal conductivity measurement

After the command has been sent, the sensor performs one thermal conductivity measurement. The measurement takes approximately 2.3 seconds. When the measurement finishes, the sensor's heater is automatically switched off, the sensor enters idle mode, and the result can be read out anytime by sending a single I²C read header.

If the result is requested while no measurement data is available yet, the sensor will respond with a NACK to the I^2C read header (I^2C address + read bit).

Preceding command	Consecutive read	Description
Trigger single thermal conductivity measurement	Byte1: Thermal Conductivity 8msb Byte2: Thermal Conductivity 8lsb Byte3: CRC Byte4: Temperature 8msb Byte5: Temperature 8lsb Byte6: CRC Byte7: Delta-Temperature 8msb Byte8: Delta-Temperature 8lsb Byte9: CRC	After the thermal conductivity measurement is finished, the measurement results can be read out. The temperature and the delta temperature signals don’t need to be read out (every time). The read sequence can be aborted by a NACK and a STOP condition.

Table 3: Read out of thermal conductivity measurement and auxiliary data

4.4 Conversion to Physical Values

The sensor output is converted to physical values using the following scale factors.

4.5 Scale Factors

Parameter	SLF3x
Thermal conductivity	1 (arbitrary units)
Temperature	200 $(°C)^{-1}$
Delta-temperature	1000 $(°C)^{-1}$

Table 4: Scale factors

4.6 Thermal Conductivity

The thermal conductivity signal read from the sensor is a 16-bit signed integer number (two’s complement number ranging from -32768 … 32767). The value is provided in arbitrary units such that the signal is 100 for air and 10’000 for water. Use this signal to identify the medium which is inside the sensor or to determine the concentration of a binary mixture.

4.7 Temperature

The digital calibrated temperature signal read from the sensor is a 16-bit signed integer number (two's complement number ranging from -32768 … 32767). The integer value can be converted to the physical value by dividing it by the scale factor (temperature in °C = sensor output ÷ scale factor).

4.8 Delta-Temperature

The difference temperature between the sensor chip and the liquid inside the sensor is read from the sensor as a 16 bit signed integer number (two's complement number ranging from -32768 … 32767). The integer value can be converted to the physical value by dividing it by the scale factor (delta-temperature in °C = sensor output ÷ scale factor).

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