Correlating Traditional Transient Plane Source Thermal Conductivity Testing Results in Monitoring the Fat Content of Milk with Modified Transient Plane Source Technique Results

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ABSTRACT

The thermal conductivity measurement in the food industry provides insight into the heat transfer properties of foods – important in the design of processing and preservation equipment. In the processing of dairy products the material is heated and cooled. In order to understand accurately the rate and amount of heat involved it is necessary to value the thermal properties of the material. The thermal conductivity of the material is impacted by a number of factors including the density, particle size, composition, etc. The application of thermal conductivity data contributes to refinements in food processing techniques, equipment and optimization of processing conditions, resulting in improved quality and safety of foods. This study applies the modified transient plane source technique to measure the thermal conductivity of milk products, in an effort to confirm the validity of this technique to distinguish between the fat content of different milk products.

The thermal conductivity of milk products with fat contents of 0%, 1%, 2% and 3.25 % were tested using C-Therm's TCi Thermal Conductivity Analyzer employing the modified transient plane source (MTPS) technique for thermal conductivity measurement and the results compared with previously published data by M. Gustaffson and S. Gustaffson . The data confirms a strong linear correlation between thermal conductivity and fat content and correlates well with results previously published in measuring similar milk samples with the traditional transient plane source (TPS) technique.

INTRODUCTION

The purpose of this investigation is to apply a novel transient plane technique to measure the thermal conductivity of milk products, in an effort to confirm the validity of this technique to distinguish between the fat content of different products. The thermal conductivity of milk products with fat contents of 0%, 1%, 2% and 3.25 % (as provided by the manufacturer) were tested using C-Therm's TCi Thermal Conductivity Analyzer, which employs the patented modified transient plane source (MTPS) technique. The MTPS technique offers an innovative solution by providing a rapid, non-destructive test method that requires no advanced training requirements to operate and can be incorporated directly in different production environments as it is used in monitoring liquids and powders within the pharmaceutical industry for real-time

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process control. The MTPS technique represents a significant advancement and simplification in the measurement of thermal conductivity with the flexibility of rapidly testing solids, liquids, powders and pastes with the same sensor.

TEST METHOD

The C-Therm TCi™ Thermal Conductivity Analyzer pictured in Figure 1 is comprised of an external sensor, controller electronics configured to handle up to two sensors and thermal analysis software installed on a standard laptop PC.

Figure 1 - TCi Thermal Conductivity Analyzer

The surface area of the external MTPS sensor is magnified in Figure 2 and provides a better view of the sensor's central heater/sensor element in the shape of a spiral surrounded by a guard ring. The guard ring generates heat in addition to the spiral heater, thus approximating a one-dimensional heat flow from the sensor into the material under test in contact with the sensor. The active area of the sensor is 17 mm in diameter and represents the green area inside the red RTV silicone seal. It is important that this green area is fully covered by the sample material being tested. The RTV silicone seal liquid-proofs the sensor and enables the direct testing of liquids, pastes and powders in addition to other solid materials.

Figure 2 - MTPS Sensor Surface

The voltage drop on the spiral heater is measured before and during the transient and the voltage data is then used to measure the thermal conductivity of the material through a patented iterative (m*) method. The voltage drop plot can be viewed within the TCi software and is pictured in Figure 3. The rise in the voltage slope correlates to the rise in temperature at the interface between the sample and sensor and is inversely proportional to the thermo physical property of the material in contact with the sensor. High conductivity samples provide a very small slope. Conversely, low conductivity samples result in a steeper slope to the voltage-plot due to the quicker build-up of heat at the sensor contact.

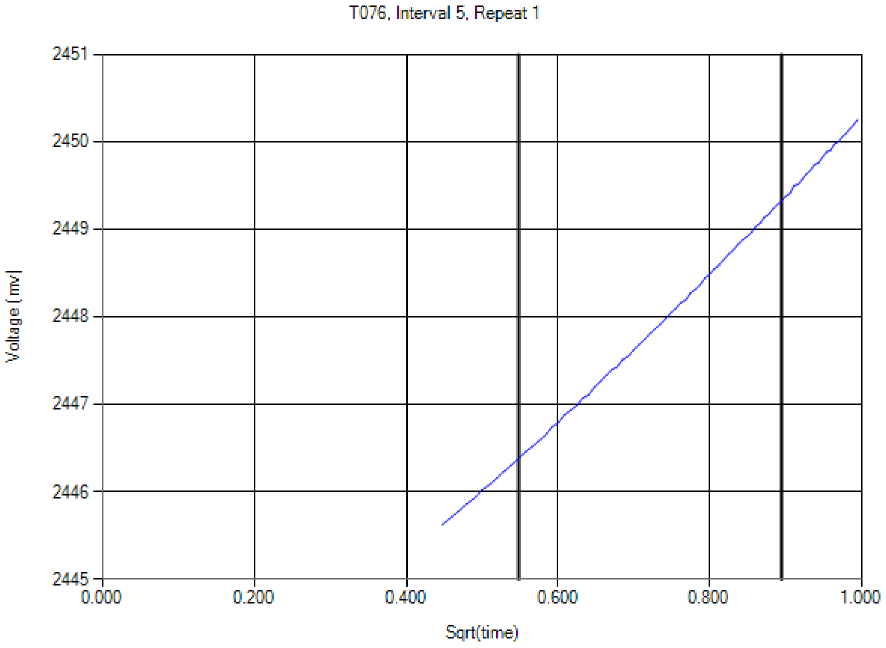

Figure 3 - Voltage Drop Plot

The MTPS' operating temperature range is -50 to 200ºC, and the technique offers accuracy and precision comparable to traditional methods for thermal conductivity testing while reducing the testing time from hours to under a second. The instrument is factory-calibrated and provided with reference standards for verifying the performance of the instrument.

Convection, the movement of heat by moving liquid, is a concern in measuring the thermal conductivity of low-viscosity liquids. Traditional techniques such as the transient hot wire method cannot remove the effect of the natural convection due to the temperature rise of the hot wire. The extent of the defect convection represents in such a transient hot wire measurements of low-viscosity liquids is dependent on the physical properties of the sample material (e.g. viscosity) and the dimension and the heat generation of the hot wire.

Transient plane source techniques offer improved accuracy in this respect. The modified transient plane source improves on several elements in how the traditional transient plane source limits the impact of convection in measuring the thermal conductivity of low-viscosity materials. First, the MTPS technique employs a very short measurement time of 0.8 seconds at low power setting vastly reducing the amount of energy being introduced to the sample and reducing any measurement-induced convection. Secondly, with the use of the small volume test kit (SVTK) accessory pictured in Figure 4 the sample volume is minimized to 1.25 ml. With less sample volume required – there is less opportunity for convective currents to develop. Finally, the MTPS sensor provides a horizontal presentation of the sample to the sensor. The natural convection error is more prominent in the case of vertically oriented sensors (e.g. hot wire) than inverted horizontal (e.g. MTPS sensors) which is consistent with convection theory.

Figure 4 - SVTK Accessory Affixed to TCi Sensor

In addition to the MTPS advantages in testing low-viscosity liquids – the technology also offers the flexibility to be integrated into production environments for real-time process monitoring applications. MTPS sensors have been widely used in the pharmaceutical and cosmetics industries for applications in monitoring homogeneity, endpoint determination in moisture control, and granulation of powders. The flexibility the one-sided interfacial non-destructive sensor offers is a key benefit to process engineers and researchers.

SAMPLES

The milk used in the experiment (pictured in Figure 5) was purchased at a local grocer, and the fat content values were recorded as provided by the manufacturer and labeled on the milk cartons.

Figure 5 - Milk Samples

The milk was poured into the SVTK accessory (Figure 6) and fully covered the active area of the TCi sensor. Care was taken to avoid the entrapment of air within the samples presented to the sensor. All samples were measured at ambient room-temperature conditions.

Figure 6 - Milk Sample in SVTK

RESULTS

A reference material was run at the beginning of the setup to ensure the system was performing to specification for accuracy and precision. Distilled water was chosen in this case due to its well characterized thermal conductivity value and similar viscosity property to the milk samples to be tested. Results for the reference test are provided in Table 1.

Table 1 - Thermal Conductivity (W/mK) Reference Material Results		
Reference Material:	Distilled Water	
Expected Value:	0.609 W/mK @ 20 deg C	
Measurement	**Thermal Conductivity (W/mK)**	**Difference from Expected Value (%)**
1	0.614	0.85%
2	0.611	0.37%
3	0.616	1.13%
4	0.614	0.86%
5	0.613	0.69%
Average	**0.614**	**0.78%**
RSD (%)	**0.28%**	

The sensor response differed to the expected value of the material by less than 1%, establishing a sufficient level of accuracy in proceeding with the sample testing. The relative standard deviation (RSD) was also under 1% and within the stated manufacturer's performance specifications for the instrumentation.

Results for the milk samples with 0, 1, 2 and 3.25% are presented in tables 2-5.

Table 2 – Skim Milk (0% Fat)		
Measurement	**Thermal Conductivity (W/mK)**	**Temperature (°C)**
1	0.585	19.4
2	0.589	20.1
3	0.584	20.0
4	0.584	19.4
5	0.585	20.3
Average	**0.585**	19.9
RSD (%)	0.36%	

Table 3 – Partly Skimmed Milk (1% Fat)

Measurement	Thermal Conductivity (W/mK)	Temperature (°C)
1	0.579	20.0
2	0.578	20.2
3	0.580	20.1
4	0.579	20.2
5	0.582	20.2
Average	**0.580**	**20.1**
RSD (%)	0.29%	

Table 4 – Partly Skimmed Milk (2% Fat)

Measurement	Thermal Conductivity (W/mK)	Temperature (°C)
1	0.577	20.2
2	0.575	20.7
3	0.574	20.0
4	0.571	19.8
5	0.574	20.4
Average	**0.574**	**20.2**
RSD (%)	0.39%	

Table 5 – Homogenized Milk (3.25% Fat)

Measurement	Thermal Conductivity (W/mK)	Temperature (°C)
1	0.564	19.8
2	0.564	19.9
3	0.565	20.1
4	0.569	20.2
5	0.567	20.2
Average	**0.566**	**20.0**
RSD (%)	0.39%	

The data is plotted graphically in Figure 7 and compared with previously published results obtained via the traditional transient plane source method.

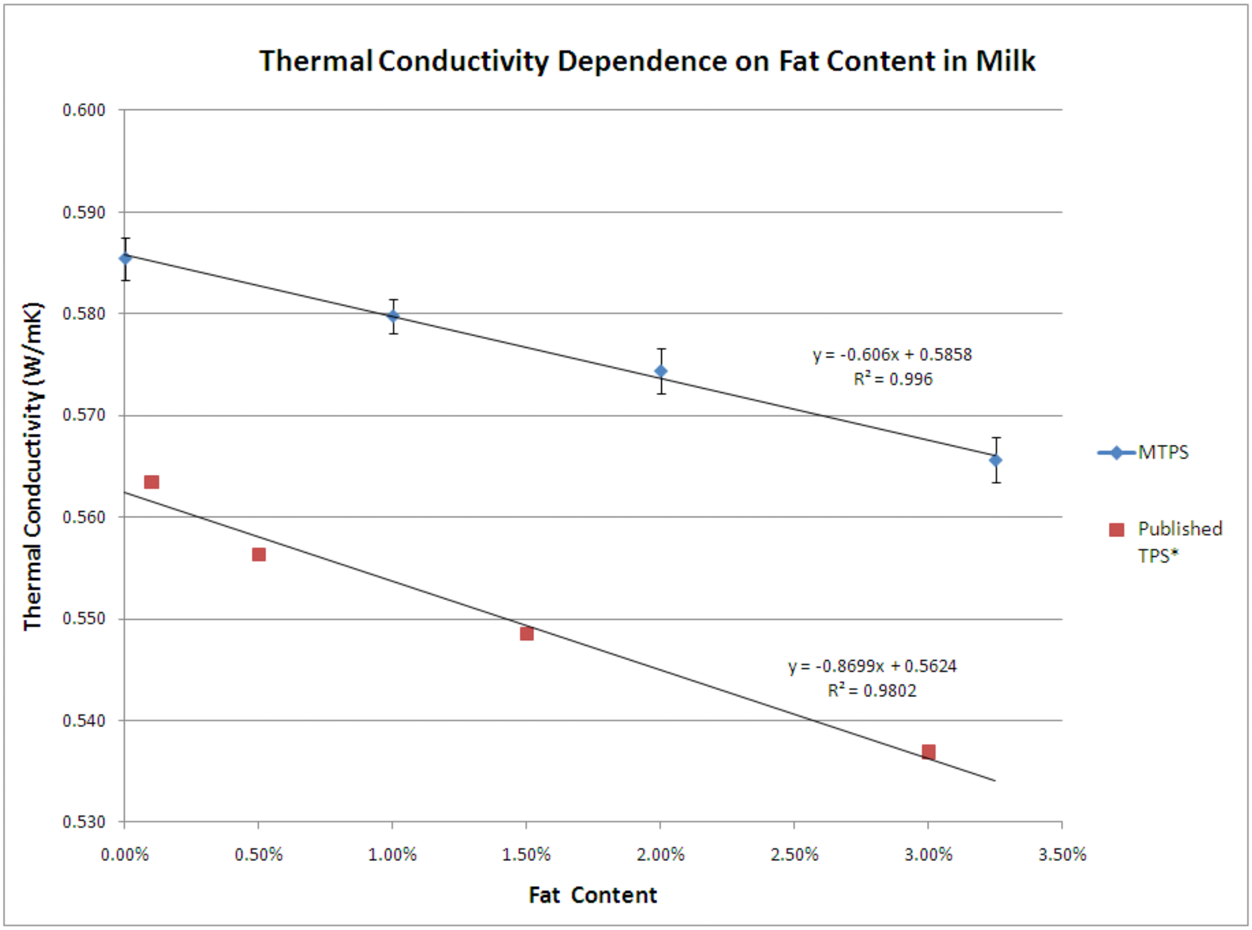

Figure 7 - Thermal Conductivity vs. Fat Content of Milk

*TPS results as previously published 2004.

For each milk product the sample material was tested five times. For all products tested the relative standard deviation (RSD) of the five measurements was better than 1% demonstrating a high level of reproducibility to the measurements. This is graphically represented in Figure 7 by the small error bars on each sample for the MTPS results representing +/- 1 standard deviation.

The MTPS results also correlate well with the previously published data measured via the traditional TPS method. For the skim milk samples (0% fat) the values differ by 3.76%. The differences in values between the techniques increases with the fat content but remains under 5.6% at the upper end of the range of fat concentrations tested (3.25% fat).

Part of the differences in the MTPS results generated and the previously published TPS results may be due to minor differences in manufacturing techniques and regional differences of the suppliers of the milk products. The milk used in generating results of the current study was produced by Baxter Milk (New Brunswick, Canada). The milk used in the previous study cited was produced by Arlan Inc (Sweden).

Both the MTPS results generated and the previously published traditional TPS results provide similar linear functions of thermal conductivity to fat content at 0.996 and 0.9802 respectively.

CONCLUSION

Test results confirm previously published transient plane resource (TPS) results identifying a strong linear correlation between the fat content of milk and thermal conductivity. Results generated with the modified transient plane source (MTPS) agreed with previously published TPS values.

The MTPS technique offers significant advantages in the thermal conductivity characterization of low-viscosity liquids in addressing the challenges presented by convection. The technique additionally offers the added flexibility to migrate from the laboratory environment directly into manufacturing spaces for application in real-time process monitoring and control.

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