ON-LINE VISCOSITY MEASUREMENT AT REFERENCE TEMPERATURE AND VISCOSITY INDEX CALCULATION

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KEYWORDS

Viscosity, Viscosity Index, Dynamic Viscosity, Kinematic Viscosity, Reference Temperature, Analyzer, On-Line, Measuring Cell, Poise, Centipoise

ABSTRACT

Viscosity index (VI) is a standardized measurement for the change of viscosity with temperature and is mainly used to characterize petroleum products and lubricating oils. Set up by the Society of Automotive Engineers (SAE), the VI scale and the procedure for its calculation are described in ASTM Method D 2270 for Calculating Viscosity Index from Kinematic Viscosity; the reference temperatures are 100 and 210°F (37.8 and 98.9°C).

While the oil manufacturing process may be at one certain temperature, viscosity index measurement and calculation is challenging as it requires measuring the oil's viscosity at two different reference temperatures (T_{Ref}). Although on-line viscosity measurement at one reference temperature is possible by generalizing the use of on-line process instrumentation, the goal of this paper is to demonstrate that an on-line analyzer is capable of realizing a reliable viscosity index measurement through viscosity measurement at reference temperature.

In a first step, the knowledge of the existing technologies for viscosity measurement at reference temperature will be discussed. These will be commented and argued in the perspective of a valid measurement at two reference temperatures. This implies on the classical technologies that they integrate two measuring cells. The main methods identified for process viscosity measurement at reference temperature are: 1) one in-line viscometer with temperature compensation, 2) a dual on-line viscometer system with interpolation, and 3) on-line analyzers at reference temperature. An efficient method for the viscosity

measurement at two reference temperatures is the use of two analyzers with two measuring cells.

Based on the former analysis, only the technologies capable of measuring the viscosity curve as a function of temperature on every measurement cycle offer the possibility to have only one measuring cell, the vibrating technology. The innovation presented in this paper is to use this technology in order to answer the requirements of a reliable and simple determination of the in-line Viscosity Index. It is the first time that an analyzer is introduced that effectively measures viscosities at the two reference temperatures with only one measuring cell.

INTRODUCTION

On-line viscosity measurement at reference temperature is needed in refineries for petroleum, oil, liquid hydrocarbons, heavy and light fuel blends. In addition, it is important for lubricant producers who focus on Viscosity Index, in the chemical industry and, to a lesser extent, in the food and beverage industry. In effect, on-line viscosity at reference temperature brings immediate and accurate responses to processes handling high value fluids.

Viscosity Index (VI) is a standardized measure for the change of viscosity with temperature. It is mainly used to characterize petroleum products and lubricating oils. The VI scale was set up by the Society of Automotive Engineers (SAE), and the procedure for VI calculation is described in ASTM Method D 2270 [1]. The reference temperatures are 100 and 210°F (37.8°C and 98.9°C); in this paper, viscosities at 40°C and 100°C will be addressed.

In the laboratory, it exist several methods for measuring the kinematic viscosity of a fluid. One of the most popular is described in the standard ASTM D 445 [2], which "specifies a procedure for the determination of the kinematic viscosity, ν, of liquid petroleum products, both transparent and opaque, by measuring the time for a volume of liquid to flow under gravity through a calibrated glass capillary viscometer". This method is not transposable to the process, as a process requires fast response times in order to answer its production efficiency needs, especially in the petroleum field. This is why in the process, all the methods that have been developed by industrials allow a correlation to the ASTM D 445 standard, in opposition to an application of it.

In the oil manufacturing process, viscosity index measurement and calculation is a challenge as it requires measuring the oil's viscosity at these two different reference temperatures (40 and 100°C), whereas the manufacturing process may be at another, different temperature. Although on-line viscosity measurement at one reference temperature has become possible by generalizing the use of on-line process instrumentation in the petroleum industry, this article is aimed to discuss the relevance of these methods for the viscosity index determination.

1- PROCESS VISCOSITY MEASUREMENT AT REFERENCE TEMPERATURE

For proceeding with on-line viscosity measurement at reference temperature, three main methods stand out: 1) using one process viscometer where viscosity varies with product quality and temperature, 2) using two interpolated viscometers for two measurements near

the reference temperature, and 3) using reference temperature analyzers which give accurate viscosity measurements at a constant reference temperature that can be higher or lower than the process temperature. This section details the advantages and drawbacks for each measurement method, from the simplest to the most sophisticated.

1.1 ONE ON-LINE PROCESS VISCOMETER WITH TEMPERATURE COMPENSATION

Viscosity at reference temperature in process conditions is calculated with viscosity and temperature measurements. Temperature compensated viscosity provides viscosity at constant reference temperature or eliminates process temperature variations.

With this solution, a viscometer continuously measures the viscosity at the process temperature, which must be near the reference temperature. A processor calculates the viscosity at reference temperature by using a variation law.

This law can be based on the ASTM D 341 Test Method [3], which details the standard procedure for plotting viscosity versus temperature charts. These charts ascertain the kinematic viscosity of a petroleum oil or liquid hydrocarbon at any temperature within a limited range, provided that the kinematic viscosities of this product at two other temperatures are known. For practical purposes, this method generally uses the mathematical equations mentioned in the annex of the standard, the most used being the simplified form:

$$\log \log (v + 0.7) = A - B \log T$$

Where log = logarithm to base 10,
v = kinematic viscosity, [mm^2/s] or [cSt]
T = temperature [K]
A and B = constants

In order to be able to use this model, it appears necessary to know in advance the product and to determine one of the parameters A or B, as well as being sure that the product doesn't change during the process. The assumption is that parameter A or B remains the same for both reference and measured products.

Using one process viscometer with this temperature compensation model presents one main advantage when measuring viscosity at reference temperature: only one instrument provides instantaneous and continuous measurement. This technique, however, may induce calculation uncertainties since accuracy may decrease when the difference between process temperature and reference temperature increases. It is possible to improve the behavior by adding an exchanger unit on a by-pass loop, but in reality we never get the correct stable temperature because of the exchanger regulation, oscillating around the reference temperature. Also, a reference product's behavior must be known, as opposed the liquid being analyzed; this is why using a single viscometer with temperature compensation is not error-proof and gives rarely good results.

1.2 TWO ON-LINE PROCESS VISCOMETERS WITH INTERPOLATION

In order to surpass the difficulties linked to the knowledge of the product as described in the previous sections, it is possible to use the same method, with two viscometers.

With two process viscometers, the viscosity measurement is realized at two different temperatures, before and after the reference temperature. In process, the product flows continuously in a by-pass loop. The first viscometer continuously measures the viscosity at a given temperature, which is close to the process temperature. The fluid is then cooled or heated, and a second viscometer continuously measures the viscosity at a second temperature. An associated processor calculates the constants A and B at those two temperatures according to ASTM D 341 model, and interpolates the viscosity at the end-user determined reference temperature.

This technique fully satisfies ASTM D 341 requirements because it constantly provides reliable viscosity measurements and calculations. Although accuracy may decrease when temperature measurements vary, the product's behavior is taken into account; temperature variation is calculated and the method is error-proof. However, two viscometers and two heat exchangers as an in-process solution represent a heavy monetary investment in equipment, time and labor.
Moreover, it is necessary to highlight here that this method is not adapted to other petroleum related products such as lubricants, lube oil or gear oils which are not referenced by the equation of this ASTM D 341 standard.

1.3. ON-LINE ANALYZER AT REFERENCE TEMPERATURE

The two methods described previously can be discussed as they both give approximation in the viscosity at reference temperature calculation, and most of all they are not applicable to all products that shall be considered for viscosity index purposes, such as lubricating oils which contain additives.

A third method to be considered is the analyzer.

Via decades of experience and technological progress, manufacturers have developed analyzer systems adapted to industrial environments. In order for the end-user to glean process knowledge, clear objectives must be set. Implementing advancements, research data, and installation parameters allow the process to become more profitable and the analyzer to demonstrate efficiency.

As with the first two examples, analyzers work continuously and provide fast response time, unlike laboratory or manual analysis. Using an analyzer, the goal is often to control a process or to execute an immediate corrective action [4], [5]. According to Figure 1, such systems commonly include 4 or 5 complementary parts, which are:

- the analyzer with continuous or sequential operation,
- the sampling system and transport,
- the sample preparation system,
- the sample recovery system, and
- the calibration control system.

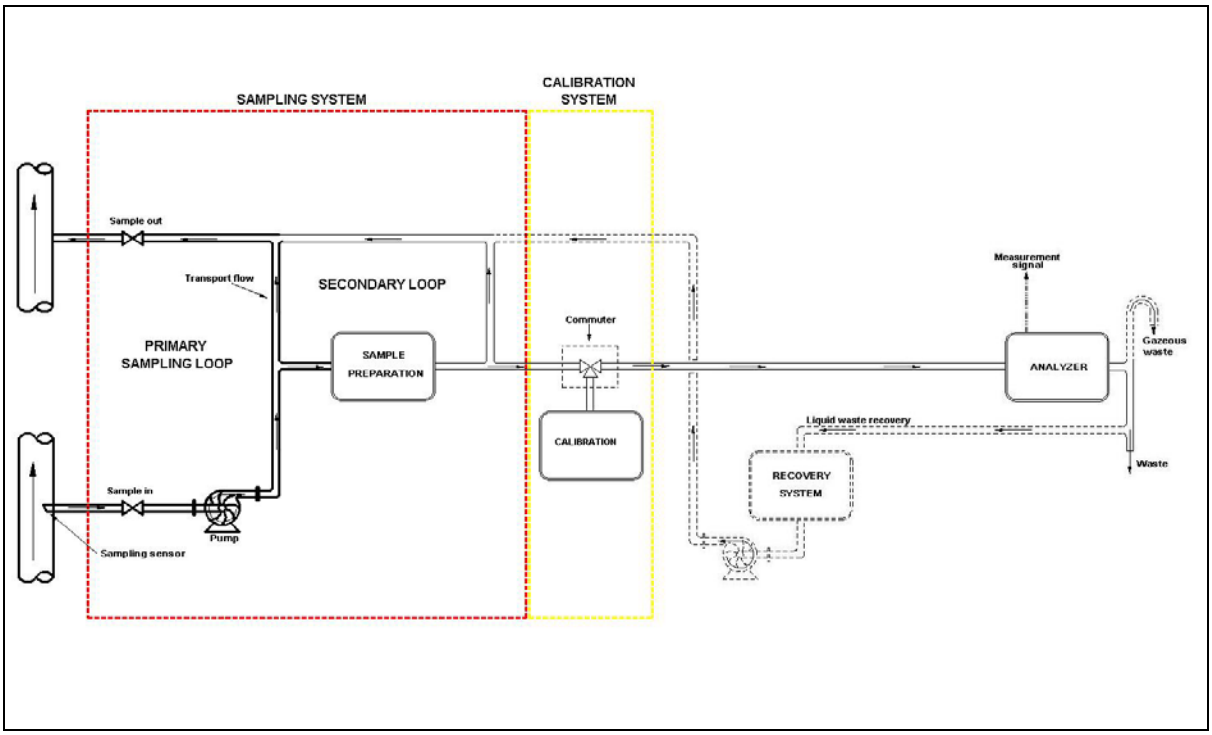

FIGURE 1. CONTINUOUS ANALYSIS SYSTEM

The analyzer principle is simple and easily recognizable, regardless of technology or manufacturer. When using an analyzer, a product sample is taken from the process and introduced to the analyzer. The product is prepared for measurement, the measurement is memorized, and the product is returned to the process. This cycle repeats and samples are continuously renewed.

Analyzers present net advantages compared to process viscometers in regards to measuring viscosity at reference temperature. In effect, the measurement is made at the actual reference temperature, regardless of product behavior. The correlation to ASTM standard is done directly and accuracy is induced by the measuring principle. By contrast, process viscometers provide a calculation approximation.

Two main analyzer technologies exist in today's market and the differences appear in the method by which the fluid is brought to the required reference temperature.

For half a century the capillary range of physical property analyzers has been recognized as an industry standard [6]. In these systems are several types of similar analyzers with either a bath or oven that brings the fluid to the required temperature. When using this type of analyzer for measuring viscosity at reference temperature, a sample flows through a conditioning system and then enters a bath or oven that is maintained at a preset temperature. A pump raises the sample to the preset flow rate and puts a portion of the sample through a capillary system. Finally, the pressure difference is converted to output signals, providing the sample's viscosity.

Another analyzer technology is the on-line automatic viscosity analyzer based on the vibrating technology viscometer, which integrates a measuring chamber [7], [8]. With this system, a product sample is isolated in the measuring chamber, and a controlled heating or cooling phase raises (or lowers) the sample to the reference temperature and the measurement is memorized. Figure 2 demonstrates this system's operating principle:

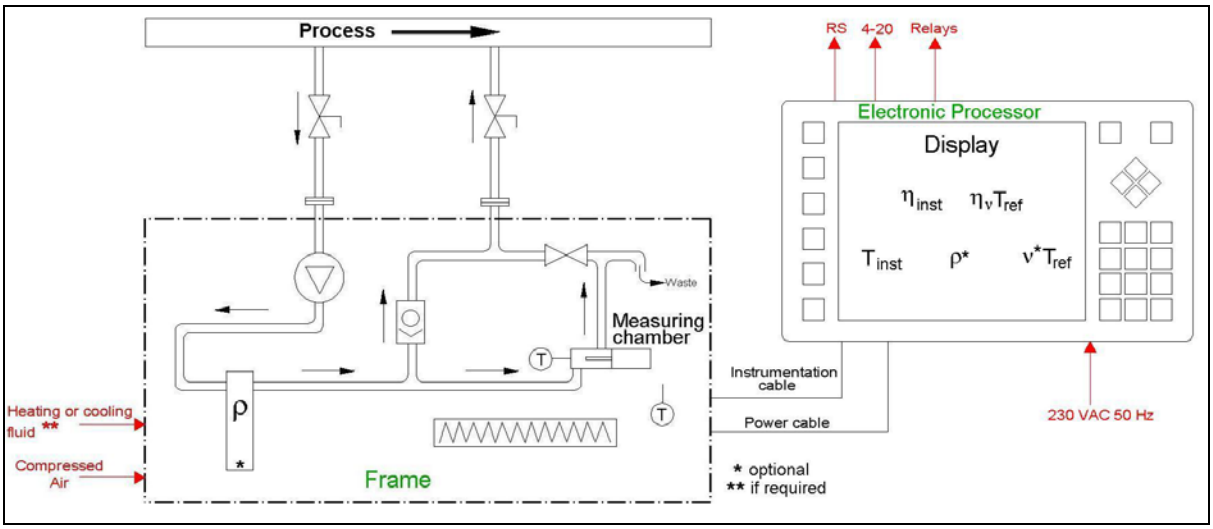

FIGURE 2. ON-LINE AUTOMATIC VISCOSITY ANALYZER OPERATING PRINCIPLE

This analyzer is based on the viscometer's vibrating technology at resonance frequency, which allows instant and continuous measurement. Viscosity ranges can be set up from 1-100 cP to 100-10 000 cP. The response time varies from 2 to 10 minutes, according to the input sample and to the reference temperature. In most cases, the system requires no annex installation as primary loop with exchangers, pump, filters, or pressure controllers. It requires insignificant and easy maintenance. The kinematic viscosity can be available through density measurement.

The analyzer's operating cycle consists of:

- Step 1: the on/off valve is opened and the product flows trough the pump and the measuring cell, renewing the product sample,
- Step 2: the on/off valve is closed, the product flows trough the pump and the loaded check-valve, the product is locked in the measuring cell,
- Step 3: the product sample is cooling down
- Step 4: at the required temperature, the viscosity is recorded.
- Step 5: the on/off valve is opened and the product sample is re-injected to the main line and the cycle starts again (back to step 1).

Figure 3 below details the analyzer with integrated measuring chamber operating cycle, and Figure 4 illustrates 6 consecutive cycles according to viscosity and temperature.

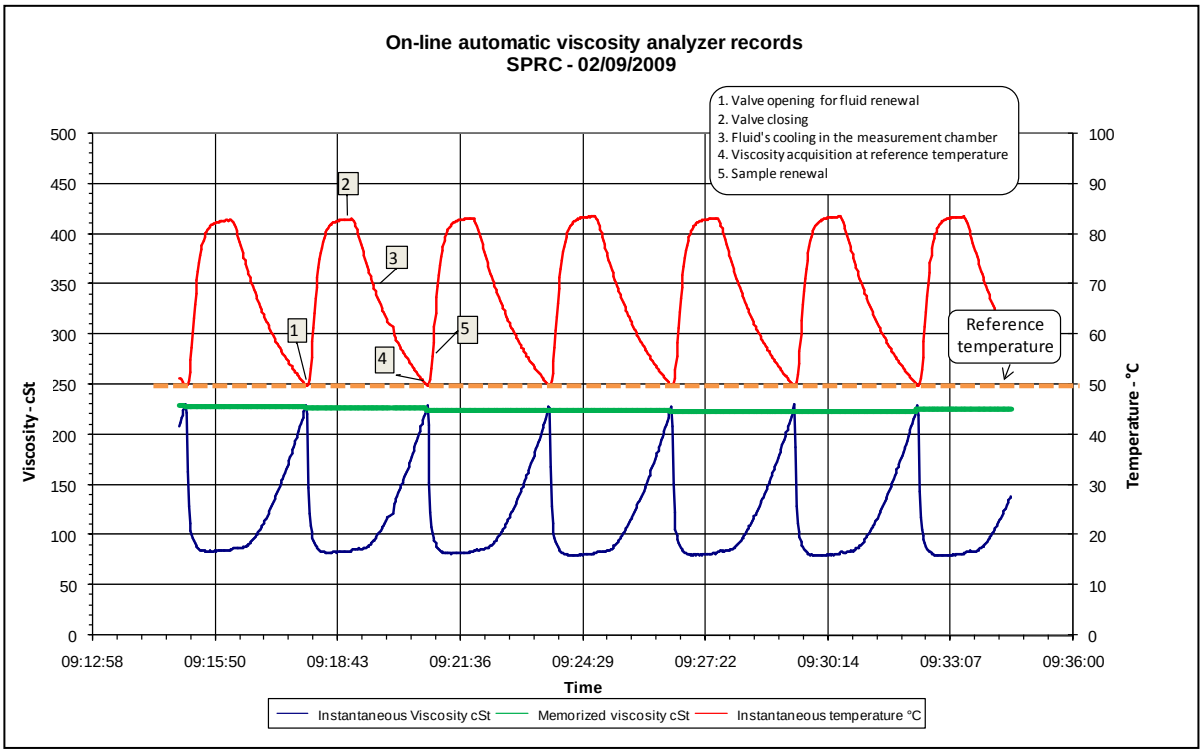

FIGURE 3. ON-LINE AUTOMATIC VISCOSITY ANALYZER CYCLE RECORDS

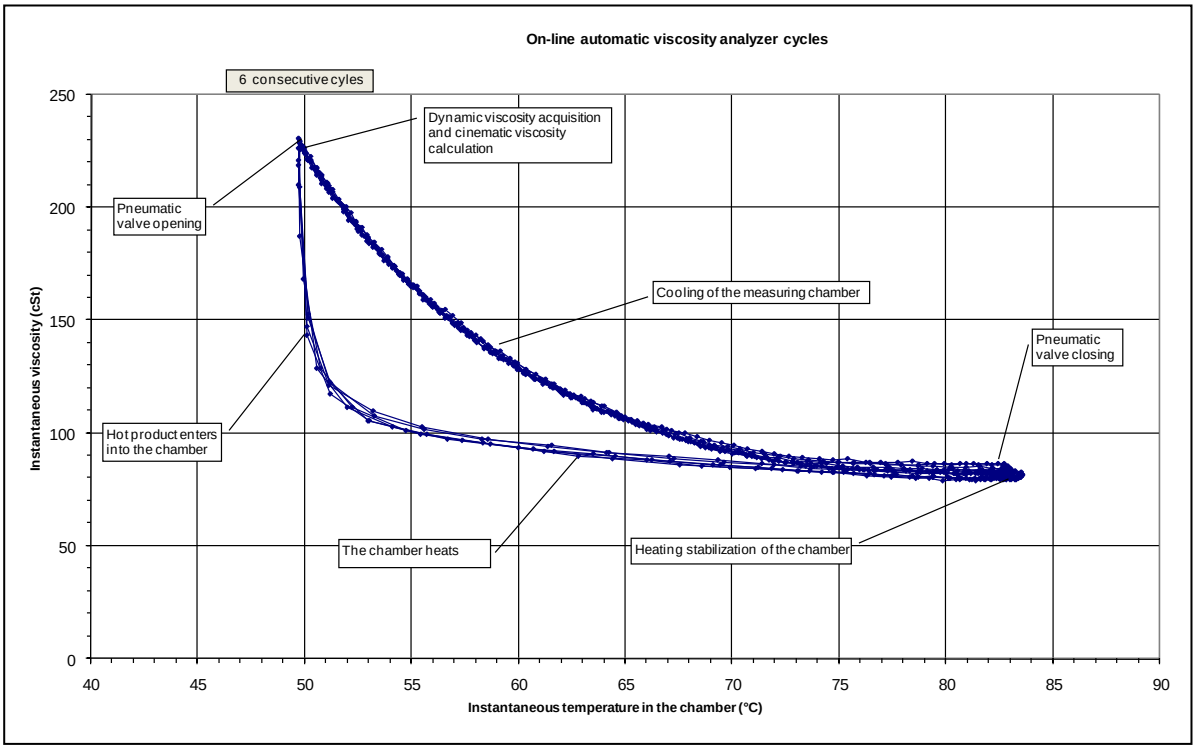

FIGURE 4. ON-LINE AUTOMATIC VISCOSITY ANALYZER CONSECUTIVE CYCLES

Several differences are apparent when comparing the two viscometers technologies implemented on their production lines, as experimented by Lubrizol [9]: viscometers with capillary tubes and vibrating rod viscometers, both used for viscosity measurement at reference temperature. The first group of characteristics that differ is based on the necessity of extra exterior installation on the capillary systems: pumps in circulation, rotating filters, security valve and pressure gauges on the external loop; whereas there is no need for this additional parts with the vibrating analyzer.

Particle size is an issue for most of the petroleum products. A thin filter at the entry of the capillary tube analyzer is absolutely necessary since these systems are not able to proceed with particles (bigger than 30 µm). In most of the cases these filters are not necessary with the vibrating systems which have a better tolerance to particles (only limited by the integrated pump specifications).

In a general way, capillary tube systems necessitate additional accessories than vibrating systems, (pre-heather, stirrer…) inducing maintenance needs, risks and costs as well as additional installation space and costs.

In terms of measurement reliability, capillary systems are clogging, causing impactful drift in time, especially when viscosity increases. By comparison, the vibrating rod analyzer with integrated measuring chamber produces reliable measurements and no drift linked to clogging on standard fuels.

In terms of production and maintenance efficiency researched by the company, the use of the vibrating rod analyzer compared to capillary tubes one brought the following advantages:

- A diminution of the risks at the maintenance functions
- A maintenance time optimization: less preventative, less curative maintenance
- A reduction of bad quality costs linked with a better prevention of non conformities
- A reduction of the spare parts inventory cost
- A reduction of natural non-renewable resources consumption such as water

These results can be summarized by savings in maintenance, production and analysis times.

1.4. SYNTHESIS

These three methods used today allow the determination of viscosity at reference temperature, whereas only the last one with analyzers allows its measurement. The methods are varied, and each one must be carefully considered prior to choosing process equipment. In all cases, it is important to remember that regardless of the system implemented, laboratory measurement remains valid, as the ASTM D 445 test method specifies that a procedure that determines the kinematic viscosity of a liquid petroleum product is realized by measuring the time for a volume of liquid to flow under gravity through a calibrated glass capillary viscometer. By definition, none of the three solutions exactly complies with this procedure. However, all are correlated. According to industrial standards, the in-line measurement shall be repeatable, simple to use and to install, and it should require minimal maintenance in time and labor.

2- MEASURING THE VISCOSITY INDEX IN PROCESS INDUSTRIES

Viscosity Index (VI) is an empirical, unit-less number indicating the effect of temperature change between 40 and 100°C on the oil's kinematic viscosity. The higher the oil's VI, the tendency for the viscosity to change with temperature is lowered. Viscosity index is measured according to ASTM D 2270-04. For a given viscosity value at 100°C, if the viscosity difference decreases between 100 and 40°C, the viscosity index increases. An application example is lube oils, which require a good viscosity at high temperature to ensure smooth working conditions inside engines [10], [11]. A higher viscosity index means lowered temperature influence on viscosity. Additional typical applications of the Viscosity Index are hydraulic fluids [12] and other petroleum products.

Viscosity index is deduced by sequential viscosity measurements at two temperature points. Based on the previous technologies described, we will explain how each one can or cannot be applied to the viscosity index measurement.

A first idea is to consider a solution which is based on a synthesis of the solutions described in chapter 1.1 and 1.2, using one in-line process viscometer with temperature compensation or a dual process viscometer with interpolation. We could cite the solution described by Andle et al. [13], but the limits of this attempt rely on the loop system and implementation of exchangers. As discussed above, the temperature is never stable and temperature inaccuracies are generated, which are added to the measurement inaccuracies – as on all measurements- furthermore in process where most of fluids are rarely homogeneous. Despite of this attempt, results are not stable.

With capillary type analyzers, there is no other solution than implementing two analyzers, even if it is possible to pool the sampling system. This solution is not practical for industrials, as it generates twice more maintenance costs and risks, which is added to a double system investment cost and complexity.

Up to now, there was no simple and reliable analyzer capable to satisfy the in-line viscosity index measurement.
For a good measurement, it is necessary to find a system where the fluid can reach accurately the two reference temperatures into the measuring cell. The vibrating type viscometer allows this in-line measurement in its analyzer version. The vibrating rod principle is interesting because of the small volume that needs to be measured, which allows short cycles.
The first measurement is memorized on the sample at the reference temperature of 100°C, as described previously in the operating cycle steps of this analyzer. Then the sample cools down in the measuring chamber. The second measurement is memorized when the temperature reaches 40°C and the processor calculates the Viscosity Index according to ASTM D 2270-04. The cycle is repeated continuously as described in Figure 5. Viscosity Index is measured on-line and improved process control is in place.

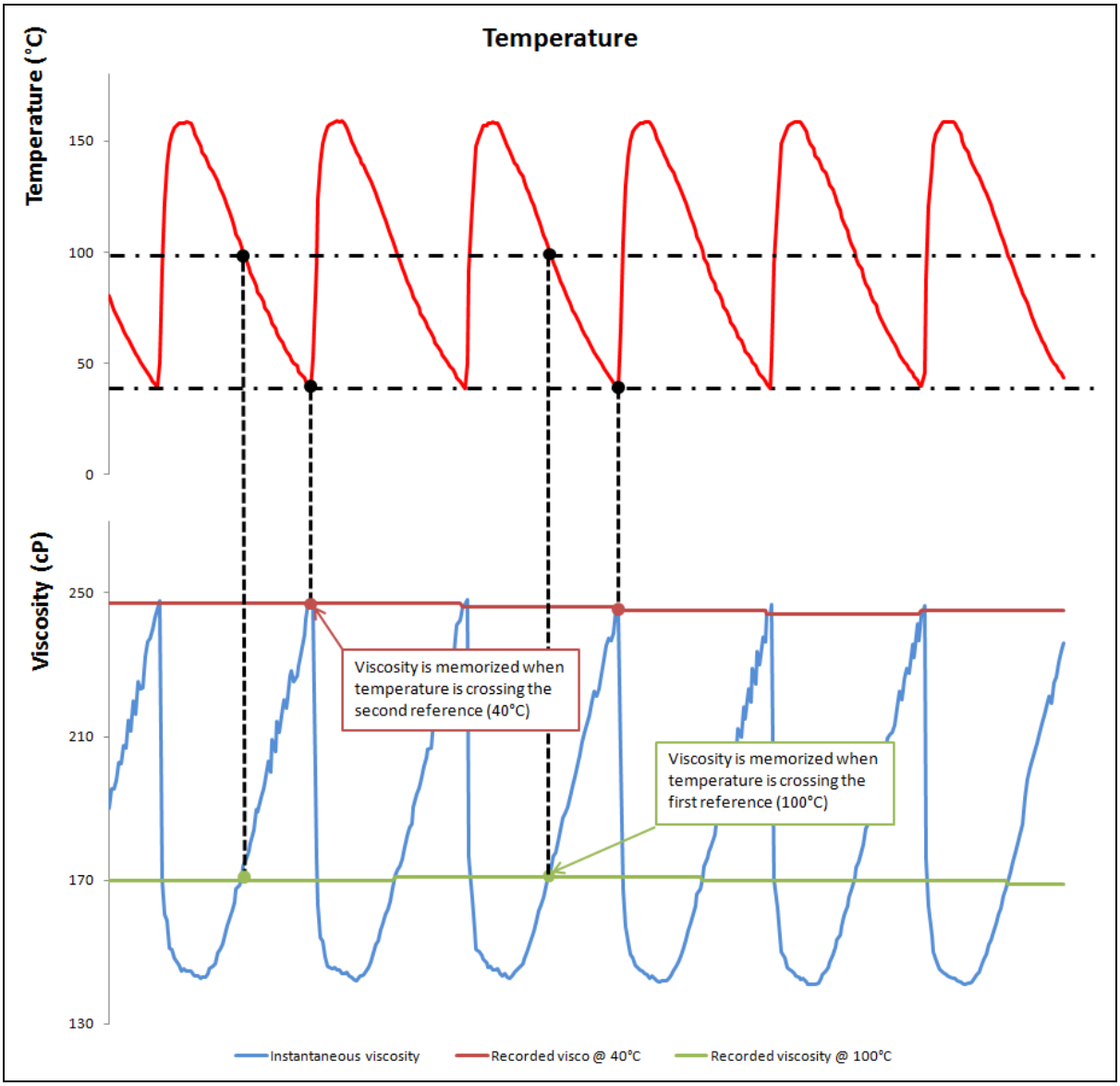

FIGURE 5. ON-LINE AUTOMATIC VISCOSITY ANALYZER CYCLE RECORDS AT TWO REFERENCE TEMPERATURE

CONCLUSIONS

The technologies described in this paper for measuring viscosity at reference temperature in process condition offer many possibilities to multiple industries. When Viscosity Index needs to be measured, however, most solutions are not perfectly adapted to the task. Only one solution, based on one single analyzer, allows on-line measurement at two reference temperatures and calculation of viscosity index according to ASTM D 2270-04. This solution is robust, cost effective and requires very little maintenance while providing long-lasting satisfaction.

While installing in the process, it inherently instills trust and confidence in all users. This innovative solution from Sofraser answers industrial requirements and opens huge possibilities for process optimization.

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