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PLC-Based Real-Time Rheological Process Analyzers for of Non-Newtonian Processes

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PLC-BASED REAL-TIME RHEOLOGICAL PROCESS ANALYZERS FOR OF NON-NEWTONIAN PROCESSES

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ABSTRACT

Designing and deploying process analyzers capable of providing real-time rheological characterization of non-Newtonian processes continues to be a challenge in general, but even more so with processes that exhibit time-varying non-Newtonian rheological characteristics. Traditionally, grab sampling is used to facilitate rheological characterization where such information is crucial to process management and plant operations of the facility. Grab sampling allows for periodic snapshots of process conditions; however, this approach has many downsides, chiefly that laboratory analysis can be time consuming, which can impact the facility's throughput and production goals. On the other hand, even though there exist various commercially-available, process-viscosity monitoring technologies, it is recognized that measurements of dynamic or apparent viscosity provided by such monitors, particularly monitors that operate at fixed shear rates, do not constitute adequate rheological characterization of non-Newtonian processes. This paper presents and compares two design solutions for implementing process analyzers intended for generalized, real-time rheological monitoring. It shows that even for designs that build on the same core technology, technical and commercial considerations could either aid or hinder the justification for integrating rheological analyzers into the design of a facility that would otherwise use grab sampling. This paper supports the approach of integrating well-established COTS technologies, such as torsional oscillation viscometers (TOVs), with programmable logic controllers (PLCs) for providing cost-effective, rheological-analyzer solutions that can be delivered within the timeframe of a demanding project schedule. In addition, based on simulation results discussed herein, this paper demonstrates the viability of implementing the rheological-analysis function on a PLC. To aid the assessment of the analyzer's functional-logic capabilities, a process model was developed to simulate time-varying rheological characteristics. The model sequentially transitioned from Shear-Thickening, to Newtonian, to Shear-Thinning, to Bingham-Plastic rheology and repeated the cycle. Both the process model and the analyzer logic were developed using Do-more Designer™ PLC programming software. The PLC code was run using the PLC software ("PLC Simulator"), which comes with the Do-more Designer™ software. PLCs remain the *de facto* platform for implementing real-time monitoring and control across a wide range of industries. PLC simulation results showed that the rheological-analyzer logic was capable of real-time tracking of the "true" values of the parameters that define the rheological characteristics of the simulated process.

Keywords: Rheological, Process Analyzer, Non-Newtonian, Shear Thickening, Shear Thinning, Bingham Plastic, Real-Time Programmable Logic Controller, Simulation, Torsional Oscillation Viscometer, PLC Simulator, Do-more Designer™

1.0 INTRODUCTION

A traditional engineering solution that continues to be offered by design agencies to address the need for rheological information, particularly for processes that exhibit time-varying, non-Newtonian behaviors, is grab-sampling. In general, design of the facility tends to include provisions that allow for periodic sampling and extraction of process material for laboratory analysis, albeit that sampling systems can themselves be automated and quite sophisticated. However, there are several disadvantages to this sample-and-analyze approach, including:

- grab sampling provides periodic snapshots of the process conditions, thus opportunities to ill-characterize a process with evolving conditions abound.
- laboratory analysis of samples is time consuming. Analysis results can take several hours or even days, which can adversely affect the facility's throughput and production goals, particularly where verifying that the rheological parameters of the process material conforms to target specifications before processing can proceed. Moreover, lengthy laboratory analysis turn-around times can delay Plant Operation's responsiveness to correcting process conditions.
- where rheological conditions can contribute or escalate conditions adverse to process operations, such as plugging of process systems and piping, delays in rheological characterization can potentially result in facility downtimes of indeterminate lengths due to unexpected plant shutdowns.
- hazardous-material samples can present a hazard to lab personnel. Moreover, disposal of hazardous samples can itself present a non-trivial concern.
- Sample extraction from the process tends to be small and may not be representative. Hence, rheological conditions are poorly characterized.

While there are many process viscosity monitoring technologies that are commercially available, design agencies recognize that apparent-viscosity measurements by such monitors are sufficient for rheological characterization of Newtonian processes, but do not adequately characterize the rheological conditions of non-Newtonian processes, such as those exhibiting Bingham-Plastic, Shear-Thickening, and Shear-Thinning characteristics. Mwembeshi and Martinelli [3] proposed a process-analyzer algorithm with the potential for extending the use of COTS process viscometers to provide more universal rheological-monitoring capabilities for non-Newtonian processes, even those with time-varying rheological characteristics. However, the viability of implementing the solution on a platform that can facilitate real-time implementation remained to be demonstrated. Moreover, ensuring that analytical-monitoring design solutions can be realized in a timely and cost-effective manner that aligns with a design agency's schedule and budget is crucial to justifying the suitability of the solution before integrating it into the design of the facility. Consider, as an example, the 20-20-20 adage of time scales in system design [5], where 20 weeks is the nominal allocation for analysis, 20 months is for the design-realization phase, and 20 years the nominal plant operations phase. Ensuring that the rheological monitoring solution being considered can be designed, procured, and installed well within the timeframe relevant to the project, such as a nominal 20-month engineering-procurement-and-construction (EPC) timeframe, is an important consideration for adoption. This paper presents and compares two rheological process analyzer designs, both of which are evolved from the same process-viscometer technology. The first configuration replaces a COTS process viscosity monitor with a turn-key analyzer unit that would constitute a new product line for an OEM. The second configuration is a packaged system consisting of an all-COTS process viscosity monitor integrated with a dedicated programmable logic controller (PLC) to provide the analysis function. The work recorded in this paper uses a PLC simulator for simulating non-Newtonian rheological conditions, as well as for assessing the ability of the analyzer algorithm to provide both quantitative and qualitative real-time monitoring capabilities.

The remainder of this paper is organized as follows. Section 2 discusses the process viscometer technology being repurposed to facilitate rheological monitoring. It briefly describes how the technology works and outlines key attractive features, as well as shortcomings of the technology. Section 3 presents the first analyzer configuration that would constitute a new product line for a viscosity-monitor OEM. Section 4 presents a PLC-based process analyzer configuration. Pros and cons of the two architectures are discussed within the respective sections.

Section 5 discusses the process simulation and the simulation of the rheological-analyzer logic that was done for this paper using a PLC simulator. The functional logic for the process analyzer is also presented. Section 6 presents the simulation results. Conclusions are presented in Section 7.

2.0 PROCESS VISCOMETER TECHNOLOGY

The technology being evolved to develop the rheological monitoring solutions discussed in the subsequent sections of this paper is Torsional Oscillation Viscometer (TOV), a technology with many attractive features, but also suffers from shortcomings that limit its utility for rheological monitoring. The schematic in Figure 1 shows a TOV monitoring system that provides online apparent viscosity (μ) measurements. These measurements are equivalent to the dynamic viscosity for a Newtonian process; but, are merely the apparent-viscosity component of the rheology where a non-Newtonian process is being measured.

The TOV monitoring system consists of the following:

a) a TOV probe that includes a sensor bulb, which is designed to be oscillated at a fixed shear rate
b) a TOV monitor that monitors the oscillations of the probe and maintains the probe at its target fixed resonant frequency (f_R). The shear rate of the TOV probe is $\gamma = 2\pi f_R$. The resonant frequency (and shear rate) is a design operating frequency set in the configuration of the TOV monitor by the manufacturer. Torsional oscillations of the sensor bulb produce shear waves in the stream. The oscillations are tiny, on the order of 1 micrometer (micron). For the remainder of this presentation, the two attributes relevant to the discussions in the subsequent sections are the shear rate (γ) and the apparent viscosity (μ) measurement.

TOV technology offers many advantages, including:

1. It has no moving parts and has minimal maintenance requirements. In addition, it requires infrequent calibration.
2. Materials of construction of wetted components include a range of generally-inert, robust, high-temperature-strength materials suited to various harsh and clean environments.
3. Ease of installation in piping or on vessels with no orientation limitations.
4. The ability to remotely locate the transmitter a nominal 1000 yards (< 915 m) away from the probe.
5. A wide dynamic-viscosity operating range spanning multiple decades.
6. Integrated temperature monitoring and compensation with temperature parameter, also assists with verifying proper wiring of device.
7. Good accuracy and repeatability, generally ≤ 1% of reading
8. Fast response time within seconds
9. Large volume of operating experience and wide deployment across industries.

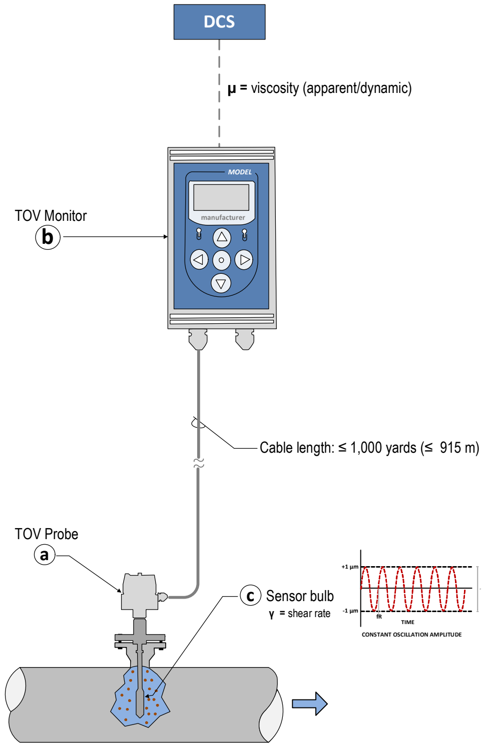


Figure 1 – TOV Monitoring System Measuring the Apparent Viscosity of a Process Line

A sample listing of TOV manufacturers can be found in Mwembeshi and Martinelli [2]. Although implementation of TOV monitoring systems differ across manufacturers, in general, however, shortcomings that hamper application of TOV technology to rheological monitoring of non-Newtonian processes include the following:

1. TOVs are process viscometers providing apparent viscosity measurements as the primary output variable.
2. TOV probes are designed and operated at a fixed shear rate.
3. TOV monitors currently available on the market are not capable of simultaneously controlling multiple TOV probes, such as three- or multi-probe configurations.
4. TOV monitors lack the necessary algorithms for providing generalized rheological monitoring for non-Newtonian behavior, such as Bingham-Plastic, Shear-Thickening, or Shear-Thinning.

Despite these shortcomings, the ability to extend TOV technology to provide rheological-analysis capabilities would greatly aid adoption of rheological process monitoring solutions. Two design solutions for rheological monitoring that built on TOV technology are discussed in Sections 3 and 4.

3.0 PROPRIETARY RHEOLOGICAL ANALYZER

One candidate TOV-based-rheological-analyzer solution, designed to address the shortcomings of TOV technology and facilitate real-time rheological monitoring, is illustrated in Figure 2 (Configuration 1).

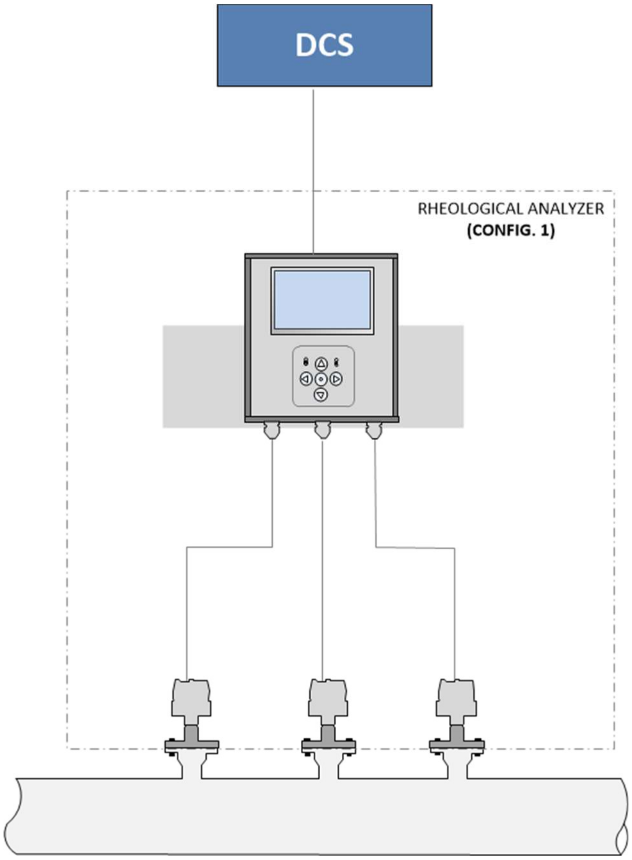


Figure 2 – Proprietary TOV-Based Rheological Analyzer

The design depicted in Figure 2 is capable of monitoring multiple TOV probes and performing real-time rheological analysis of non-Newtonian processes. The process-analyzers-system components in this configuration include:

a) a minimum of 3 TOV probes. The TOV probes are COTS products.

b) a rheological monitor that operates the TOV probes at distinctly-different shear rates ($\gamma_1, \gamma_2, \gamma_3$).

The design of this rheological monitor is novel [3], as there are no TOV-based analyzers with this capability available on the market. It replaces and re-engineers the TOV monitor (Figure 1, item (c)) into a single monitor unit that combines the capabilities of three or more TOV monitors. Like TOV monitors, it computes corresponding apparent viscosities (μ_1, μ_2, μ_3) and, using this information, computes the rheological parameters (outputs) shown in section 2 of Table 2.

In addition to overcoming the TOV shortcomings, this configuration offers a compact solution with a minimum number of devices required to provide the needed functionality. However, this approach may not necessarily readily lend itself to a project with tight schedule and budget constraints given the following considerations:

- The purchaser has limited options for suppliers. Suppliers would have to be a TOV or process viscometer OEM.
- The high likelihood of incurring high capital costs and long procurement lead times. This is because the rheological monitor is a first-of-a-kind (FOAK) design, as there are no previous implementations commercially available. As a turnkey solution, this would likely be a complex procurement. It requires development of new hardware and software, validation of a prototype unit and communication protocols, design iteration, as needed, as well as qualification of the device to various certifications that may be required, such as NRTL, EMI, etc.; necessary to produce a first-generation monitor.
- Onerous quality-assurance-program requirements on the requisition, such as ASME NQA-1, could also greatly increase both the capital cost and procurement lead time.

Other relevant considerations for a design agency and the end user include the following:

- Software supplied with equipment – The embedded software supplied with this rheological monitor would potentially be delivered to the purchaser and end user as non-modifiable, configurable software. Development of the software, however, would potentially be through a full-variability programming language such as C. Moreover, the manufacturer would potentially consider the source code as proprietary, so that the implementation would not be as tractable or reviewable by the end user as may be desired. In addition, where future modifications to the code are required during operations, the plant would have to rely on the OEM to make the modifications.

- Reliability – As the first generation of a new rheological-monitor design, the monitors might be subject to high infant mortality based on general bathtub-curve considerations.

4.0 PLC-BASED RHEOLOGICAL ANALYZER

Another candidate TOV-based rheological-analyzer solution designed to address apparent-viscosity-measurement shortcomings and provide real-time, rheological-monitoring functionality is illustrated in Figure 3 (Configuration 2).

The design depicted in Figure 3 integrates three TOV monitoring systems with a PLC performing a real-time rheological analysis of a non-Newtonian process. This rheological analyzer is envisioned as a packaged system that integrates the following components:

- A trio of TOV monitoring systems. Each system consists of a TOV probe and a TOV monitor.
- A PLC that serves as the rheological analyzer and performs the real-time rheological analysis.
- A human-machine interface (HMI).

This solution is similar to the solution covered in Section 3 ("Proprietary Rheological Analyzer") to the extent that both solutions:

- Leverage TOV technology in the design
- Overcome the shortcomings of the TOV technology outlined in Section 2
- Can provide the intended real-time rheological monitoring for non-Newtonian processes, such as through implementing the analysis functional logic provided in Table 2 based on TOV-probe configuration parameters ($\gamma_1, \gamma_2, \gamma_3$) and TOV apparent-viscosity measurements (μ_1, μ_2, μ_3).

As can be seen from the configurations in Figures 2 and 3, both solutions can use the same three TOV probes. However, the three TOV monitors, PLC, and HMI in Figure 3 (configuration 2) have their functionality of these components integrated into a single monitor illustrated in Figure 2. The differences between the proprietary rheological analyzer and the PLC-based analyzer are many and significant, in so far as their favorability for adoption by a project with tight schedule and budget constraints.

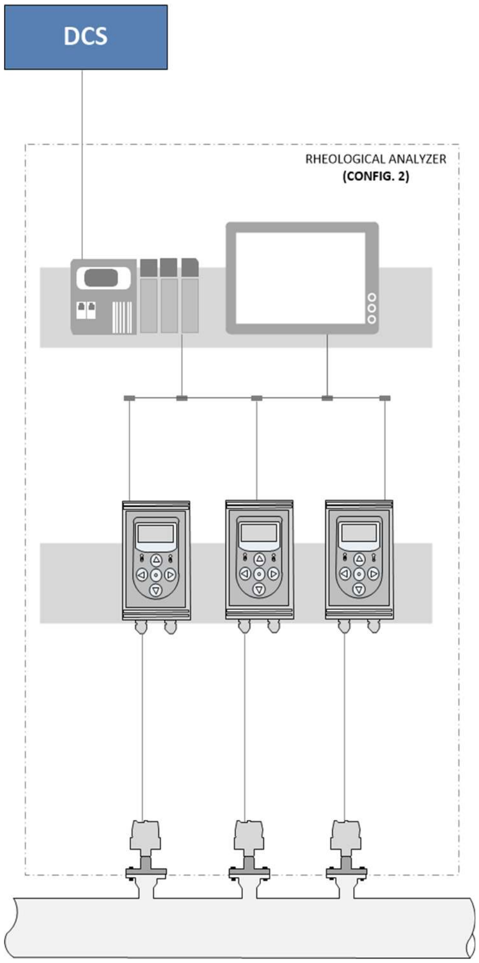


Figure 3 – PLC-Based Rheological Analyzer.

The PLC-based rheological analyzer approach circumvents many of the concerns outlined regarding the proprietary-analyzer configuration, including the following:

- The purchaser can procure the packaged system from a process-viscometer OEM, system integrator, or another engineering contractor.
- Reduced capital costs and reduced procurement lead time. This consideration is largely because the configuration is based on all-COTS hardware, including all the TOV probes, TOV monitors, and PLC and HMI, all with a long history of commercial use. Also, use of HMIs with PLCs is a part of the standard automation solution for most projects.

Indeed, costs of PLCs are reasonable. Moreover, the option to utilize relatively lower-cost, and compact or micro PLCs is also possible for implementing this solution. Some

PLCs, such as the Do-more series of PLCs, are furnished with free PLC programming software. Furthermore, PLCs can come with in-built digital-communication capabilities, such as ethernet communication, or built-in communication protocols such as Modbus TCP and EtherNet/IP. In addition, all the hardware is more likely to have necessary certifications (such as NRTL, etc.) already completed.

- A key focus of delivering this system becomes developing, deploying, and testing the PLC program that implements rheological analysis in an integrated system before delivery to the purchaser. Coincidently, PLCs have a very long history of use as a real-time monitoring or control platform across a wide range of industries. Moreover, PLC programming is widely standardized to IEC 61131-3 [1].
- The software application program for the PLC is developed using a limited-variability programming language. The application program is not proprietary and can be modified as needed by the end user. Furthermore, the logic implemented in the PLC is tractable and is documented based on widely accepted standards such as SAMA or ISA logic diagrams.
- In-built and readily expandable I/O capability.
- Use of software PLCs (e.g., PLC Simulator) that can run the PLC code on a computer without PLC hardware assists with simulation-based evaluation of the code. PLC simulators can also aid with early debugging and optimization of the code.

All in all, the PLC-based rheological analyzer approach could potentially offer a readily-realizable, timely, and cost-effective design solution compared to the proprietary solution in Section 3.

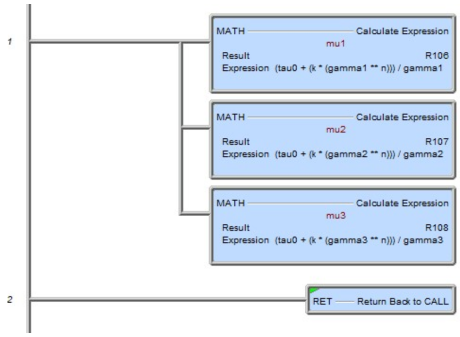
5.0 PROCESS AND ANALYZER SIMULATION

To set the scene for evaluating the viability of implementing the rheological-analysis algorithm proposed in Mwembeshi and Martinelli [3], a model of a theoretical process that exhibits time-varying rheological characteristics was first developed to represent the "true process". The process model was based on the Herschel-Bulkley equation, a generalized equation that allows the modeling of Newtonian, Bingham-Plastic, Shear-Thickening and Shear-Thinning characteristics [3]. The process model outputs three apparent-viscosity measurements (μ_1, μ_2, μ_3) produced at shear rates ($\gamma_1, \gamma_2, \gamma_3$), respectively. The rheological-analysis algorithm was also simulated and output Herschel-Bulkley parameters (τ_0, k, n) computed. Both the process-simulation model (see Table 1) and the rheological analyzer (see Table 2) were implemented using Do-more Designer™ software [4]. Do-more Designer™ is free PLC programming software for Do-more series PLCs. This software is available from AutomationDirect.com [4]. The process-simulation model was implemented using the parameters outlined in Table 1. The equations used in the simulation, including how the output parameters (apparent viscosities) are calculated, are provided within the table.

Table 1 – Rheological Process Simulation

#	Description	Equation or Parameters	Eqn #
1	Rheological Process Simulation Model	$\tau = \tau_0 + k\gamma^n$ Where: τ = shear stress τ_0 = yield stress k = consistency γ = shear rate n = power-law exponent	Eqn 1
2	Simulation Parameters		
	a) Shear Thickening	τ_0 = 0.0 k = 0.000065 $\gamma = [\gamma_1, \gamma_2, \gamma_3]$ n = 2.0	
	b) Newtonian	τ_0 = 0.0 k = 0.065 $\gamma = [\gamma_1, \gamma_2, \gamma_3]$ n = 1.0	
	c) Shear Thinning	τ_0 = 0.0 k = 1.8935 $\gamma = [\gamma_1, \gamma_2, \gamma_3]$ n = 0.51	
	d) Bingham Plastic	τ_0 = 30 k = 0.035 $\gamma = [\gamma_1, \gamma_2, \gamma_3]$ n = 1.0	
3	Simulation Model Outputs	$\mu_1 = \frac{\tau_1}{\gamma_1} = \frac{(\tau_0 + k\gamma_1^n)}{\gamma_1}$	Eqn 2
		$\mu_2 = \frac{\tau_2}{\gamma_2} = \frac{(\tau_0 + k\gamma_2^n)}{\gamma_2}$	Eqn 3
		$\mu_3 = \frac{\tau_3}{\gamma_3} = \frac{(\tau_0 + k\gamma_3^n)}{\gamma_3}$	Eqn 4

The process-simulation-model outputs given in Table 1, section 3 are developed using Ladder programming logic and Math functions provided within Do-more Designer™. Figure 4 provides a snapshot of the logic implementing the simulation-model outputs (Table 1, section 3).



```
1   MATH ---------------- Calculate Expression
                  mu1
     Result                               R106
     Expression  (tau0 + (k * (gamma1 ** n))) / gamma1

    MATH ---------------- Calculate Expression
                  mu2
     Result                               R107
     Expression  (tau0 + (k * (gamma2 ** n))) / gamma2

    MATH ---------------- Calculate Expression
                  mu3
     Result                               R108
     Expression  (tau0 + (k * (gamma3 ** n))) / gamma3

2                         RET ---- Return Back to CALL
```

Figure 4 – Snapshot of Do-more Designer™ Ladder Logic Subroutine Implementing Process Model Simulation Outputs

Furthermore, Do-more Designer™ was used to sequentially transition from one rheological characteristic to another after every 5 seconds. The transitions employed in the simulation are illustrated in Figure 5. Transitions follow the sequence illustrated below and were implemented using Stage Programming within Do-more Designer™.

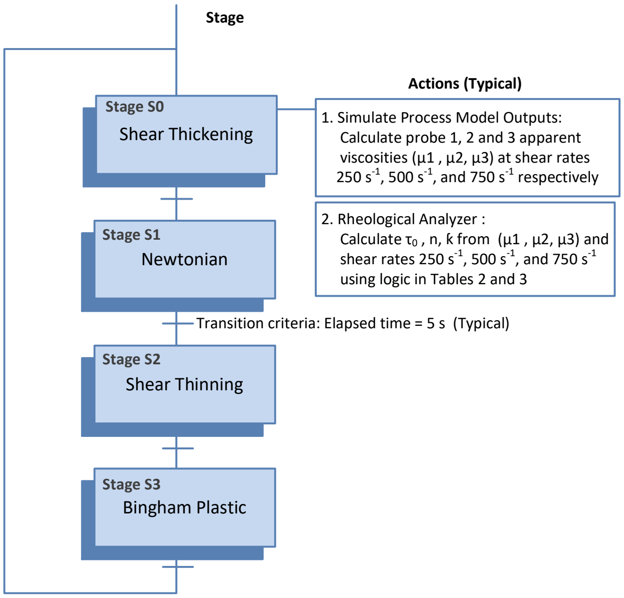


Figure 5 – Simplified Overview of Sequential Simulation of Rheological Characteristics

Each stage first executes the process-model subroutine and determines output apparent-viscosity values (μ_1, μ_2, μ_3). It thereafter executes the rheological-analyzer subroutine. The rheological-analyzer subroutine receives the apparent-viscosities values as inputs, along with the shear rates ($\gamma_1, \gamma_2, \gamma_3$), which are configurable engineering parameters, as would be the case with the actual implementation of the analysis algorithm. Table 2 summarizes the inputs, computations, and outputs from the rheological analyzer.

Table 2 – Simulation of Rheological Process Analyzer (inputs, outputs, and computations)

#	Description	Equation or Parameters	Eqn #
1	Inputs		
	a) Apparent viscosity measurements	μ_1 μ_2 μ_3	
	b) Configuration Parameters – Probe shear rates	γ_1 γ_2 γ_3	
2	Computations		
	a) k_{12}	$k_{12} = \frac{(\tau_2 - \tau_1)}{\gamma_2 - \gamma_1}$ $= \frac{(\mu_2\gamma_2 - \mu_1\gamma_1)}{\gamma_2 - \gamma_1}$	Eqn 5
	b) k_{23}	$k_{23} = \frac{(\tau_3 - \tau_2)}{\gamma_3 - \gamma_2}$ $= \frac{(\mu_3\gamma_3 - \mu_2\gamma_2)}{\gamma_3 - \gamma_2}$	Eqn 6
	c) Functional logic	Refer to Table 3 for functional logic.	
	d) Outputs (quantitative)	τ_0 k n	
	e) Outputs (qualitative)	Rheological characteristic	

Table 3 provides the functional logic of the analyzer.

Table 3 – Functional Logic of Rheological Process Analyzer Based on Heuristic Algorithm in Mwembeshi and Martinelli [3]

RULE #	COND -ITION A	COND -ITION B	COND ITION C	RHEOLOGICAL CHARACT-ERISTICS	RHEOLOGICAL PARAMETERS
1	$\mu_1 < \mu_2$	$\mu_2 < \mu_3$	$k_{23}/k_{12} > 1$	*Shear Thickening*	$\tau_0 = 0$ $n = 1 + [\log_{10}(\mu_2/\mu_1)/\log_{10}(\gamma_2/\gamma_1)]$ $k = (\mu_2/\gamma_2)^{(n-1)}$
2	$\mu_1 = \mu_2$	$\mu_2 = \mu_3$	$k_{23}/k_{12} = 1$	*Newtonian*	$\tau_0 = 0$ $n = 1$ $k = \mu_1$
3	$\mu_1 > \mu_2$	$\mu_2 > \mu_3$	$k_{23}/k_{12} < 1$	Shear Thinning	$\tau_0 = 0$ $n = 1 + [\log_{10}(\mu_2/\mu_1)/\log_{10}(\gamma_2/\gamma_1)]$ $k = (\mu_2/\gamma_2)^{(n-1)}$
4	$\mu_1 > \mu_2$	$\mu_2 > \mu_3$	$k_{23}/k_{12} = 1$	Bingham Plastic	$\tau_0 = (\mu_1 - k)\gamma_1$ $n = 1$ $k = (\mu_2\gamma_2 - \mu_1\gamma_1)/(\gamma_2 - \gamma_1)$

A functional logic diagram showing a nominal implementation of the logic in Table 3 is shown in Figure 6.

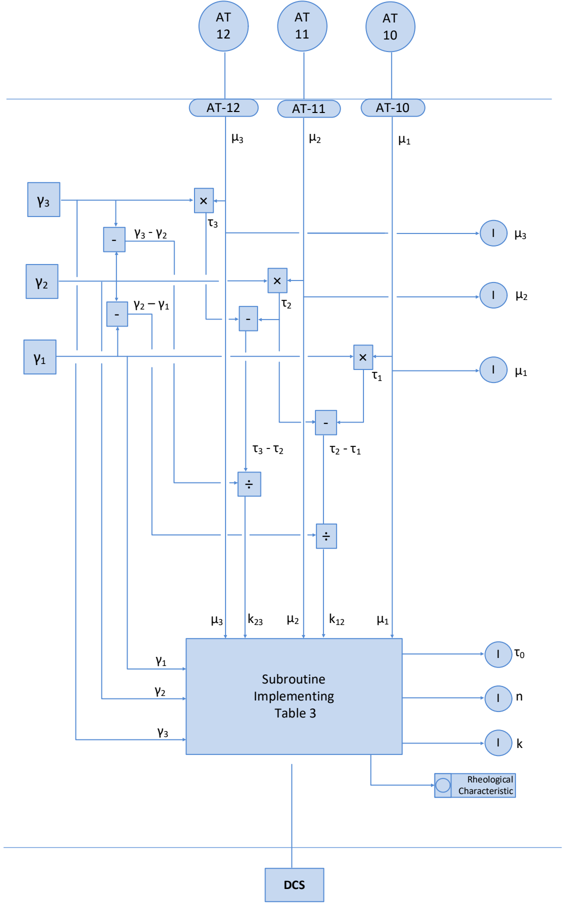
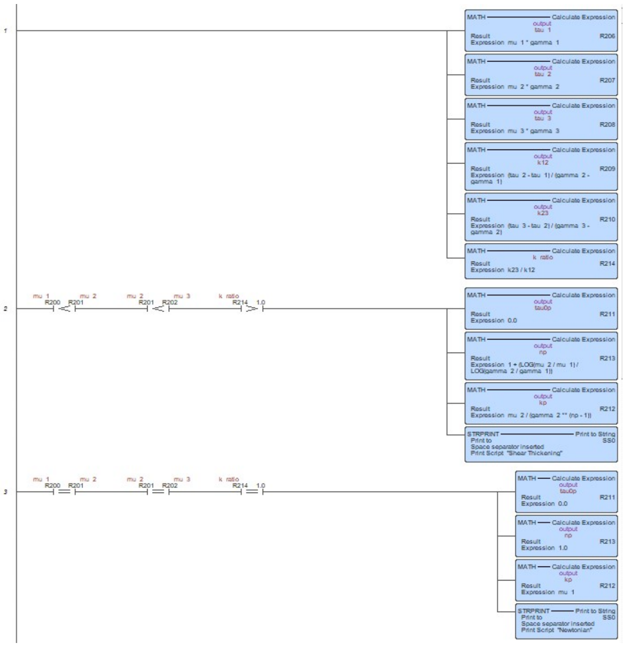


Figure 6 – Rheological Analyzer Functional Logic Diagram

A partial snapshot of the ladder logic in Do-more Designer™, implementing the functional logic outlined in Table 3 and Figure 6, is depicted in Figure 7. The analyzer was implemented as a subroutine in Do-more Designer™.


```
1
MATH — Calculate Expression
  output tau 1
  Result R206
  Expression mu 1 * gamma 1
MATH — Calculate Expression
  output tau 2
  Result R207
  Expression mu 2 * gamma 2
MATH — Calculate Expression
  output tau 3
  Result R208
  Expression mu 3 * gamma 3
MATH — Calculate Expression
  output k12
  Result R209
  Expression (tau 2 - tau 1) / (gamma 2 - gamma 1)
MATH — Calculate Expression
  output k23
  Result R210
  Expression (tau 3 - tau 2) / (gamma 3 - gamma 2)
MATH — Calculate Expression
  k ratio
  Result R214
  Expression k23 / k12

2
mu 1 R200 < mu 2 R201    mu 2 R201 < mu 3 R202    k ratio R214 > 1.0
MATH — Calculate Expression
  output tau0p
  Result R211
  Expression 0.0
MATH — Calculate Expression
  output np
  Result R213
  Expression 1 + (LOG(mu 2 / mu 1) / LOG(gamma 2 / gamma 1))
MATH — Calculate Expression
  output kp
  Result R212
  Expression mu 2 / (gamma 2 ** (np - 1))
STRPRINT — Print to String
  Print to SS0
  Space separator inserted
  Print Script "Shear Thickening"

3
mu 1 R200 == mu 2 R201    mu 2 R201 == mu 3 R202    k ratio R214 == 1.0
MATH — Calculate Expression
  output tau0p
  Result R211
  Expression 0.0
MATH — Calculate Expression
  output np
  Result R213
  Expression 1.0
MATH — Calculate Expression
  output kp
  Result R212
  Expression mu 1
STRPRINT — Print to String
  Print to SS0
  Space separator inserted
  Print Script "Newtonian"
```

Figure 7 – Partial Snapshot of PLC Ladder Logic Implementing Functional Logic of Rheological Analyzer

6.0 SIMULATION RESULTS

The PLC program with the process model and rheological analyzer was run on the PLC Simulator. The PLC Simulator provided with the Do-more Designer™ software is a software PLC that allows the PLC code to be downloaded and run on the PLC Simulator and does not need one to have a Do-more series PLC to perform the simulation. The PLC Simulator runs the PLC code the same way the hardware PLC would run the code. Do-more Designer™ software also includes real-time-trending capabilities that provide visual feedback on the state of information running on either the software or hardware PLC.

Figure 8 shows the real-time trending that was produced by Do-more Designer™ of the apparent-viscosity outputs (μ_1, μ_2, μ_3) from the simulation model and the k-ratio (k_{23}/k_{12}) computed from the k_{23} and k_{12} values (see section 2 of Table 2).

The trend shows changes in the following variables as the process model simulates the different rheological stages:

- μ_1 register R200 (reddish-orange line)
- μ_2 register R201 (green line)
- μ_3 register R202 (light-blue line)
- k_{23}/k_{12} register R214 (yellow line).

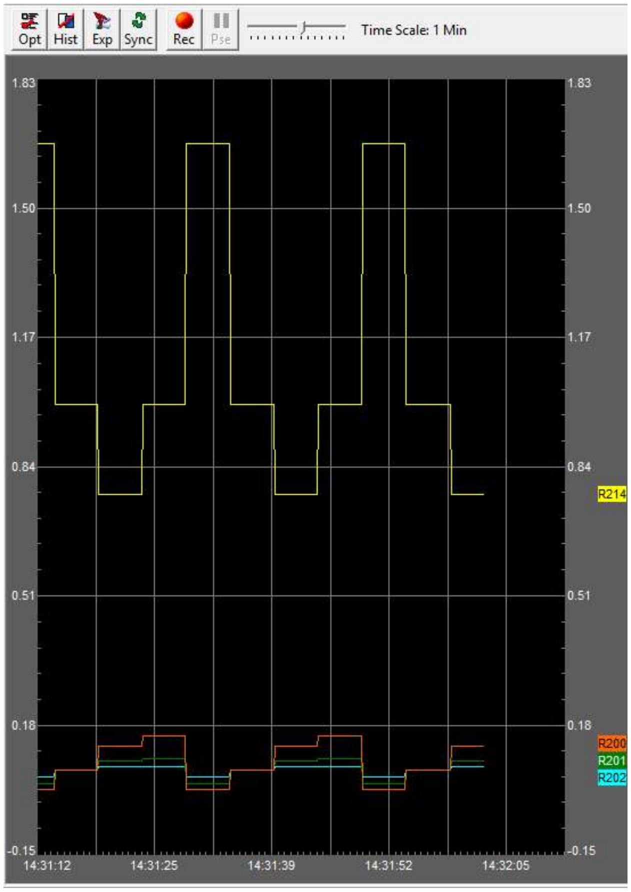


Figure 8 – Real-Time Trend View in Do-more Designer™ PLC Simulator (showing variations in (μ_1, μ_2, μ_3) and (k_{23}/ k_{12}) as simulation-process-model transitions from one rheological characteristic to another)

Figure 9 shows three subplots that depict how the three rheological parameters of interest (τ_0, k, n) compare to the "true" value (in red) and the predicated value (in blue). The PLC memory registers for τ_0, k, and n ("true" values denoted as R100, R101, and R102 are in red) and (predicted values R211, R212, and R213 in blue) overlap throughout the trend as rheological conditions transition. These results graphically demonstrate that the analyzer accurately predicts the rheological parameters.

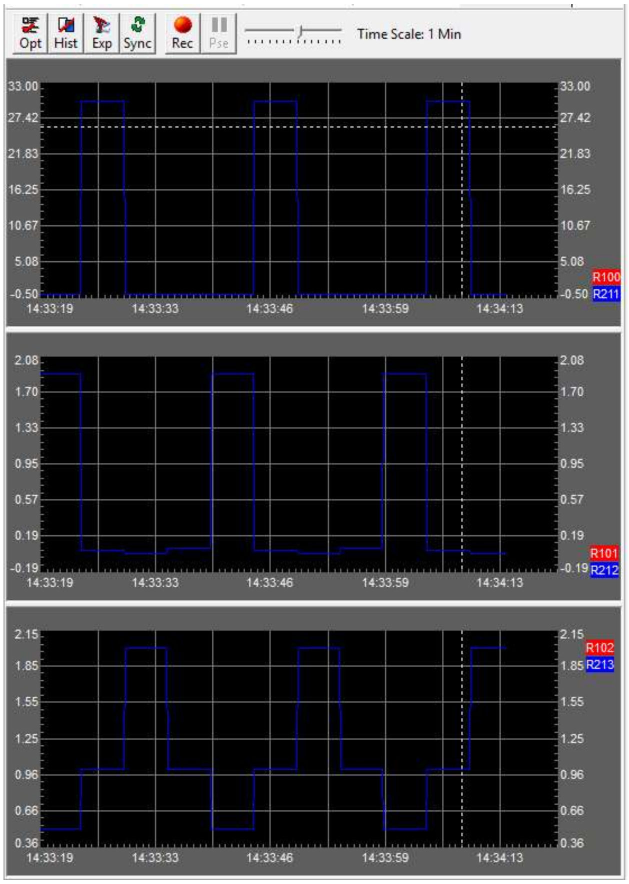


Figure 9 – Snapshot of PLC Simulation (real-time trend showing overlap (red-behind-blue) between "true" values of rheological parameters and values predicted by the rheological-analyzer algorithm)

Parameters in the subplots are as follows:

- First subplot: τ_0 R100 (red, actual) vs R211 (blue, analyzer estimate)
- Second subplot: k R101 (red, actual) vs R212 (blue, analyzer estimate)
- Third subplot: n R102 (red, actual) vs R213 (blue, analyzer estimate).

In addition to the quantitative estimates illustrated in the simulation results above, the rheological analyzer was also found to accurately determine the rheological characteristic of the process using the logic in Table 3 and exhibited the characteristic as "Newtonian", "Shear Thickening", "Shear Thinning" or "Bingham Plastic".

7.0 CONCLUSIONS

This paper presented and compared two design solutions that advance the prospects of integrating real-time, rheological process analyzers for facilities with non-Newtonian processes that need to be characterized to support process management and control. The design solutions would automate rheological monitoring, effectively eliminating grab sampling for rheological information gathering. Eliminating grab sampling is desirable as the sample-and-analyze approach can be time consuming, which can unduly impact a facility's throughput and production capability. Although the two rheological-analyzer configurations discussed in this paper overcome the limitations of torsional oscillation viscometers (TOVs), allowing use of this technology for generalized rheological monitoring, the approaches have significant differences that could aid or hamper the justification for incorporating the technology into the design of a facility. The proprietary analyzer configuration (design solution 1), although desirable as it has a minimum number of components needed to perform the rheological-monitoring function, this solution is first-of-kind (FOAK) design. It requires new proprietary hardware and software with potentially high capital costs and lengthy procurement lead times. The PLC-based rheological analyzer (design solution 2), in comparison, potentially offers a rheological-analyzer solution that is readily realizable, more cost-effective, and might better align with a time-constraint schedule. Furthermore, this paper also evaluated the rheological analyzer's functional logic using a PLC simulator. The simulation results showed that a proposed rheological-analyzer algorithm is a viable solution for real-time characterization of non-Newtonian processes, even with time-varying rheological characteristics.

8.0 REFERENCES

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9.0 ABBREVIATIONS

ASME	American Society of Mechanical Engineers
COTS	Commercial-off-the-shelf
DCS	Distributed Control System
EMI	Electromagnetic Interference
EPC	Engineering Procurement and Construction
FOAK	First-of-a-kind
HMI	Human Machine Interface
I/O	Input/Output
IEC	International Electrotechnical Committee
ISA	International Society of Automation (formerly Instrument Society of America)
NRTL	Nationally Recognized Testing Laboratory
PLC	Programmable Logic Controller
OEM	Original Equipment Manufacturer
SAMA	Scientific Apparatus Makers Association
TCP	Transmission Control Protocol
TOV	Torsional Oscillation Viscometer

10.0 LIST OF SYMBOLS

f_R.	Resonant frequency of TOV probe
τ	shear stress
τ_0	yield stress
τ_1	shear stress of TOV probe 1
τ_2	shear stress of TOV probe 2
τ_2	shear stress of TOV probe 3
k	consistency index
k_{12}	shear-stress/shear-rate ratio between TOV 2 and 1
k_{23}	shear-stress/shear-rate ratio between TOV 3 and 2
γ	shear rate
n	power law exponent
μ_1	apparent-viscosity value from TOV probe 1
μ_2	apparent-viscosity value from TOV probe 2
μ_3	apparent-viscosity value from TOV probe 3