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Real-Time Control of Viscosity Curve for a Continuous Production Process of a Non-Newtonian Fluid

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This work aims to develop a control system capable to maintain the viscosity curve measured in-line during the continuous production of a non-Newtonian fluid inside a range of values of viscosity which represent the target. Rheological models capable of relating the viscosity curve of the final product to the input variables were introduced to mimic changes in the production of a non-Newtonian fabric. A one-point control has been developed that acts modifying the mass flows of ingredients injected in the production plant to reject disturbances or track set-point changes. The developed controller is capable to maintain the viscosity curve inside the desired confidence range of viscosities. The methodology is easy to implement in similar continuous production processes by adjusting the model for other ingredients.

1. Introduction

Nowadays in many industrial continuous production processes of complex fluids, the rheological properties of the products are measured and verified only when the production is finished, with random checks and using off-line instruments like rheometers. If specifications are not met, products could not be suitable to their placing on the market or to their utilization in possible next steps of production. When dealing with non-Newtonian fluids, problems become much more complex because of the possible significant changes in the product behavior, as flowing rate varies during the process. Flow properties such as the shear rate dependent viscosity, affect product quality and therefore represent important control parameters. The available measurement methods, such as offline rotational rheometers, cannot be used for automatic control, whereas a few in-line rheometers have been tested in industrial applications and no practical solutions are available for non-Newtonian and opaque industrial fluids (Meacci et al., 2016). Another drawback of the available in-line sensors is that they are typically able to estimate the viscosity only at a single shear rate, therefore their use for control purposes is not successful.

Because the continuous monitoring of quality indexes of industrial fluids during production is of paramount importance for process and quality control, in the last few years several studies have been made to develop new sensors capable of in-line measurement (Zhang et al., 2014). For the rheological behavior of complex fluids, non-invasive ultrasound techniques have been proposed for estimating velocity profile of the fluid, as evidenced in recent investigations on this topic (Meacci et al, 2016; Kotzé et al., 2013; 2015, 2016). When such technologies will become mature and available on the market, a real-time control of viscosity curve could be implemented in production plants in order to maintain the rheological properties of the product inside the specific range.

This work looks ahead and aims to provide a preliminary analysis of these types of problems. First, rheological models capable of relating the viscosity curve of the final product to the amount of a specific ingredients have been developed. The models are calibrated and validated using the experimental values obtained with the rheological characterization of a detergent. For confidentiality reasons the product composition cannot be disclosed. A dynamic representation of the fluid system in term of viscosity is obtained to fit control design and evaluation purposes. Assuming that only one manipulated variable is available, a one-point PI controller is applied to the simulated process considering the viscosity at different shear rate values as controlled output. In the studied case, multiple process measurements may be available for the given manipulated variable that needs to be regulated through a single control action. It is evident that the control strategy should be based on the most critical measurement condition for the process variable and a systematic analysis on the possibility to reach a specified control objective is developed (Ghadipasha et al., 2015; Cogoni et al., 2014). The target is to minimize the distance between the reference curve and the obtained one without an excessive load on the manipulated input, by properly selecting the point viscosity measured at a given shear rate.

2. Process description and modelling

The production of a detergent is considered to address the control of the rheological properties. The end product is a mixture of different components showing a highly complex rheological behavior. Notice that the blends rheology is generally strongly affected by several factors such as rheology of the single components, temperature, interfacial tension, polydispersity and others (Mewis and Wagner, 2012, Reinheimer et al. 2012).
The process has been studied on Pilot Plant (PP) scale exploiting the facilities made available by the Brussels Innovation Centre (BIC) in Belgium. The PP was designed as a series of tanks, each of them containing one of the ingredients used for the detergent production. After injection of each new component, a static mixer is present to obtain a good blending of the different constituents. For further details on the process see Corominas et al. (2013).
Ingredients and plant configuration details cannot be disclosed for confidentiality reasons. However, the real nature of ingredients is not necessary for the present scope, and information on the plant are only related to the description of the process dynamics. A scheme of the process under investigation is reported in Figure 1. Hereafter we refer to the ingredients of the detergent with the capital letters A, B, C and D. Information on the system dynamics is gained using different pressure and temperature sensors and an in-line Endress-Hauser Proline Promass 83I Coriolis flowmeter, which also gives a point measurement of viscosity. When dealing with non-Newtonian fluids, such output is not exhaustive. For this reason, offline rheological measurements were also carried out on the samples gathered in the outlet stream with a rheometer AR-2000 TA stress controlled. The dependence of the apparent viscosity η_a from the shear rate $\dot{\gamma}$ is eventually inferred.

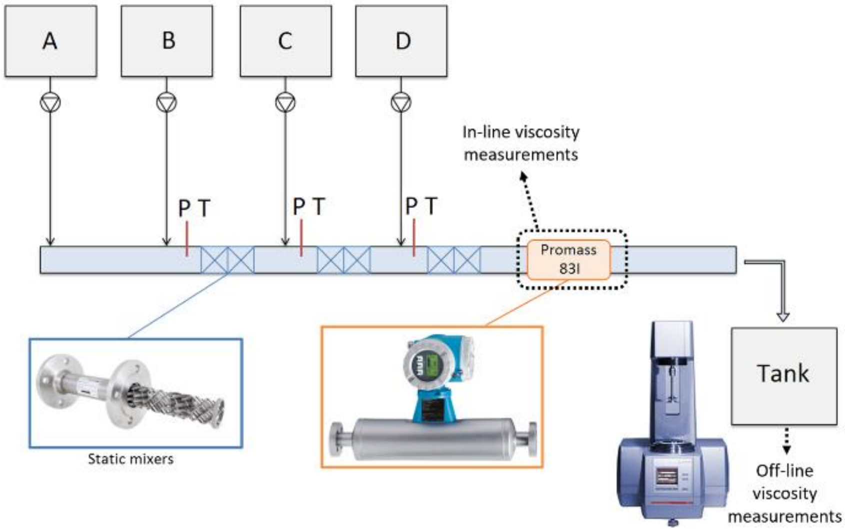

Figure 1: Scheme of the process

The pilot plant process dynamics is therefore analyzed from data obtained by applying step changes to the input variables. For control purposes, it is important to evaluate the response of the measured outputs (pressure, temperature, viscosity, rheological curve) with respect to the manipulated inputs (detergent ingredients flow rate).
Data gathered on-line in presence of the step variation of the ingredient D flow is represented in Figure 2, where the output responses provided by temperature sensors and the Promass flowmeter are reported. Temperature changes (Figure 2b) are registered after the injection of D and they are due to different conditions of the tank containing the detergent ingredient and mixing phenomena. Ingredient D seems to act a

viscosity decrease (Figure 2c), that it is also affected by temperature variations that can be considered as a disturbance for the process.
The off-line rheological data were described with the Carreau model (Macosko, 1984), reported in Eq. (1), where the dependence of the fluid on the flow is described in terms of a parsimonious number of parameters: i) the zero-shear rate viscosity η_0; ii) the infinite shear rate viscosity η_∞; iii) the time constant λ and iv) the power index *n*.

$$\eta_a(\dot{\gamma}) = \eta_\infty + \frac{\eta_0 - \eta_\infty}{(1 + (\lambda\,\dot{\gamma})^2)^{n/2}} \tag{1}$$

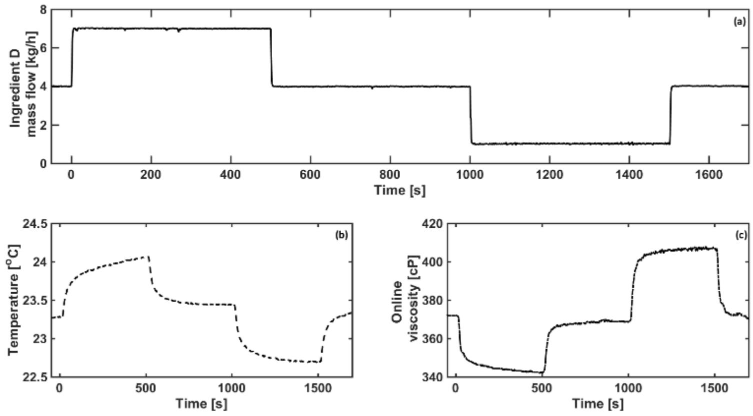

Figure 2: Step variation of the ingredient D flow and output responses of temperature and online viscosity.

3. Model development

3.1 Rheological characterization

Off-line rheological measurements showed that the complex fluid exhibits a non-Newtonian behavior, that changes with the input variations. An example of such feature is depicted in Figure 3, where the model predictions are reported with lines and experimental data with points (cross points refer to the nominal process condition, white circles to 40% increase in the flow rate of D, white squares to a 40% decrease). Notice that the Carreau model in Eq(1) quantitatively agrees with the experimental data at any experimental condition. In addition, it was observed that, as D feed flow rate increases, (i) the zero-shear rate viscosity increases, (ii) the infinite shear rate viscosity decreases, (iii) the power index n increases, as it can be supposed by visual inspection of Figure 3.

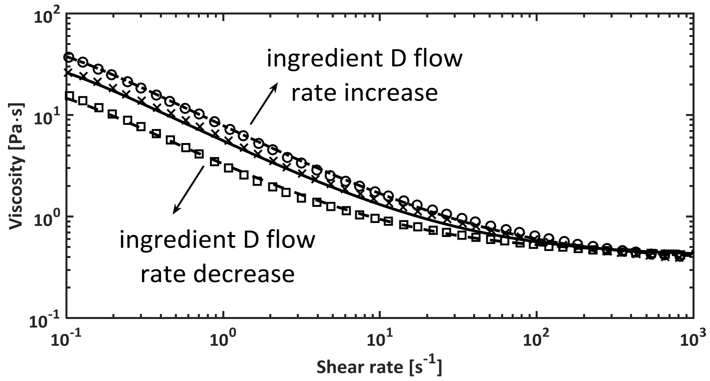

Figure 3: Rheological behavior of the detergent at different process conditions.

It is worth noticing that the effect of the D ingredient variation is more significant at low shear rate, whereas for circa $\dot{\gamma} = 300\ s^{-1}$, the effect of the manipulated variable is almost negligible and the viscosity variations are relatively small. It is interesting to note that the behavior of the viscosity for shear rate values less than circa

100 s^{-1} is opposite with respect to the on-line viscosity response; conversely there is agreement with the results obtained with the on-line viscometer at high shear rate. Another observation useful for the design of the proper control action is that large variations of the viscosity are appreciated at low shear rate values (20 Pa·s).

3.2 System identification

Using the off-line experimental data obtained with the step tests described in Section 2, the input-output relationship between the rheological behavior of the blend and the D ingredient feed flow rate is developed. A dependence on the temperature is also taken into account, with the aim of simulating the effect of a disturbance and test the proposed controller strategies. Simple, but effective, empirical relationships relating the rheological parameters to the ingredient mass flow rate at room temperature are provided in Eq. (2):

$$\begin{aligned} \lambda &= 14.85 \\ n &= 0.756 \\ \eta_0 &= 10.51\, Q_D - 1.665 \\ \eta_\infty &= -0.0203\, Q_D + 0.487 \end{aligned} \tag{2}$$

Eq. (2) along with the dynamic information acquired with the step test responses are used to obtain a dynamical model which relates viscosity at a given share rate and D flow rate. In more detail, a first order plus delay model is assumed to describe the behavior of the viscosity as a function of Q_D (see Eq. (3))

$$\frac{\Delta\eta(\dot{\gamma})}{\Delta Q_D} = \frac{K_p}{\tau_p s+1} e^{-t_d \cdot s} \tag{3}$$

where the process gain constant is calculated by means of Eq. (2) while time delay and characteristic time from the dynamic response of the punctual viscosity are calculated with the in-line Coriolis flowmeter. In particular, characteristic time is set equal to 16.63 *s* and the delay time is set equal to 16.50 *s*. Figure 3 shows the comparison between the model prediction and the off-line experimental data for viscosity corresponding at $\dot{\gamma} = 0.1\ s^{-1}$ in presence of a 20% increase of the D flow feed.

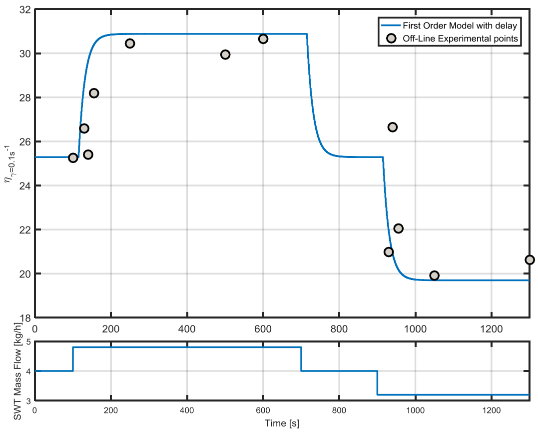

Figure 4: Prediction of the empirical model (solid line) compared with experimental points (full circles) in presence of a 20% step-test variation in the D ingredient flow feed

4. Control

The objective of the controller is to maintain the viscosity curve of the detergent as closest as possible to a reference curve. The main critical issue of the control problem is that only one manipulated input (ingredient D feed flow rate) can be used for several possible outputs (the viscosity values at different shear rate). A SISO (single input – single output) feedback controller can be a suitable choice if it is possible to assess the shear rate value which guarantees the proper control of the blend characteristics, in the understanding that the point control should be able to reduce the effect of perturbation even at the other shear rate values.

The analysis of the rheological curve (Figure 3) suggested that viscosity at higher shear does not change significantly, at least in the case of the D ingredient fluctuations, while greater effect can be observed at the lower values thus suggesting that the viscosity point to be controlled should be at low shear rate. For these purposes, a systematic analysis has been performed with the aim of evaluating the response of a PI controller for different $\dot{\gamma}$ and the results are reported in Table 1. The distance between the target and the final curves is evaluated by means of the mean square error (MSE), which is defined in Eq. (4). The load on the manipulated input has been calculated with Eq. (5). It is important to underline that sensor and actuator dynamics are neglected during the simulations.

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(\eta(\dot{\gamma}_i)_{ref} - \eta(\dot{\gamma}_i)\right)^2 \tag{4}$$

$$load = \frac{\max(\Delta Q_D)}{\Delta T} \tag{5}$$

The obtained results show that the minimum distance between the obtained viscosity curve and the target is when $\dot{\gamma}$=0.17, for an acceptable load on the manipulated input.

Table 1: Performance of the controller for $\eta(\dot{\gamma})$ at different shear rates

$\dot{\gamma}$	Load	MSE
0.1	0.1234	0.25218
0.17	0.1515	0.12882
0.25	0.1763	0.15174
0.5	0.2198	0.48892
1	0.2478	0.90507
5	0.2364	0.71567
10	0.2170	0.4559
100	0.2292	0.6121

By way of illustration, Figure 5 reports an example of the performance of the controller action when the viscosity at $\dot{\gamma} = 0.17\ s^{-1}$ ($\Delta\eta$ = 2.5 Pa·s) is selected as controlled output. A temperature increase (ΔT = 5°C) occurring at time t=200 s (5a) moves the system away from the nominal condition. The controller correctly adjusts the D feed flow rate rejecting the effect of the disturbance and tracking the viscosity curve close to the target, as it is shown in Figure 5d. The system response in absence of controller is also reported for comparison. Figure 5e reports a zoom of the viscosity curve at low shear rate value, in order show the behavior of the system in the neighborhood of the controlled output.

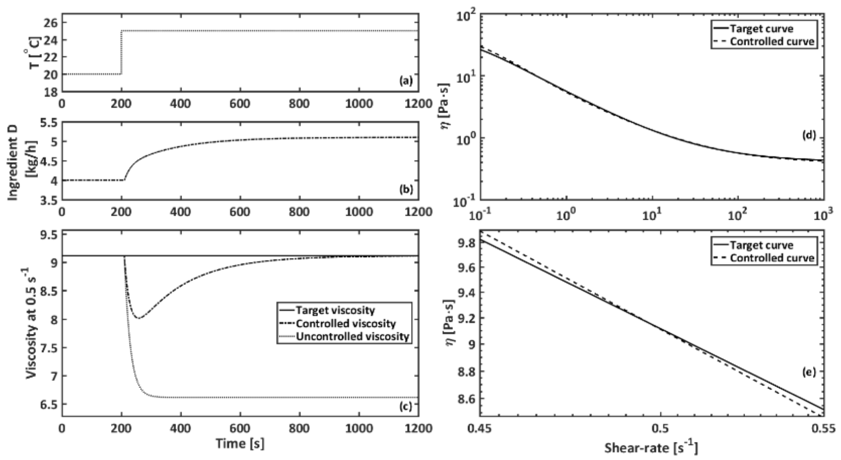

Figure 5: Controlled system responses

5. Conclusions

This work focuses on the main issues concerning the real-time control of viscosity curve for continuous production processes of non-Newtonian fluids. The production of a detergent obtained by mixing four ingredients has been selected as case study, and the experimental data obtained in pilot plant have been used to construct a simulation model to be used to develop and assess the control strategies. The developed model describes the relationship between the unique manipulated variable and the rheological curve of the

system taking into account the effect of temperature, which acts as a disturbance. The here proposed model is rather simple and the behavior is assumed to be linear, but it can give useful insights on the main issues related to the control of shear rate dependent viscosity, in the understanding that the target of the problem is not a point value but infinite points lying on a one-dimensional manifold (the viscosity curve). The rheological properties may deviate from the nominal ones, because of process disturbances, and they can be adjusted by varying the ingredients flow rates which have a major impact without affecting excessively detergent characteristics.
A point control for the viscosity curve of the non-Newtonian detergent is implemented, where the objective is to maintain the viscosity curve inside a specific range of values which represent the target. The analysis leads to individuate at which shear rate value the viscosity has to be kept constant at a given set-point in order to guarantee the minimum distance from the target properties.
It should be pointed out that the obtained result depends on the rheological behavior of the specific material. Therefore, a different position could be recommended when changing the material and the adjustment of the PI tuning parameters should also be necessary. The proposed procedure could be implemented in the future as suited in-line rheological sensors become reliable, whereas collection of more experimental data can be useful to develop more detailed nonlinear models of the process.

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