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Esterification in an Autonomously Controlled Reactor: Exploiting the Chemo-Mechanical Properties of a Smart Organogel

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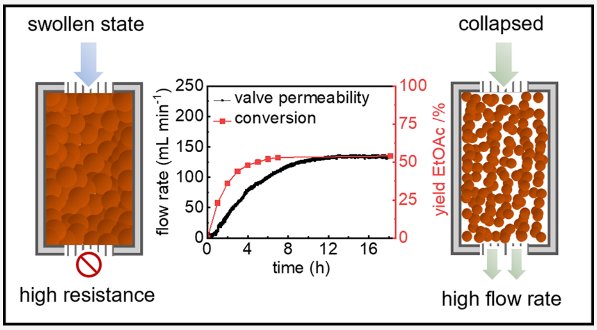
ABSTRACT: Iron(III)-reinforced poly(*N*-isopropylacrylamide-*co*-acrylic acid) organogel beads inside a casing give an intrinsic chemo-mechanical valve. The valve was incorporated in a setup with a stirred reactor for the heterogeneously acid-catalyzed esterification of acetic acid and ethanol. A noninvasive gravimetric control loop was used to validate the autonomous modulation of the hydrodynamic residence time in response to the composition of the reaction mixture. Operating at a 1:1 molar feed ratio, the valve restricted the initial outflow to less than 7 mL·min^{-1} and autonomously ramped up to a steady state flow of 135 mL·min^{-1} as the esterification approached thermodynamic equilibrium. The valve opening rate was about half of the reaction rate. The ionically reinforced organogel had enough resilience inside the casing for multiple uses. Soft actuators were thus successfully applied for reaching a self-regulating reactor loop driven by intrinsic chemical feedback of a smart material.



1. INTRODUCTION

The transition from discontinuous batch production to continuous flow processes is a key strategy for process intensification in the chemical industry and comes along with fundamental challenges in the form of product quality and operational safety.[1−3] Micro- and mesoflow reactors offer excellent heat and mass transfer properties but often come at the cost of increased peripheral complexity. Flow systems require precise control for product consistency, which typically necessitates a close-knit network of online analytics (PAT), digital control loops, and electromechanical actuators.[4,5] Contrasting this development is the interest in the context of Industry 4.0 for strongly reduced external infrastructure in decentralized, modular production concepts ("smart reactors").[6] One incentive is to create autonomous systems that respond to process deviations through their intrinsic material properties. This is inspired by biological parallels such as plant stomata or heart valves, which respond to local stimuli without a central nervous system.[7−10] An "intelligent" reactor would be able to couple the discharge rate directly to the reaction progress, for example, by severely restricting the outflow of reactants during the starting phase and continuously increasing the throughput as the product concentration approaches equilibrium. A recent example showed that the heat of polymerization can be a trigger for a valve with thermoresponsive beads (thermoresponsive microvalves have been known for over 20 years).[11,12]

Controlling equilibrium-limited condensation reactions, such as the esterification of carboxylic acids with alcohols, represents a higher process engineering challenge not only in the context of a smart setup.[13−16] The execution in the form of the formation of ethyl acetate from ethanol and acetic acid was taken here as a showcase. It basically is a thermoneutral reaction with a low rate, and monitoring the progress comes along with the detection of the chemical composition. This implies that the intelligence of the setup must respond to the latter. It requires a smart valve that actively reacts to the chemical identity of the reaction mixture.[17−19] The autonomous operation of a setup with a stirred tank reactor for batch esterification and an external loop with such a valve was achieved. This smart valve functions as a chemical, autonomous gatekeeper, keeping the reactants in the reactor and thus at the reaction temperature. This gatekeeper regulates

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the hydrodynamic residence time of the liquid. It was in the closed state as long as the polar reactant mixture was predominant in the reactor and opened when conversion reached equilibrium, i.e., when the polarity decreased by the increasing concentration of the ester/water product mixture. Further processing then can follow for separation of the product.

Stimuli-responsive hydrogels principally can offer a mechanical response in the form of a volume change to a change in the chemical environment. Incorporation of such hydrogels in an appropriate casing can, upon swelling, lead to a mechanical blockage, which corresponds to the function of a valve.[11,20−22] Many examples of pH- or thermoresponsive systems in aqueous media have been reported; these studies were primarily driven by an interest in biomedical applications.[23−30] Responsive gels in organic media for applications in synthetic chemistry have been researched far less extensively.[31,32] Recently, macroporous poly(*N*-isopropylacrylamide-*co*-acrylic acid) (P(NiPAAm-*co*-AA)) beads synthesized by UV droplet polymerization were prepared that were shown to have distinct volumes in various solvents.[33] Changing the medium, e.g., from ethanol to ethyl acetate, leads to a useful change of volume for a derived mechanical action. This intrinsic chemo-responsivity makes the beads potential candidates for a chemical check valve construction in the context of esterification and possibly other reactions as well.[34,35]

A follow-up study addressed the mechanical resilience of soft P(NiPAAm-*co*-AA) beads. The chemically cross-linked gels have high swelling and medium sensitivity but lack mechanical stability when swollen. The hydraulic pressure differences in a pumped circuit can (irreversibly) deform these soft networks, compress them, and/or protrude them through retention screens. The latter leads to a rapid loss of valve functionality. A common postsynthetic treatment of the beads with multivalent ions led to core-Fe(III)-shell bead particles with much better mechanical resilience while retaining substantial solvent responsiveness.[36−41]

This study presents the development and validation of an autonomously controlled smart reactor system for the heterogeneously acid-catalyzed esterification of acetic acid with ethanol. Confined core-Fe(III)-shell P(NiPAAm-*co*-AA) beads in a casing function as the active gatekeeper at the bottom outlet of a stirred tank reactor. A gravimetrically determined operation in which mass flow serves as a direct indicator of the opening state of the valve was realized. This allowed monitoring of the state of swelling of the gel, which changed depending on the progress of the esterification. The system principally switches between closed (reactant retention) and open (product removal) modes. It was thus demonstrated that a gel-based smart valve can be used for autonomous fluid control in an equilibrium-limited reaction in an organic medium. This development extends beyond the explored gels in aqueous media for biomedical purposes, i.e., for the controlled release of an active compound upon a stimulus,[22,42] or in microflow systems.[43−45,46,47] The work holds promise for further macroscopic engineering applications. The simple design of a setup with a feedback loop shows how the need for external electronic control loops or continuous inline analytics can be reduced. The presented system with a robust soft material is also cost-effective, where an intrinsic chemical feedback directly governs the reactor residence time. This work also connects soft matter materials science to autonomous chemical process engineering at the macroscale.

2. EXPERIMENTAL SECTION

2.1. Materials

Amberlite IRC-120 Ion Exchange Resin (Sigma-Aldrich, Taufkirchen, Germany), ethanol absolute ≥99.8% (VWR Chemicals, Darmstadt, Germany), and ethyl acetate (BCD Chemie GmbH, Hamburg, Germany) were obtained from indicated sources. Organogel beads P(NiPAAm-*co*-AA)/Fe-Low were synthesized as previously described.[41] The Amberlite IRC120H catalyst was washed with ethanol (3× 150 mL per 35 g) prior to use and then dried under vacuum at 40 °C for 24 h. The enzymes tested were CALB (Sigma-Aldrich), amano-lipase-PS from *Burkholderia cepacia* (Sigma-Aldrich), and a lipase from *Candida rugosa* (Sigma-Aldrich).

2.2. Reactor Setup and Process Control

The autonomous loop reaction system was built around a 500 mL double-walled glass reactor (Rettberg GmbH, Germany) with a central bottom outlet (Figure 1). The reactor was modified with an integrated glass frit (porosity 0) to serve as a retention barrier for the heterogeneous acid catalyst Amberlite IRC120H. Temperature control was achieved using a thermostat (Julabo EH5, Seelbach, Germany), which circulated water through the jacket of the vessel to maintain a constant reaction temperature of 50 °C (±0.1 °C). The mixture in the reactor was stirred with an electronic overhead stirrer (IKA EUROSTAR digital, Staufen, Germany). The propeller stirrer was operated at 1000 rpm. The smart valve consisted of a custom-made stainless steel flange valve (25 mm height, 25 mm inner diameter) attached directly to the reactor outlet. An additional custom-made glass flange valve (70 mm height, 25 mm inner diameter) was manufactured to allow for direct observation of the hydrogel behavior. The iron(III)-functionalized organogel beads were filled into this casing and retained there by a chemically inert stainless steel mesh with a pore size of 1 mm. The bead size was 6.4 ± 0.6 mm (conditioned in ethanol).

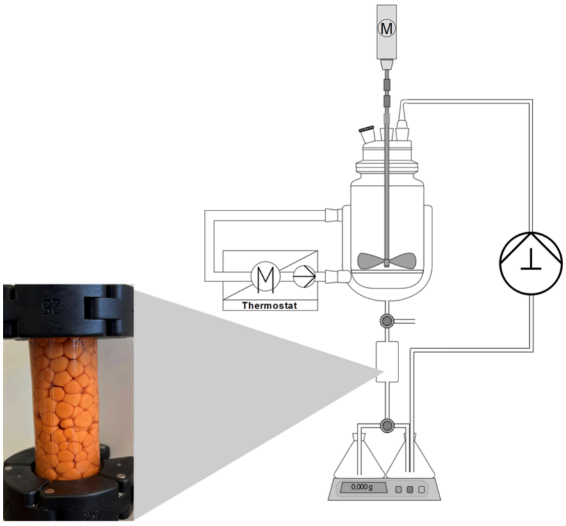

Figure 1. Loop reactor setup for the esterification reaction; inset: swollen beads in the glass casing.

The reaction mixture was allowed to leave the reactor through the organogel valve into a collection container placed on a precision balance (Mettler Toledo, Giessen, Germany). A diaphragm metering pump (ProMinent Delta optoDrive, Heidelberg, Germany) with a maximum delivery rate of 160 strokes per minute and a maximum flow rate of 30 L·h^{-1} continuously fed the reaction mixture from this container back to the main reactor vessel. A proportional-integral control algorithm implemented in the software regulated the pump

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frequency in real time to maintain a constant mass in the lower container. The entire process automation was controlled by a LabManager system (LM-LABBM2B, HiTec Zang GmbH, Herzogenrath, Germany). The pump stroke frequency was recorded to serve as a flow meter for the valve.

2.3. General Procedure for Batch Esterification (Closed System)

The orientating esterification reactions were carried out in sealed glass vessels containing a total volume of 15 mL of the ethanol/acetic acid reactant mixture at molar feed ratios of 1:1 and 2:1. The temperature of the mixture was set to 50 °C, and the reaction was initiated by adding 10 wt % of the dried Amberlite catalyst (relative to the total liquid mass). The mixture was stirred at 600 rpm. Conversion was monitored by taking and evaluating proton nuclear magnetic resonance spectra of the samples (^{1}H NMR obtained from a Bruker 300 MHz spectrometer). Samples (0.05 mL) were withdrawn from the reaction supernatant at hourly intervals for the first 5 h, followed by a final measurement after 24 h. Each aliquot was immediately diluted with 0.5 mL of deuterated dimethyl sulfoxide (DMSO-d_6), and the ^{1}H NMR spectrum was recorded. The molar conversion was calculated from the integrated signals of the methyl group of ethyl acetate and acetic acid.

2.4. Volumetric Tracking of Swelling Behavior

The swelling kinetics of beads were monitored using a previously established optical tracking setup.[41] Image sequences of the beads were recorded at 30 s intervals (Canon EOS R50) and processed via a custom Python algorithm to determine their diameter. The distinct deep orange coloration of the Fe^{3+}-loaded beads facilitated a robust segmentation against a black background by applying color thresholding. Hydrodynamic radii were calculated from the detected contours by using a metric calibration scale.

3. RESULTS AND DISCUSSION

The reactor setup shown in Figure 1 was assembled and used for the esterification of ethanol and acetic acid. The main reactor contains the solid Amberlite acid catalyst, which is the main driver for the reaction to reach equilibrium. Several enzymes were also screened for the esterification; however, for the relatively small polar reactants, the Amberlite catalyst gave better results and faster reactions. The kinetics of esterification under acid catalysts usually follow a second-order rate law, i.e., first-order in the concentration of both reactants, as is the case for the back reaction, the hydrolysis of ethyl acetate.[48,49] The reactor contains a frit to keep the solid catalyst particles confined to the reactor. The reactants and products can leave the reactor through the bottom opening by gravitation. The liquids subsequently pass through a casing with the iron cross-linked organogel beads of the P(NiPAAm-*co*-AA) copolymer. The state of swelling of the beads determines the rate of free flow. The liquids are collected in a flask that is placed on a scale. A computer-controlled pump keeps the mass in the flask constant by returning the excess back to the main reactor.

The pump volume is thus a measurement for the mass of the liquids leaving the reactor. The gravimetric closed-loop system thus has a robust flow sensor when a constant mass level in the intermediate tank is accurately maintained by the pump. This is achieved using a proportional-integral controller (PI controller). It regulates this balance with a negative proportional gain (K_p of -4) and an integral time t_n of 25 s. This configuration enables the system to compensate for flow deviations within the operating range of the pump. Linear calibration converts the control signal (stroke frequency) into a volume flow with a maximum capacity of 30 L·h^{-1}.

Cyclical switching (manually) of the solvent in the reactor between ethanol and ethyl acetate was used to assess the behavior of the setup. These compounds were also chosen because they are the dominant factors for the degree of swelling of the gel. The degree of swelling of the beads changes by 0.32 between ethanol and ethyl acetate, whereas this number reduces marginally to 0.19 between equimolar mixtures of ethanol/acetic acid as reactants and the corresponding equilibrium mixture containing all four compounds. A dynamic response and good mechanical stability of the system under flow conditions were found (Figure 2). Ethyl acetate acts as the trigger to the shrunken state: its presence causes the beads to shrink and is characterized by a time constant of about 140 s (Figure S1a, SI). The system response is one of opening the valve, which leads to a higher flow out of the reactor and subsequently an increased pump volume. A switch to ethanol causes the polymer network to swell, be it at a somewhat lower rate (time constant of 260 s; Figure S1b).[11] The controller consequently throttles the pump to below 10 mL·h^{-1} to compensate for the blocked outlet. The reversible actuation mirrors the swelling kinetics previously established.[41] The iron-reinforced beads exhibit consistent performance over a period of 5 h without mechanical degradation or drift. This mechanical integrity under hydrodynamic stress distinguishes the reinforced hybrid material from the more compliant parent P(NiPAAm-*co*-AA) gels.

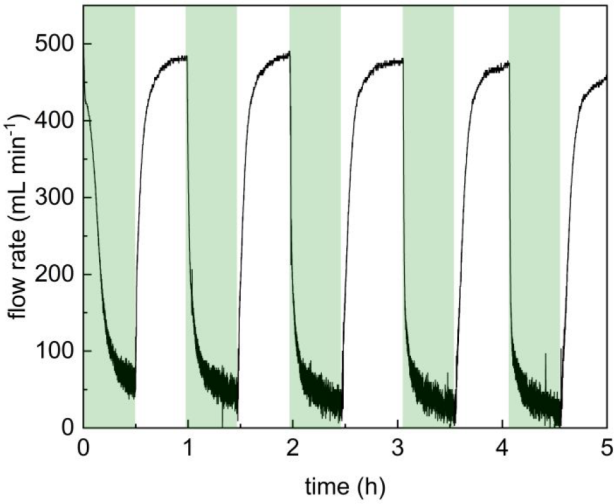

Figure 2. Pump volume level response to cyclic changing of the solvent in the main reactor from ethanol to ethyl acetate (green underlay) at 25 °C.

3.1. Operating Window

Conditions for the esterification of ethanol and acetic acid were elaborated with the aim to use the setup for detecting conversion and for controlling the reactor. Therefore, batch screening experiments were performed for finding a useful rate for experimenting and a suitable ratio of reagents. A conversion close to equilibrium after 5 h was taken as a criterion, which was found to be realized at 50 °C at 10 wt % of Amberlite catalyst. The value for the equilibrium constant at 50 °C is found to be close to 2.4, i.e., when starting from an equimolar mixture (Table S1).[50] The indicated final values of acid conversion (i.e., ethyl acetate formation) and the overall rates are higher for mixtures with an increasing excess of ethanol, as expected on account of the simple kinetics (Figure 3).

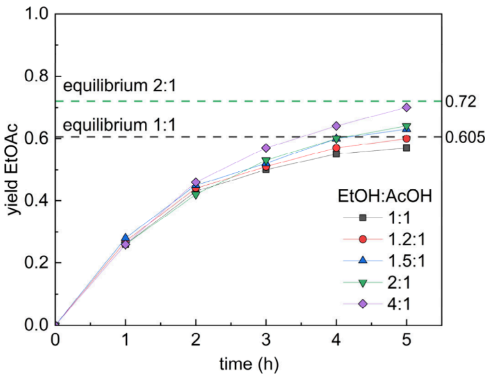

Figure 3. Batch esterification reactions at different ratios of ethanol/acetic acid at 50 °C (cf. Figure S3, Table S1; dashed lines indicate the calculated equilibrium conversion).

Increasing the excess of ethanol from 1:1 to 4:1 leads to a shift in the conversion of acetic acid from 57% to 70%, and the rate is also higher. The concomitant concentration of ethyl acetate in the mixture decreases, however, by a factor of about 2 by the ethanol excess.

Further testing was carried out on the iron(III) cross-linked core−shell beads for their behavior in different mixtures of ethanol and ethyl acetate. Previous studies showed that the concentration of ethyl acetate is of particular importance for the state of swelling of the NiPAAm-AA copolymer. The Fe(III)-enhanced beads show a reasonable difference in volume in mixtures of ethanol and ethyl acetate, as long as the dilution of either is not large.

The low ratios of ethanol to ethyl acetate (mol:mol) of 1:1 and 2:1 seem most relevant (Table 1) for this study. The rate of the volume change of the beads is reasonable with a half-life of about 8 min for the slower shrinkage in ethyl acetate-containing mixtures (Figure 4a, Figure S2). However, the amount of ethanol in the 2:1 mixture prevents the polymer network from shrinking sufficiently: a volume reduction of only 9% is found insufficient to reliably open the valve in the current construction. The 1:1 molar ethanol acetic acid reactant mixture was therefore taken for the continuous operation. The rate and ratio of compounds after 5 h are suitable, and the beads are expected to decrease just under 20% in volume at final conversion. It is the compromise of accepting a moderately lower 5 h acid conversion that enables the volume shrinkage required for autonomous process control. This expectation is based on room temperature (25 °C) measurements of the gels and using the difference in equilibrium swelling in equimolar mixtures of ethanol and acetic acid, respectively, in the corresponding esterification equilibrium. Measurements of the behavior of the gels at 50 °C are not easily achieved in the current setup. Phenomenologically, the temperature effects also seem small in the interval to 50 °C. The temperature of the casing at room temperature with the beads, which makes up the valve, will be somewhere in the interval of 25−50 °C, depending on the flow rate. Therefore, the assessment at 25 °C was taken as accurate enough for this study.

It must be noted that the organogel used is a material with a differential response, and its volume does not change linearly with composition (Figure 4b). The dependence of the degree of swelling with composition in the quaternary mixture of ethanol, acetic acid, water, and ethyl acetate with several types of hydrogen bonding a priori is not easy to understand. The normalized volume of the beads (measured at 25 °C) is about quadratically dependent on the theoretical conversion of the ethanol/acetic acid esterification with a negative factor (i.e., to the mole fraction of ethyl acetate). This weaker than linear response can be advantageous: a valve would open more slowly than on account of conversion. An ideal valve would stay closed until conversion reaches a desired value and then open fully. The minimum relative bead volume is observed at conversions above 75%, i.e., beyond the conditions at the esterification equilibrium of a 1:1 (mol:mol) starting point. No cononsolvency of the copolymer was observed anymore in the mixtures of ethanol, acetic acid, water, and ethyl acetate, contrasting the behavior in organic media without water.[41] The

Table 1. Chemical Composition of the Reaction Mixtures and Resulting Actuator Response

state	ethanol (mol)	acetic acid (mol)	ethyl acetate (mol)	acid conversion (%)	actuator response $\Delta V/V_0$
Feed	1	1	-	0	-
5 h	0.43	0.43	0.57	57	0.19
Feed	2	1	-	0	-
5 h	1.36	0.36	0.64	64	0.09

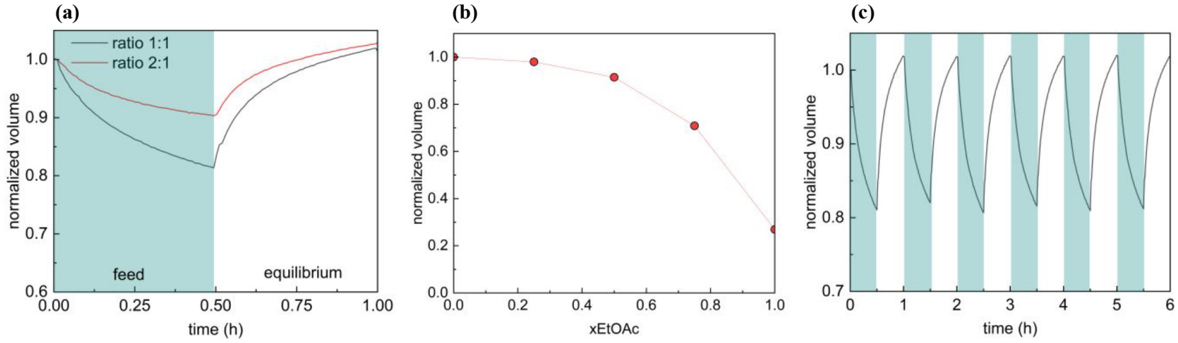

Figure 4. (a) Time-dependent swelling/shrinkage of the beads in ethanol/ethyl acetate mixtures of 5 h of esterification compositions (green underlay) from feed composition and vice versa (right). (b) Volume of the beads in mixtures corresponding to a 1:1 ethanol/acetic acid esterification. All at 25 °C; xEtOAc is the mole fraction of ethyl acetate (and also of water). (c) Normalized volume of gel beads in response to immersion in ethanol/acetic acid mixtures (swelling) and the quaternary mixture of ethanol, acetic acid, water, and ethyl acetate of the corresponding esterification mixture (green underlay; shrinkage) after 5 h at 50 °C (vide infra).

organogel maintained complete reversibility in the full quaternary 1:1 reaction mixture. The system successfully completed six consecutive switching cycles (Figure 4c).

3.2. Autonomously Controlled Esterification

The reactor setup of Figure 1 was subsequently used for the esterification of a 1:1 mixture of ethanol and acetic acid. The valve casing was loaded with the core-Fe^{3+}-shell organogel beads conditioned in ethanol (swollen state). The temperature was 50 °C, and 10 wt % of Amberlite catalyst particles was submitted to start the esterification. The ethanol/acetic acid mobile phase at the start maintains the valve in a swollen, "high-resistance-to-flow" state. The gravimetric controller accordingly operates at a pump frequency of a basic minimum flow of approximately 7 mL·min^{-1}, which corresponds to the lowest leakage volume of the smart valve. This small flow is necessary to equilibrate the medium around the beads with the reaction mixture.

The valve keeps restricting the discharge of the reaction mixture for about 1 h before the flow noticeably increases, although conversion sets in instantly (Figure 5). This favorable (pseudo)induction period of the valve is readily explained by the small change in the state of solution of the beads (Figure 4b). The small initial flow also results in a delay of medium equalization between that in the reactor (partitioned by the frit) and that around the full periphery of the beads. The responsive beads are pressed onto each other in the constraints of the casing. They are not homogeneously in contact with the medium slowly flowing through the valve (Figure 6). The valve thus has a clear lag related to the nonlinear response of the beads and time of equilibration to the reaction medium in the casing at 50 °C. No efforts were undertaken yet to model the nonsimple response of the valve to the inherent properties of the beads and their packing.

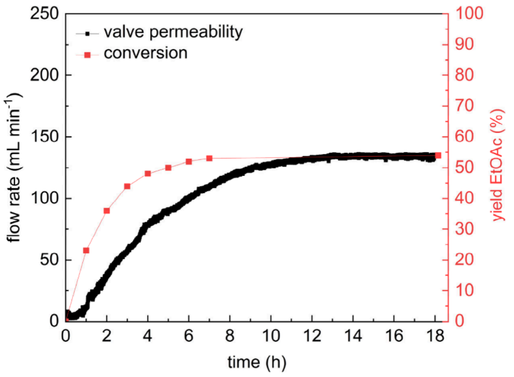

Figure 5. Pump volume and ethyl acetate formation from a 1:1 (mol:mol) ethanol/acetic acid mixture at 50 °C.

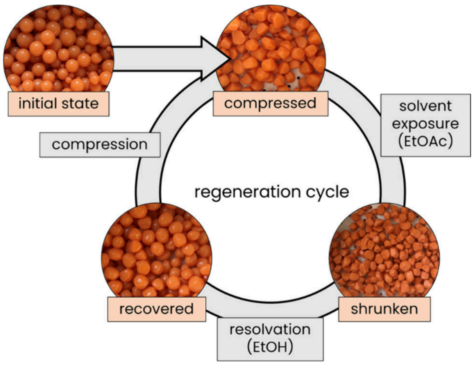

Figure 6. Macroscopic regeneration cycle of organogel beads; the beads were photographed immediately after the liquid was drained.

The cumulative change in composition with more ethyl acetate triggers a gradual size reduction of the beads. The flow out of the reactor increases, and the pump volume rises continuously from 12 mL·min^{-1} after 1 h to 40 mL·min^{-1} after 2 h. The controller eventually ramps up the pump rate to a steady state of 135 mL·min^{-1} as the conversion approaches equilibrium. This observation confirms that the organogel gives a "smartness" to the valve: it is driven by the local solvent quality. The consumption of ethanol and the concomitant generation of ethyl acetate decreases the solvation quality (lower solubility parameter) for the NiPAAm-AA segments of the beads.[51] The gel undergoes an ever increasing shrinkage with conversion (up to equilibrium) with the consequence that the valve becomes more permeable (with a time delay). The valve thus retains the fluid until sufficient ethyl acetate accumulates, "releasing" the product near thermodynamic equilibrium (polymer networks absorb a negligible amount of liquid compared to the 500 mL reactor volume).

Both the time-dependent concentration profile of the product formation and the pump volume can satisfactorily be described by an exponential function of the type $f(t) = a + b \exp(-ct)$ (cf. Figure S4). Formally, the time-dependent concentration profile of an esterification of equal amounts of reactants to equilibrium would be the solution to a first-order nonlinear differential equation (leading to Riccati type equations[52] with a $\tanh(kt)$ function as the solution). The function would have a dependence on the geometrical mean of the rate constants of esterification and the ester hydrolysis back reaction. This mean would be numerically close to the rate constant c of the exponential equation given above, and c thus can be used to characterize the esterification process. The overall rate constant of "change of the reaction mixture" is approximately 0.56 h^{-1}, about twice the value of the exponential rate of change of the pump volume (0.25 h^{-1}). The medium induced shrinkage of the beads inside the casing is thus a process with its own overall response constant, which preferably is shorter than that of the reaction. Here the design of the valve in combination with the solvation characteristics of the beads gives a somewhat unfavorably lower rate of response in combination with a short initial period of almost no flow. However, the setup allows us to detect the esterification reaction, and the product mixture could be released at a chosen rate (but not faster than the adaption time of the valve).

A smart organogel (valve) with sharper differentiation and shorter response times would of course be favorable for controlling faster reactions. The current beads, however, do have the advantage of good mechanical resilience. The beads, swollen in the valve casing, expand to fill the space between them, which is useful for having a low level of leakage. As pointed out above, contact of the beads to the reaction content is necessary for a fast response, and some leakage is desired.

Exposure of the beads in the valve to ethyl acetate forced a full shrinkage, ensuring the removal of residual reaction components. Flushing subsequently with ethanol is accompanied by the intended swelling. The swelling restores the original round shape of the beads to a very large extent, and no hints of permanent compression sets are found. Visual inspection revealed no mechanical damage or irreversible

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deformation despite this rigorous history of cyclic switching, continuous reaction, and final recovery by shrinkage and reswelling (Figure 6). This resilience confirms the suitability of the ionic reinforcement strategy of the organogels for reusable self-regulating reactor concepts. At the same time, the lag between the progress of the esterification and the reaction of the gel is appropriate for improvement. Further efforts are directed toward adapting the shape of the valve and the gel polymer. Gels with a sharper transition between the quality of solvation (between reactants and products) are more discriminating for the progress of the reaction (Figure 4b). This requires an adaptation of chemical composition. In addition, the morphology of the gel should be changed to one with a lower density and larger pores, which overall has the fast response rate of the first phase of shrinkage or swelling (Figure 2). Features with a smaller volume of the organogel may be necessary for fast internal solvent diffusion.[44,45] All of this is currently considered for macroscopic systems.

4. CONCLUSIONS

Although stimuli-responsive hydrogels have long been discussed as functional actuators, their implementation in chemical manufacturing has been limited. Previously developed iron-reinforced P(NiPAAm-*co*-AA) beads can effectively be used as smart material components of a robust autonomous process controller for an organic-phase reaction. The hydrodynamic residence time in a reactor is thus intrinsically determined by the reaction progress, be it with some time lag to the chemical process. This demonstrates a concept for a self-optimizing reactor that autonomously prioritizes kinetic completion over the hydraulic throughput. Successful longer-term operation also confirms that the ionically stabilized actuators can withstand the mechanical stresses of a fixed-bed environment. Looking ahead, the concept paves the way for logic-controlled reactors in which specific, solvent-sensitive triggers control selectivity in competitive reaction networks and release intermediates only when certain chemical conditions are met.

■ ASSOCIATED CONTENT

Data Availability Statement

Data sets of the experiments are available free of charge at 10.15480/882.16807. Data are listed on the swelling/shrinkage kinetics of the Fe^{3+}-reinforced P(NiPAAm-*co*-AA) organogel beads in relevant environments to the esterification of ethanol and acetic acid. These include raw and processed data sets of the pump rate versus time during the dynamic swelling experiments, as well as the time-dependent pixel tracking data extracted from the optical swelling analysis.

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.iecr.6c00973.

> Kinetic analysis of the chemo-mechanical actuation under flow conditions, determination of the swelling half-life time, ^{1}H NMR spectrum of the esterification reaction mixture after 5 h, and exponential fitting of the kinetic reaction profile and the resulting valve permeability (pump volume) (PDF)

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Notes

The authors declare no competing financial interest.

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