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NONLINEAR APPROACH FOR THE VFA REGULATION IN AN ANAEROBIC DIGESTER

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Abstract: This paper presents the design and the experimental validation of a nonlinear control approach for the regulation of volatile fatty acids (VFA) in an anaerobic digester. Such an approach is conformed by an output feedback control and an extended Luenberger observer which allows the estimation of the uncertain terms associated to the VFA dynamics (*i.e.*, influent composition and kinetic terms). The nonlinear approach is experimentally validated in a 0.528m^3 up-flow fixed-bed anaerobic digester used for the treatment of industrial wine distillery wastewater. The experimental results show that the VFA regulation is achieved in spite of uncertain kinetics, restrictions in the control input and unknown load disturbances. *Copyright ©2007 IFAC*

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1. INTRODUCTION

In the last few years, there has been an increasing interest in the application of advanced control strategies to wastewater treatment processes in order to fulfill the actual environmental laws (Olsson *et al.* 2005). Recently, anaerobic digestion (AD) has recovered the attention of the scientific community, since it represents a suitable and promising solution to reduce the organic matter from wastewater (Henze *et al.* 1997). Nevertheless, the AD process is not widely applied at the industrial scale (Totzke 1999), because it is known as an unstable process in the sense that large variations of the dilution rate and influent organic composition may lead to the crash of the digester. This is why actually the scientific efforts are focused not only to extend the number of AD applications, but also in increase the robustness of the process against disturbances (Steyer *et al.* 2006).

The variables frequently used to monitoring the digester-stability (also called operational stability) are the biogas production rate and the chemical oxygen demand (COD), VFA and alkalinity effluent concentrations. Particularly, VFA are one of the most important intermediaries in the AD process, because their accumulation (generally induced by toxic substrates and organic overloads) may lead to the process failure due to the pH-drop that they induce and their inhibitory effects in the acid form (Hill *et al.* 1987). Therefore, the monitoring and control of VFA is extremely important to guarantee the operational stability in AD processes. However, this is not an easy task, because several factors must be considered in the controller design: (i) uncertain load disturbances, because the monitoring of substrates and metabolites is difficult and expensive; (ii) uncertain kinetics due to the complex nonlinear nature of the process and (iii) the dilution rate (generally used as the control input) is constrained in practice to avoid undesired operating conditions such as the washout condition (Bailey and Ollis 1986). As a consequence, few contributions concerning to the VFA regulation in AD processes can be found in the current literature (Alcaraz-González *et al.* 2000, Puñal *et al.* 2002, Méndez-Acosta *et al.* 2006), where only the fuzzy approach developed by Puñal *et al.* (2002) has been experimentally validated. This fact motivates and justifies the present work, where a nonlinear control scheme capable to achieve the VFA regulation in spite of factors (i)-(iii) is proposed by using the input flow rate as manipulated variable. The paper is organized as follows. First, the considered AD model is briefly described and the control problem is stated in terms of the model. After, the geometric properties of the model are analyzed and the nonlinear control approach is established. Then, the proposed approach is experimentally validated in an AD pilot-scale plant, in order to evaluate the controller performance and robustness under the influence of factors (i)-(iii). Finally, some concluding remarks are pointed out.

2. THE CONSIDERED AD MODEL

In this paper, the AD model proposed and validated by Bernard *et al.* (2001) is used in the development of the nonlinear approach. The use of this model is justified by two facts: (a) this model has demonstrated to be useful in the monitoring and control of AD processes and, (b) the semi-industrial AD process used in the validation and identification of the model will be also used in the experimental validation.

The considered model is given by

$$\begin{aligned}
\dot{X}_1 &= (\mu_1(.) - \alpha D)X_1 \\
\dot{X}_2 &= (\mu_2(.) - \alpha D)X_2 \\
\dot{S}_1 &= (S_{1,in} - S_1)D - k_1\mu_1(.)X_1 \\
\dot{S}_2 &= (S_{2,in} - S_2)D + k_2\mu_1(.)X_1 - k_3\mu_2(.)X_2
\end{aligned} \tag{1}$$

where X_1, X_2, S_1 and S_2 are respectively the concentrations of acidogenic bacteria (g/L), methanogenic bacteria (g/L), organic substrate, COD (g/L) and VFA (meq/L). The subscript *in* is used to identify the concentration of each component in the feeding flow. The dilution rate, D (h^{-1}) is defined as the ratio between the input flow rate, Q (L/h) and the digester volume, V (L). This model assumes that a constant fraction of biomass is in the liquid phase. Thus, the parameter α (of experimental determination) reflects the process heterogeneity and it is defined in the interval $0 \leq \alpha \leq 1$, where $\alpha = 0$ corresponds to an ideal fixed-bed reactor, while $\alpha = 1$ represents a continuous stirred tank reactor (CSTR). $\mu_1(.)$ and $\mu_2(.)$ are respectively the growth rates associated to the acidogenic and methanogenic bacteria within the digester. Particularly, this model uses the Monod and Haldane kinetics to approach the bacterial growth rates for acidogenic (X_1) and methanogenic (X_2) bacteria, respectively.

In general, when dealing with AD processes two operating conditions can be identified:

Unstable Condition. Here, the bacterial culture into the digester remains inactive or dead which implies that X_1, $X_2 = 0$ for all $t \geq 0$. Then, it can be proved that under this condition, the steady state reached by the AD process (1) is given by the influent concentration (i.e., $S_1^{eq} = S_{1,in}$ and $S_2^{eq} = S_{2,in}$ see Table 1). This means that the polluting agents within the wastewater are not removed by the digester. As a consequence, this operating condition is undesired and must be avoided to any cost. In practice, this condition can be induced by an overload of organic matter or the presence of toxic agents, which suddenly increase the VFA concentration, decreasing the pH of the system and the sludge stability (Rozzi 1991).

Normal Operating Condition (NOC). Under this condition the biomass concentration remains active and the sludge stability is preserved (i.e., X_1, $X_2 > 0$ for all $t \geq 0$). This physically means that part of the polluting agents entering to the digester are consumed by the bacterial culture within the digester (i.e., $(S_{1,in} - S_1) > 0$ and $(S_{2,in} - S_2) > 0$). The equilibrium points of the AD model (1) are depicted in Table 1, where it is straightforward to see that only the point P4 has physical meaning under NOC (Méndez-Acosta *et al.* 2005).

2.1 Control problem statement

As was pointed out, the main control objective when dealing with AD processes is the stability (Olsson *et al.* 2005). Therefore, the challenge is to design control schemes that guarantee the operational stability of the process. As a first contribution in this direction, this paper focuses in the VFA regulation. Then, the control problem can be stated as: the proposal of a nonlinear control scheme capable to regulate the VFA concentration, S_2 around a desired set-point, S_2^* in the presence of factors (i)-(iii), for AD processes operating under NOC and whose dynamic behavior can be described by the model (1).

Table 1. Equilibrium points of the AD model (1)

	X_1^{eq}	X_2^{eq}	S_1^{eq}	S_2^{eq}
P1	0	0	$S_{1,in}$	$S_{2,in}$
P2	0	$\frac{(S_{2,in}-S_2^{eq})}{\alpha k_3}$	$S_{1,in}$	$\mu_2^{eq}(.) = \alpha D^{eq}$
P3	$\frac{(S_{1,in}-S_1^{eq})}{\alpha k_1}$	0	$\mu_1^{eq}(.) = \alpha D^{eq}$	$S_{2,in} + k_2 \alpha X_1^{eq}$
P4	$\frac{(S_{1,in}-S_1^{eq})}{\alpha k_1}$	$\frac{(S_{2,in}-S_1^{eq})+\alpha k_2 X_1^{eq}}{\alpha k_3}$	$\mu_1^{eq}(.) = \alpha D^{eq}$	$\mu_2^{eq}(.) = \alpha D^{eq}$

3. CONTROLLER DESIGN

In the last decade, the control based on differential geometry has emerged as a powerful tool to deal with a great variety of dynamic nonlinear systems (Henson and Seborg 1997, Isidori 1995, Nijmeijer and van der Schaft 1991). This control tools allows the transformation of a nonlinear system into a partially or totally linear one, by means of a nonlinear state transformation obtained from directional derivatives of the output (Lie derivatives). However, the main drawback in the use of this control tools is the dependence on the exact cancellation of the system nonlinear dynamics, in order to obtain an input-output linear dynamic behavior. As a consequence, the perfect knowledge of the system is required. This means that the presence of modeling errors, unmeasured disturbances and parametric uncertainties are not considered in the controller design. This explains maybe why this control tools have not been applied and experimentally validated in the control of AD processes (Antonelli *et al.* 2003). Here, a nonlinear control approach is proposed to overcome this drawback by defining an uncertain but observable function (η), whose dynamic behavior is estimated from available measurements by using an extended Luenberger observer.

3.1 Geometric properties

Here, the geometric properties of the AD model (1) are analyzed as a first step in the proposal of the nonlinear control approach. First, let us rewrite the AD model (1) in the affine form

$$\dot{x} = f(x) + g(x)u, \qquad y = h(x)$$

where $x \in \mathbb{R}_+^4$ is the state vector, $y \in \mathbb{R}_+$ is the system output given by the VFA concentration (i.e., $y = S_2$) and $u \in \mathbb{R}_+$ is the control input given by the dilution rate (i.e., $u = D$). Based on biological evidence, it is non restrictive to assume that the vector fields $f(x), g(x)$ and the system output $y = S_2$ are smooth.

Lemma 1. Let $y = S_2$ the output of the system. Then, the AD model (1) has a well-defined relative degree $r = 1$ under NOC.

Proof. By calculating the Lie derivative of the output along the vector fields $f(x)$ and $g(x)$, it is obtained that $L_g L_f^0 h(x) = (S_{2,in} - S_2)$. Then, since $(S_{2,in} - S_2) > 0$ under NOC, the relative degree $r = 1$ is well-defined for all $x \in U \subset \mathbb{R}_+^4$, where U is the space where the trajectories of the AD model (1) lives under NOC.

Since the relative degree is less than the order of the system (i.e., $r = 1 < n = 4$), it is necessary to define ϕ_{n-r} complementary functions in order to complete a mapping $\Phi(x)$ that allows to rewrite the AD model (1) into the normal form (Isidori 1995). Here, the following complementary functions are proposed: $\phi_2 = X_1/(S_{2,in} - S_2)^\alpha$, $\phi_3 = X_2/(S_{2,in} - S_2)^\alpha$ and $\phi_4 = X_2/(S_{1,in} - S_1)^\alpha$, such that the mapping is given by

$$\Phi(x) = \begin{pmatrix} S_2 \\ X_1/(S_{2,in} - S_2)^\alpha \\ X_2/(S_{2,in} - S_2)^\alpha \\ X_2/(S_{1,in} - S_1)^\alpha \end{pmatrix} \tag{2}$$

From the local coordinate transformation defined by the mapping (2), the AD model (1) can be rewritten in the following normal form

$$\begin{aligned} \dot{z}_1 &= (S_{2,in} - z_1)D + k_2\mu_1(.)X_1 - k_3\mu_2(.)X_2 \\ \dot{z}_2 &= \frac{X_1}{(S_{2,in} - z_1)^\alpha}\left[\mu_1(.) - \Pi(x)\right] \\ \dot{z}_3 &= \frac{X_2}{(S_{2,in} - z_1)^\alpha}\left[\mu_2(.) - \Pi(x)\right] \\ \dot{z}_4 &= \frac{X_2}{(S_{1,in} - S_1)^\alpha}\left[\mu_2(.) - \frac{\alpha k_1 \mu_1(.) X_1}{(S_{2,in} - z_1)}\right] \end{aligned} \tag{3}$$

where $\Pi(x) = \alpha\frac{k_3\mu_2(.)X_2 - k_2\mu_1(.)X_1}{(S_{2,in} - z_1)}$, $z_1 \in \mathbb{R}_+$ denotes the controllable and observable part of the system when the dilution rate, D is used as the control input, whereas the remaining states $z_2, z_3, z_4 \in \mathbb{R}_+^3$ represent the uncontrollable and unobservable part, also called internal dynamics (Nijmeijer and van der Schaft 1991). Then, in order to guarantee the stability of the closed-loop system, it is required that the internal dynamics be stable, at least, in the BIBO sense (bounded input - bounded output).

Proposition 2. The AD model (1) is a minimum-phase system under NOC.

Proof. Now, in order to evaluate the stability of the internal dynamics of the AD process (1), the following candidate Lyapunov function (CLF) is proposed

$$\Psi = \frac{\phi_2 \phi_4}{\phi_3} = \frac{X_1}{(S_{1,in} - S_1)^\alpha}$$

which under NOC is positive defined because $S_{1,in} > S_1$ and $X_1 > 0$. By taking the derivative of the CLF with respect to time and evaluating around the equilibrium point P4 (the only one that has physical meaning under NOC, see Table 1), it is obtained that

$$\begin{aligned}\dot{\Psi} &= \frac{X_1^{eq}}{(S_{1,in} - S_1^{eq})^{\alpha}} \left[\mu_1^{eq}(.) - \frac{\alpha k_1 \mu_1(.)^{eq} X_1^{eq}}{(S_{1,in} - S_1^{eq})} \right] \\ &= \Psi \left[\mu_1^{eq}(.) - \alpha D^{eq} \right] = 0\end{aligned}$$

Then, since $\Psi > 0$ and $\dot{\Psi} \le 0$ for all $t \ge 0$, the asymptotic stability of the internal dynamics is proved.

Remark 3. It is well-known from the geometric control theory that, if the AD process (1) is a minimum-phase system and it has a well-defined relative degree, the following input-output linearizing controller will make converge exponentially the VFA concentration, S_2 to a desired value, S_2^* (Isidori 1995)

$$D = \frac{1}{L_g L_f^{r-1} h(x)} \left[-L_f^r h(x) - \omega(x) \right] \qquad (4)$$

where $L_g L_f^{r-1} h(x) = (S_{2,in} - S_2)$, $L_f^r h(x) = k_2 \mu_1(.) X_1 + k_3 \mu_2(.) X_2$, $\omega(x) = Kc(S_2 - S_2^*)$ and Kc is a positive constant. However, in order to implement the control law (4), a perfect knowledge of the inlet concentration and the process kinetics (parameters and growth functions) are required. Therefore, the control law (4) cannot be applied in practice due to the factors (i)-(iii). Then, to overcome this drawback a nonlinear control approach is proposed in the next section.

3.2 Nonlinear Control Approach

In order to take into account the factors (i)-(iii) in the controller design, the following assumptions are considered: (A1) The outlet VFA concentration is available from on-line measurements (Steyer *et al.* 2002). (A2) The kinetic functions $\mu_1(.), \mu_2(.)$ are unknown in the sense that no analytical expressions of these functions are available. Based on biological evidence, it is non restrictive to assume that the kinetic functions $\mu_1(.), \mu_2(.)$ are continuous-bounded positive-defined functions. In addition, it is assumed that the influent concentration $S_{i,in}$ for $i = 1, 2$ is unknown, piecewise constant and bounded (i.e., $S_{i,in}^{min} \le S_{i,in} \le S_{i,in}^{max}$). Also, without lost of generality, it is considered that the inlet concentration can be described by $S_{i,in} = \tilde{S}_{i,in} + \Delta_{S_i}$, where Δ_{S_i} is an uncertain and bounded function related to the variation of the influent composition around a nominal value $\tilde{S}_{i,in}$. In practice, $\tilde{S}_{i,in}$ can be calculated by a single off-line measurement of the wastewater to be treated. (A3) The dilution rate D is constrained by the following saturation function to emulate the fact that it is restricted in practice to avoid undesired operation conditions

$$sat(D) = \begin{cases} \overline{D}, & D \ge \overline{D} \\ D, & \underline{D} < D < \overline{D} \\ \underline{D}, & D \le \underline{D} \end{cases} \qquad (5)$$

where the bounds $\overline{D}$ and $\underline{D}$ are well-known and $D_{sat} = sat(D)$.

Now, let us define the following function

$$\eta \equiv k_2 \mu_1(.) X_1 - k_3 \mu_2(.) X_2 + \Delta_{S_2} D$$

where the uncertain terms associated to the VFA dynamics (S_2) are lumped. Then, it is possible to rewrite the system (3) in the following extended state-space representation

$$\begin{aligned}\dot{z}_1 &= \eta + (\tilde{S}_{2,in} - z_1) D \\ \dot{\eta} &= \Xi(z, D) \\ \dot{z}_j &= q(z), \qquad j = 2, 3, 4\end{aligned} \qquad (6)$$

where two important properties can be highlighted (Femat et al., 1999): (a) it can be proved that the trajectories of the system (3) are a projection of that described by the extended state-space (6) and, (b) a feature of system (6) is that the uncertainties have been lumped into an uncertain function $\Xi(z, u)$ which can be estimated by an unmeasured but observable state η. Here, the following extended Luenberger observer is proposed to estimate the uncertain function

$$\begin{aligned}\dot{\hat{z}}_1 &= \hat{\eta} + (\tilde{S}_{2,in} - \hat{z}_1) D + \Gamma g_1 (z_1 - \hat{z}_1) \\ \dot{\hat{\eta}} &= \Gamma^2 g_2 (z_1 - \hat{z}_1)\end{aligned} \qquad (7)$$

where the constants g_1 and g_2 are chosen such that the polynomial $s^2 + g_2 s + g_1 = 0$ is Hurwitz and Γ is a tuning parameter. Observer (7) guarantees that the error vector $[z_1 - \hat{z}_1, \eta - \hat{\eta}]^T \rightarrow \epsilon$ as $t \rightarrow \infty$, where ϵ is an arbitrarily small neighborhood around the origin. Then, by combining the observer (7) and the linearizing control law (4), the here proposed nonlinear approach is obtained

$$\begin{aligned}\dot{\hat{z}}_1 &= \hat{\eta} + (\tilde{S}_{2,in} - \hat{z}_1) D_{sat} + \Gamma g_1 (z_1 - \hat{z}_1) \\ \dot{\hat{\eta}} &= \Gamma^2 g_2 (z_1 - \hat{z}_1) \\ D &= \frac{1}{(\tilde{S}_{2,in} - \hat{z}_1)} \left[-\hat{\eta} - Kc(\hat{z}_1 - S_2^*) \right]\end{aligned} \qquad (8)$$

where an observer-based anti-windup structure is added from feeding back the signal D_{sat} to the observer (7) (Méndez-Acosta *et al.* 2004).

Remark 4. It is important to remark that the controller robustness is highly influenced by the observer performance. Nevertheless, since the asymptotical convergence of the observer (7) is guaranteed and the sampling time is fast enough compared with the process response, then the controller robustness against variations in the uncertain terms related to the VFA dynamics is also guaranteed.

4. EXPERIMENTAL IMPLEMENTATION

In this section, the results obtained from the experimental validation of the nonlinear approach (8) are presented. The experimental validation was carried out one month after the AD process was re-started after seven months of inactivity assuring highly uncertain conditions. The effective volume of the digester is 0.528m^3, whereas the influent restrictions were fixed in terms of the influent flow rate as $Q^{min} = 1$L/hr and $Q^{max} = 22$L/hr.

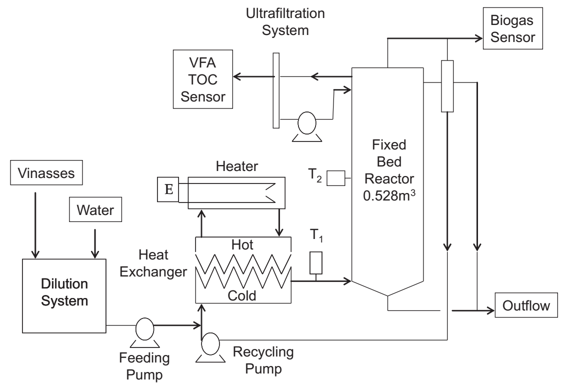

Fig. 1. Anaerobic upflow fixed-bed digester used for the treatment of wine distillery vinasses

The control algorithm was implemented by using a software developed in the INRA-LBE called ODIN. In addition, a commercial automatic titrimetric analyzer named AnaSense was used to measure on-line the VFA concentration (Molina *et al.* 2004). This device is capable to measure the VFA concentration with a sampling time of 30min, which is fast enough compared to the hydraulic residence time of the process (between 10 to 12 h) allowing the assumption of continuous control. The control parameters were determined via numerical simulations, by using experimental data: $Kc = 0.4$, $g_1 = 0.7$, $g_2 = 0.7$ and $\tilde{S}_{2,in} =$ 7500mgVFA/L which corresponds to a single off-line measurement of the VFA concentration of a sample of raw vinasses. This value was selected to induce an important error in $S_{2,in}$ to test the controller robustness, since diluted vinasses were used along the experiment, whose nominal value $S_{2,in}$ is aproximatelly 5200mgVFA/L. Particularly, three set-point changes were performed. First, the set-point was fixed at $S_2^* = 1400$mgVFA/L for 30h$< t <$90h. Then, the set-point was changed to $S_2^* = 1000$mgVFA/L in the interval time of 90h$< t <$140h. Finally, the set-point was varied to $S_2^* = 1800$mgVFA/L for 140h$< t <$200h.

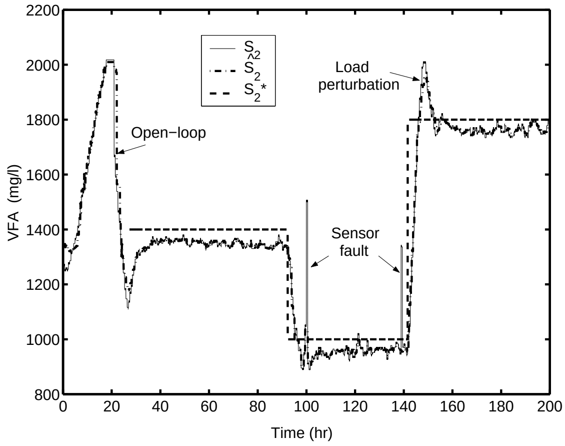

Fig. 2. Response of the AGV concentration when the nonlinear approach (8) is experimentally implemented

The response of the VFA concentration is shown in Figure 2. In general, it can be observed that the controller performance along the experiment is quite acceptable even when a constant nominal value $\tilde{S}_{2,in}$ was used and the presence of several disturbances. For example, at $t = 140$h a load perturbation was induced by changing the dilution factor such that $S_{2,in}$ change from 5200mgVFA/L to 6700mgVFA/L, approximately. Note that the proposed scheme (8) shows an acceptable robustness in the presence of both, important uncertainties in the inlet composition and the full ignorance of the of the kinetic terms. On the other hand, the controller response is also acceptable, which is less than 5h after each set-point change.

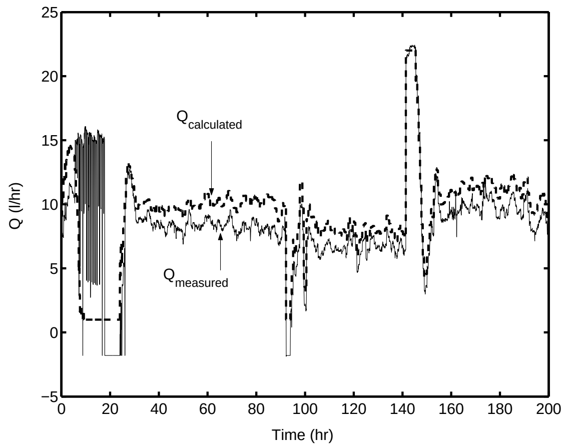

Fig. 3. Behavior of the inlet flow rate used as manipulated variable

Figure 3 shows the performance of the manipulated variable, Q along the experiment. See that the calculated value (dashed line) by the nonlinear approach (8) is greater than that measured at the entrance of the digester (solid line). This is due to a calibration problem in the feeding pump. This problem explain the constant error (off-set) between the output, S_2 and the set-point, S_2^* (see Figure 2). On the other hand, it can be seen that after the set-point is changed, the input flow rate, Q gets saturated (i.e., Q^{min} or Q^{max}). Nevertheless, the controller performance is not deteriorated by this fact.

5. CONCLUSIONS

This paper presents the design and the experimental validation of a nonlinear control approach for the regulation of volatile fatty acids (VFA) in an anaerobic digester. Such an approach is conformed by an output feedback control and an extended Luenberger observer which allows the estimation of the uncertain terms associated to the VFA dynamics. The nonlinear approach was experimentally validated in a pilot-scale process. Although the reactor was in stabilization process, the control scheme shows an acceptable performance and robustness in spite of uncertain kinetics, restrictions in the control input and unknown load disturbances.

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