

Asymptotic behavior of solutions to chemical reaction-diffusion systems

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Abstract

This paper concerns the study of the asymptotic behavior of solutions to reaction-diffusion systems modeling multi-components reversible chemistry with spatial diffusion. By solution, we understand any limit of adequate approximate solutions. It is proved in any space dimension that, as time tends to infinity, the solution converges exponentially to the unique homogeneous stationary solution. We adapt and extend to any number of components, the entropy decay estimates which have been exploited for some particular 3×3 and 4×4 systems.

Keywords: reaction-diffusion equation, chemical reaction, asymptotic behavior, entropy method, renormalized solution

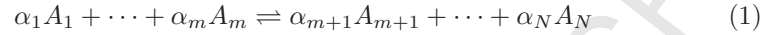
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1. Introduction

The purpose of the present paper is to describe the *asymptotic behavior* as time tends to infinity of the solutions to reaction-diffusion systems arising in the modelization of reversible chemical reaction with multi-components $\{A_i\}_{1 \leq i \leq N}$



where $m, N, \alpha_k, k = 1, \dots, N$ are positive integers with $1 \leq m < N$.

Let $u_k = u_k(x, t)$ be the concentration of A_k at position $x \in \Omega \subset \mathbb{R}^n$ and time $t \in [0, T], T > 0$ (Ω will be assumed to be open, bounded and with a regular boundary throughout the paper). According to the mass action law (with reaction rates c_1 from left to right and c_2 from right to left) and according to Fick's law for the diffusion, the evolution of $u = (u_1, \dots, u_N)$ is described by the reaction-diffusion system

$$\begin{cases} \frac{\partial u_k}{\partial t} - d_k \Delta u_k = \chi_k f(u) & \text{in } Q_T = \Omega \times (0, T), \\ \frac{\partial u_k}{\partial \nu} \Big|_{\partial \Omega} = 0, \quad u_k|_{t=0} = u_{k0}(x) \geq 0, & 1 \leq k \leq N, \end{cases} \quad (2)$$

where $d_k > 0, 1 \leq k \leq N$, ν is the outer unit normal vector and

$$f(u) = c_1 \prod_{j=1}^m u_j^{\alpha_j} - c_2 \prod_{j=m+1}^N u_j^{\alpha_j}, \quad \chi_k = \begin{cases} -\alpha_k, & 1 \leq k \leq m \\ \alpha_k, & m+1 \leq k \leq N. \end{cases} \quad (3)$$

We prove in this paper that "global solutions" on $[0, \infty)$ of (2) converge exponentially in $L^1(\Omega)$ as $t \rightarrow +\infty$ to a well-defined (and unique) homogeneous stationary solution of System (2) (see Theorem 3 for a precise statement). As explained below, this extends to the general situation (2) similar results obtained in case of 3×3 or 4×4 systems [8, 9, 10, 12].

In order to state precisely our asymptotic result (see Theorem 3), let us first recall what is known about the rather difficult question of *global existence in time* of solutions to (2). Note for instance, that it is not yet understood in dimension $n \geq 3$ and for general diffusion coefficients $d_k \in (0, \infty)$, whether global classical solutions exist for the model quadratic case $m = 2, N = 4, \alpha_k = 1$, that is $f(u) = c_1 u_1 u_2 - c_2 u_3 u_4$!

15 Global classical solutions do exist for this f in space dimension $n = 1, 2$ (see e.g. [16, 23, 4]). More generally, global existence is also proved for (2) when the space-dimension n is small enough with respect to the degree of the polynomial f or when the diffusion coefficients d_k are close enough to each other (see the discussion in [21]).

20 But let us recall what the situation is for a general space-dimension n and general positive $d_k \in (0, \infty)$ (we assume $c_1 = c_2 = 1$ for simplicity).

1. If $m = 1, N = 2$ (that is $f(u) = u_1^{\alpha_1} - u_1^{\alpha_2}$), then global existence of uniformly bounded (and therefore classical) solutions easily follows from the invariance of the rectangles

$$\{(u_1, u_2); 0 \leq u_1 \leq M_1, 0 \leq u_2 \leq M_2\} \text{ where } M_1^{\alpha_1} = M_2^{\alpha_2}.$$

2. If $N = m + 1, \alpha_N = 1$ (i.e. $f(u) = \prod_{k=1}^m u_k^{\alpha_k} - u_N$), then global classical solutions do also exist (see [2]). The same symmetrically holds if $m = 1, \alpha_1 = 1$ ($f(u) = u_1 - \prod_{k=2}^N u_k^{\alpha_k}$).

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3. If $m = 2, N = 3$ and $\alpha_3 > \alpha_1 + \alpha_2$ (i.e. $f(u) = u_1^{\alpha_1} u_2^{\alpha_2} - u_3^{\alpha_3}$), then again global existence of classical solutions is proved in [18]. But the same result is not known if $\alpha_3 \leq \alpha_1 + \alpha_2$.

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4. For sub-quadratic reaction-diffusion systems, global smooth solutions are proved to exist (see [3]) while for super-quadratic systems, the existence of global classical solutions are verified if extra conditions are satisfied combining the d_i , the growth of f and the dimension (see [14]).

Global classical solutions are not known to exist for any space dimension and any $d_k \in (0, \infty)$. Weaker notions of solution need to be considered.

35 Let us describe known results in this direction.

5. If again $m = 2, N = 4$, ($f(u) = u_1 u_2 - u_3 u_4$), then global so-called *weak solutions* are proved to exist (see [20, 11]). *Weak solution* means that $f(u) \in L^1([0, T] \times \Omega)$ for all $T > 0$ and equations (2) are satisfied in the sense of distributions or in the sense of semigroups (see [20, 11, 21] for precise definitions).
- 40

6. More generally, if for some reason, the nonlinearity $f(u)$ is a priori bounded in $L^1((0, T) \times \Omega)$ for all $T > 0$, then global *weak solutions* do exist (see [20, 21]). Thanks to quadratic a priori estimates valid for these systems, this is for instance the case if

$$\begin{aligned} N = m + 1, \quad f(u) &= \prod_{k=1}^m u_k^{\alpha_k} - u_N^2; \\ N = m + 2, \quad f(u) &= \prod_{k=1}^m u_k^{\alpha_k} - u_{m+1} u_{m+2}. \end{aligned}$$

7. In the general situation of System (2), existence of global *weak solutions* in the above sense seems to be an open problem. No counterexample is known either. On the other hand, global existence of *still weaker solutions* is proved in [15]. They are called *renormalized solutions* and defined in the spirit of the famous renormalized solutions by Di Perna-Lions for the Boltzmann equation. A definition of such a solution for systems like (2) is introduced in [15] and global such solutions are also proved to exist in this same paper [15].

We will not need the definition of such *renormalized solutions* here. We will only use the fact that they are obtained as limit of solutions of a standard approximate "regularized" system. And we will directly prove that any such limits are actually exponentially asymptotically stable. It is actually interesting to describe precisely the asymptotic behavior of these solutions without knowing much about them.

Let us consider the approximate solution $u^\varepsilon = (u_k^\varepsilon(x, t))$ to

$$\begin{cases} \tau_k \frac{\partial u_k^\varepsilon}{\partial t} - d_k \Delta u_k^\varepsilon = \chi_k f_\varepsilon(u^\varepsilon) & \text{in } Q_T = \Omega \times (0, T) \\ \frac{\partial u_k^\varepsilon}{\partial \nu} \Big|_{\partial \Omega} = 0, \quad u_k^\varepsilon|_{t=0} = u_{k0}^\varepsilon(x) \geq 0, \quad 1 \leq k \leq N \end{cases} \quad (4)$$

where $\tau_k \in (0, \infty)$, $1 \leq k \leq N$ and

$$f_\varepsilon(u) = \frac{f(u)}{1 + \varepsilon |f(u)|}, \quad u_{k0}^\varepsilon = \inf\{u_{k0}, \varepsilon^{-1}\}, \quad u_{k0} \geq 0, \quad 1 \leq k \leq N. \quad (5)$$

The introduction of the $\tau_k \neq 1$ is for later purposes (see Section 2.3). Note that $|f_\varepsilon(u)| \leq 1/\varepsilon$. Thus, given $(u_{k0}) \in L^1(\Omega)^N$, there exists a unique classical solution to (4)-(5) globally in time. Thanks to the *quasipositivity* of the nonlinearity,

that is

$$\chi_k f_\epsilon(u) \geq 0, \text{ for all } u \in [0, \infty)^N \text{ with } u_k = 0, 1 \leq k \leq N,$$

this solution u^ϵ is nonnegative. Then, the following convergence result holds.

Proposition 1. [15] Assume $u_{k0} \log u_{k0} \in L^1(\Omega)$ for $1 \leq k \leq N$. Then each $\{u^{\epsilon_\ell}\}$ with $\epsilon_\ell \downarrow 0$ admits a subsequence converging in $L^1_{loc}([0, \infty); L^1(\Omega)^N)$ and a.e. to some $u \in L^\infty([0, \infty); L^1(\Omega))^N$ such that

$$u_k \log u_k \in L^\infty_{loc}([0, \infty); L^1(\Omega)) \text{ for all } 1 \leq k \leq N.$$

Remark 2. This proposition is essentially proved in [15]. We will give the needed extra details at the beginning of next section. When $\tau_k = 1$ for all k , the limit u is a *weak solution* of System (2), in the sense defined in the point 5 above, as soon as $f(u) \in L^1_{loc}([0, \infty); L^1(\Omega))$ (see [15] again). It is only a *renormalized solution* in the sense of [15] in general.

The conservation properties (where \bar{f}_Ω denotes the average $|\Omega|^{-1} \int_\Omega$)

$$\int_\Omega \tau_i u_i^\epsilon(t) + \tau_j u_j^\epsilon(t) = \int_\Omega \tau_i u_{i0}^\epsilon + \tau_j u_{j0}^\epsilon \text{ for all } 1 \leq i \leq m < j \leq N, \quad (6)$$

hold, thanks to the homogeneous Neumann boundary conditions and they are preserved at the limit for u , at least a.e. $t \in [0, \infty)$. For $w : \Omega \rightarrow \mathbb{R}$, we will throughout denote

$$\bar{w} := \int_\Omega w.$$

Now the main result of this paper is the following theorem.

Theorem 3. Let u be as in Proposition 1. Assume moreover that

$$\bar{u}_{i0} + \bar{u}_{j0} > 0 \text{ for all } 1 \leq i \leq m < j \leq N. \quad (7)$$

Then, there exists $C, a > 0$ depending only on $\|u_0\|_{L^1(\Omega)^N}$ and the data such that

$$\|u(\cdot, t) - z\|_{L^1(\Omega)^N} \leq C e^{-a t}, \quad \forall t \geq 0 \quad (8)$$

where $z = (z_j)_{1 \leq j \leq N} \in (0, \infty)^N$ is the unique nonnegative solution of

$$f(z) = 0, \quad \tau_i z_i + \tau_j z_j = \tau_i \bar{u}_{i0} + \tau_j \bar{u}_{j0} \text{ for all } 1 \leq i \leq m < j \leq N. \quad (9)$$

The same conclusion would actually hold for *any limit* u of adequate approximate solutions of System (2), and not only for the solutions of the specific system (4), (5): this is discussed later in Remark 9.

The positivity condition (7) is not restrictive as explained in Section 5.

The asymptotic result of Theorem 3 has already been proved in the two particular situations of the points 3 et 4 above for 3×3 or 4×4 specific systems (see [8, 9, 10, 12]). As in these papers, the proof is based here on the use of the *entropy functional* defined as follows. Let

$$E(w \mid v) = \int_{\Omega} v \Phi\left(\frac{w}{v}\right) dx, \quad \Phi(s) = s(\log s - 1) + 1 \geq 0, \quad \forall s > 0, \quad (10)$$

where w, v are measurable nonnegative functions (with $v(x)^2 + w^2(x) > 0$ a.e. $x \in \Omega$). This entropy is extended to the vector valued functions $u = (u_k)_{1 \leq k \leq N}, z = (z_k)_{1 \leq k \leq N}$ as

$$\mathbf{E}(u \mid z) = \sum_{k=1}^N \tau_k E(u_k \mid z_k). \quad (11)$$

We will more simply write

$$E(w \mid 1) = E(w), \quad \mathbf{E}(u) = \sum_{k=1}^N \tau_k E(u_k), \quad \mathbf{E}(z) = \sum_{k=1}^N \tau_k E(z_k). \quad (12)$$

The main point is to prove that

Proposition 4. *With the notation and assumptions of Theorem 3*

$$\frac{d}{dt} \mathbf{E}(u(t) \mid z) \leq -2a \mathbf{E}(u(t) \mid z), \quad (13)$$

in the sense of distributions in $(0, \infty)$.

By Proposition 1, $\mathbf{E}(u(t) \mid z)$ is bounded for t near 0 (say by C_0). Therefore (13) implies

$$\mathbf{E}(u(t) \mid z) \leq C_0 e^{-2a t}, \quad \forall t \geq 0. \quad (14)$$

We then apply a *Csiszár-Kullback type inequality*, namely (see Lemma 10)

$$\|u(t) - z\|_{L^1(\Omega)^N} \leq C \mathbf{E}(u(t) \mid z),$$

which implies our main result (8).

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Let us now recall the strategy to prove the main inequality (13). Assume for simplicity that, in the definition (3) of f and χ_k , we have

$$c_1 = c_2 = 1 = \alpha_k, \forall 1 \leq k \leq N. \quad (15)$$

Actually, we will see later that there is no loss of generality when considering this specific case (see Section 2.3). Then, if u is a solution of (2), we have, at least *formally*

$$\frac{d}{dt} E(u_k(t)) = \int_{\Omega} \log u_k \partial_t u_k = \int_{\Omega} -d_k \frac{|\nabla u_k|^2}{u_k} + \chi_k \log u_k f(u).$$

This implies that for $\mathbf{E}(u) = \sum_{k=1}^N E(u_k)$ (since here $\tau_k = 1$ for all k)

$$\frac{d}{dt} \mathbf{E}(u(t)) = -D(u(t)), \quad (16)$$

where

$$\begin{aligned} D(u) &= 4 \sum_{k=1}^N d_k \int_{\Omega} |\nabla \sqrt{u_k}|^2 \\ &+ \int_{\Omega} \left(\log \prod_{k=1}^m u_k - \log \prod_{k=m+1}^N u_k \right) \left(\prod_{k=1}^m u_k - \prod_{k=m+1}^N u_k \right). \end{aligned} \quad (17)$$

Thanks to the definition of z , as proved in Lemma 7,

$$\mathbf{E}(u(t) | z) = \mathbf{E}(u(t)) - \mathbf{E}(z) \text{ so that } \frac{d}{dt} \mathbf{E}(u(t) | z) = \frac{d}{dt} \mathbf{E}(u(t)). \quad (18)$$

Now, Proposition 4 will be a consequence of the following lemma.

Lemma 5. *Assume (15). With the notation and assumptions of Theorem 3, the following holds*

$$D(u(t)) \geq 2a \mathbf{E}(u(t)|z), \quad (19)$$

in the sense of distribution on $(0, \infty)$.

It is now clear that combining (16), (18) and (19) yields Proposition 4, at least
75 under Assumption (15) (and this will be general).

We prove in Section 2.3 why working with the particular case (15) is sufficient. The derivation in (16) is indeed very formal since here u is only obtained as the limit of regular solutions but may not be regular itself. In fact, we will
 80 only prove the inequality $\frac{d}{dt}\mathbf{E}(u(t)) \leq -D(u(t))$ which, obviously, is sufficient to deduce inequality (13) in Proposition 4. This will be done in Section 3 where a complete proof of Proposition 4 (and therefore of our main result of Theorem 3) will be given, assuming Lemma 5.

The proof of Lemma 5 is completely algebraic. It only uses from the solution $u(t)$ that it satisfies the conservation properties

$$\bar{u}_i(t) + \bar{u}_j(t) = \bar{u}_{i0} + \bar{u}_{j0} =: U_{ij}, \quad \forall 1 \leq i \leq m < j \leq N. \quad (20)$$

In the particular cases already known (namely in the points 3 and 4 above [8, 9,
 85 10, 12]), this part of the proof is rather involved and requires much technicality. A main contribution here is to simplify rather significantly this part of the proof and consequently to be able to reach the general case (2). For instance, we compare the variation of \sqrt{u} with the square root $\sqrt{\bar{u}}$ of its average rather than with the average of the square root. The corresponding computation turns
 90 out to be quite simpler and sufficient for the expected estimate of Lemma 13. We also simplify the proof of the estimate from below of $f(\sqrt{u})$ (see Lemma 12)).

2. Some preliminaries

Let us first give the necessary extra details for the proof of Proposition 1.

95 2.1. Proof of Proposition 1.

Let us check that the results of [15] do apply here. Let us denote $U_k^\epsilon := \tau_k u_k^\epsilon$. Then System (4) may be rewritten

$$\begin{cases} \frac{\partial U_k^\epsilon}{\partial t} - \frac{d_k}{\tau_k} \Delta U_k^\epsilon = \chi_k \frac{F(U^\epsilon)}{1 + \epsilon |F(U^\epsilon)|} & \text{in } Q_T = \Omega \times (0, T) \\ \frac{\partial U_k^\epsilon}{\partial \nu} \Big|_{\partial \Omega} = 0, \quad U_k^\epsilon|_{t=0} = \tau_k u_{k0}^\epsilon(x) \geq 0, \quad 1 \leq k \leq N, \end{cases} \quad (21)$$

where, for all $U \in [0, \infty)^N$

$$F(U) = C_1 \prod_{i=1}^m U_i^{\alpha_i} - C_2 \prod_{j=m+1}^N U_j^{\alpha_j},$$

$$C_1 = c_1 \prod_{i=1}^m (\tau_i)^{-\alpha_i}, C_2 = c_2 \prod_{j=m+1}^N (\tau_j)^{-\alpha_j}.$$

For this new system, the *entropy* structure required on the nonlinearity F in [15] holds, namely: for all $U \in [0, \infty)^N$

$$\sum_{k=1}^N \chi_k F(U) [\mu_k + \log U_k] = -F(U) \left[\log \left(C_1 \prod_{i=1}^m (U_i)^{\alpha_i} \right) - \log \left(C_2 \prod_{j=m+1}^N (U_j)^{\alpha_j} \right) \right] \leq 0,$$

with $\mu_k = \log(C_2/C_1)/(N\chi_k)$, $1 \leq k \leq N$. The a.e. convergence of U^ϵ (up to a subsequence) is stated in Lemma 7 of [15], whence the a.e. convergence of u^ϵ . Together with the estimate of $U_k^\epsilon \log U_k^\epsilon$ in $L_{loc}^\infty([0, \infty); L^1(\Omega))$ proved in Lemma 6 of [15], it also implies the convergence of U_k^ϵ and therefore of u_k^ϵ in $L_{loc}^1([0, \infty); L^1(\Omega))$. Moreover, by Fatou's Lemma

$$u \in L^\infty([0, \infty); L^1(\Omega)) \text{ and } u_k \log u_k \in L_{loc}^\infty([0, \infty); L^1(\Omega)), \forall k.$$

□

2.2. Uniqueness of z .

100 We now state the uniqueness of z as defined in Theorem 3 and as also stated in [17, 19, 13]. We also provide the proof for the sake of completeness.

Proposition 6. *Under the assumptions of Theorem 3, there exists a unique $z = (z_k) \in [0, \infty)^N$ such that*

$$f(z) = 0, \quad \tau_i z_i + \tau_j z_j = \tau_i \bar{u}_{i0} + \tau_j \bar{u}_{j0}, \quad 1 \leq i \leq m < j \leq N. \quad (22)$$

Moreover, $z_k > 0$, $\forall 1 \leq k \leq N$.

Proof. Let $U_{ij} := \tau_i \bar{u}_{i0} + \tau_j \bar{u}_{j0}$. By (15), $U_{ij} > 0$ for $1 \leq i \leq m < j \leq N$. The relations (22) are equivalent to

$$\begin{cases} z_j = [U_{1j} - \tau_1 z_1] / \tau_j \geq 0, \quad \forall m+1 \leq j \leq N, \\ z_i = [\tau_1 z_1 + U_{iN} - U_{1N}] / \tau_i \geq 0, \quad \forall 2 \leq i \leq m, \\ g(z_1) = 0, \end{cases} \quad (23)$$

where

$$g(z_1) := c_1 z_1 \prod_{i=2}^m \frac{[\tau_1 z_1 + U_{iN} - U_{1N}]^{\alpha_i}}{\tau_i^{\alpha_i}} - c_2 \prod_{j=m+1}^N \frac{[U_{1j} - \tau_1 z_1]^{\alpha_j}}{\tau_j^{\alpha_j}}.$$

Let us define

$$M_0 := \min_{m+1 \leq j \leq N} U_{1j}/\tau_1, \quad m_0 := \max_{2 \leq i \leq m} [U_{1N} - U_{iN}]^+/\tau_1.$$

Note that $U_{1N} - U_{iN} = U_{1j} - U_{ij} = \tau_1 \bar{u}_{10} - \tau_i \bar{u}_{i0}$ is independent of $j = m + 1, \dots, N$. It follows that $m_0 < M_0$. The function $g : [m_0, M_0] \rightarrow \mathbb{R}$ is continuous, strictly increasing and satisfies $g(m_0) < 0$, $g(M_0) > 0$. Therefore there exists a unique $z_1 \in (m_0, M_0)$ such that $g(z_1) = 0$. For this z_1 , the z_i, z_j defined by (23) are nonnegative and do satisfy the expected relations (22). They are all strictly positive: indeed, if one had $z_i = 0$ for some $1 \leq i \leq m$, then $f(z) = 0$ would imply that $z_j = 0$ also for some $m + 1 \leq j \leq N$ which is a contradiction with $\tau_i z_i + \tau_j z_j = U_{ij} > 0$. \square

2.3. Reduction of System (4) to the case $c_1 = c_2 = 1, \alpha_k = 1, 1 \leq k \leq N$.

Let us show that we may only consider these particular values without loss of generality. Indeed, at least formally, System (2) is equivalent to a similar system with the simpler form

$$\tau_l \partial v_l / \partial t - D_l \Delta v_l = \chi_l F(v), \quad F(v) = \prod_{l=1}^{l_m} v_l - \prod_{l=l_m+1}^{l_N} v_l, \quad |\chi_l| = 1,$$

and whose solutions $v_l, 1 \leq l \leq l_N$ are successively α_k copies of the u_k . We describe this more precisely below. To do it rigorously in order to provide a complete proof of Theorem 3, we need a uniqueness property of solutions for the v_l -system.. Therefore we do it on the corresponding ϵ -approximate system (24) below for which uniqueness holds.

Let us define

$$l_0 = 0, l_k = \sum_{j=1}^k \alpha_j, \quad \forall 1 \leq k \leq N; \quad \lambda^{-l_m} := c_1, \quad \mu^{l_m - l_N} := c_2,$$

$$D_l := \lambda d_k / \alpha_k, \quad \tau_l := \lambda \tau_k / \alpha_k, \quad \forall l_{k-1} < l \leq l_k, \quad \forall 1 \leq k \leq m,$$

$$D_l := \mu d_k / \alpha_k, \tau_l := \mu \tau_k / \alpha_k, \forall l_{k-1} < l \leq l_k, \forall m+1 \leq k \leq N.$$

We consider the extended system

$$\begin{cases} \tau_l \frac{\partial v_l^\epsilon}{\partial t} - D_l \Delta v_l^\epsilon = \chi_l g(v^\epsilon) / [1 + \epsilon |g(v^\epsilon)|] & \text{in } Q_T = \Omega \times (0, T), \\ \frac{\partial v_l^\epsilon}{\partial \nu} \Big|_{\partial \Omega} = 0, g(v^\epsilon) = \prod_{l=1}^{l_m} v_l^\epsilon - \prod_{l=l_m+1}^{l_N} v_l^\epsilon, v^\epsilon = (v_l^\epsilon)_{1 \leq l \leq l_N}, \\ \chi_l = -1, \forall 1 \leq l \leq l_m; v_l^\epsilon|_{t=0} = u_{k0}^\epsilon / \lambda, \forall l_{k-1} < l \leq l_k, \forall 1 \leq k \leq m, \\ \chi_l = 1, \forall l_m < l \leq l_N; v_l^\epsilon|_{t=0} = u_{k0}^\epsilon / \mu, \forall l_{k-1} < l \leq l_k, \forall m+1 \leq k \leq N. \end{cases} \quad (24)$$

Since $v \in [0, \infty)^N \rightarrow g(v) / [1 + \epsilon |g(v)|] \in \mathbb{R}$ is uniformly bounded by $1/\epsilon$, this system has a unique classical global solution. By uniqueness, we also have

$$v_l^\epsilon = v_{l_k}^\epsilon, \forall l_{k-1} < l \leq l_k, 1 \leq k \leq N.$$

Let us set

$$u_k^\epsilon := \lambda v_{l_k}^\epsilon, \forall 1 \leq k \leq m, u_k^\epsilon := \mu v_{l_k}^\epsilon, \forall m+1 \leq k \leq N.$$

Then,

$$g(v^\epsilon) = \prod_{k=1}^m (v_{l_k}^\epsilon)^{\alpha_k} - \prod_{k=m+1}^N (v_{l_k}^\epsilon)^{\alpha_k} = \lambda^{-l_m} \prod_{k=1}^m (u_k^\epsilon)^{\alpha_k} - \mu^{l_N - l_m} \prod_{k=m+1}^N (u_k^\epsilon)^{\alpha_k},$$

that is: $g(v^\epsilon) = f(u^\epsilon)$.

Moreover, we easily check that u^ϵ is the solution of System (4). \square

We will now always assume that

$$c_1 = c_2 = 1, \alpha_k = 1, \forall 1 \leq k \leq N, \quad (25)$$

3. Lemma 5 implies Theorem 3

Let us first recall the following well known identity and for convenience, we also recall its proof.

Lemma 7. *Under the assumptions of Lemma 5*

$$\mathbf{E}(u(t)|z) = \mathbf{E}(u(t)) - \mathbf{E}(z), \forall t \geq 0. \quad (26)$$

Proof. The function $E(\cdot \mid \cdot)$, $\mathbf{E}(\cdot \mid \cdot)$, $E(\cdot)$, $\mathbf{E}(\cdot)$ are defined in (10), (11), (12). The following property is valid for any $w \in L^1(\Omega)^+$ and $w_* \in (0, \infty)$:

$$E(w \mid w_*) = E(w) - E(w_*) - (\bar{w} - w_*) \log w_*. \quad (27)$$

We apply this to $w = u_k(t)$, $w_* = z_k$ for all $1 \leq k \leq N$ and we sum over k . Then (26) is reduced to checking

$$\sum_{k=1}^N \tau_k (\bar{u}_k(t) - z_k) \log z_k = 0. \quad (28)$$

We have by (6) and for all $\epsilon > 0$

$$\tau_i \bar{u}_i^\epsilon(t) + \tau_j \bar{u}_j^\epsilon(t) = \tau_i \bar{u}_{i0}^\epsilon + \tau_j \bar{u}_{j0}^\epsilon, \quad \forall 1 \leq i \leq m < j \leq N.$$

This is preserved at the limit and gives

$$\tau_i \bar{u}_i(t) + \tau_j \bar{u}_j(t) = \tau_i \bar{u}_{i0} + \tau_j \bar{u}_{j0}, \quad \forall 1 \leq i \leq m < j \leq N. \quad (29)$$

Since $\tau_i z_i + \tau_j z_j = \tau_i \bar{u}_{i0} + \tau_j \bar{u}_{j0}$, this may be rewritten as

$$\tau_k (\bar{u}_k(t) - z_k) = \begin{cases} \tau_1 (\bar{u}_1(t) - z_1) & \text{for all } 1 \leq k \leq m, \\ -\tau_1 (\bar{u}_1(t) - z_1) & \text{for all } m+1 \leq k \leq N, \end{cases} \quad (30)$$

Then we write (28) as

$$\sum_{k=1}^N \tau_k (\bar{u}_k(t) - z_k) \log z_k = \tau_1 (\bar{u}_1(t) - z_1) \left\{ \sum_{k=1}^m \log z_k - \sum_{k=m+1}^N \log z_k \right\} = 0,$$

using $f(z) = 0$ (recall that (25) holds so that $f(z) = \prod_{i=1}^m z_i - \prod_{j=m+1}^N z_j$). \square

We now show the key lemma of this section.

Lemma 8. *With the notation and assumptions of Theorem 3, together with (25), we have*

$$\frac{d}{dt} \mathbf{E}(u) \leq -D(u) \quad (31)$$

in the sense of distributions on $(0, \infty)$.

Proof. For the classical solution $u^\epsilon = (u_k^\epsilon(\cdot, t))$ to approximate scheme (4)-(5), it holds that

$$\frac{d}{dt} \mathbf{E}(u^\epsilon) + D_\epsilon(u^\epsilon) = 0, \quad (32)$$

where (together with (25))

$$D_\epsilon(u) = 4 \sum_{k=1}^N d_k \|\nabla \sqrt{u_k}\|_2^2 + \int_{\Omega} \frac{f(u)}{1 + \epsilon|f(u)|} \log \frac{\prod_{k=1}^m u_k}{\prod_{k=m+1}^N u_k} \geq 0. \quad (33)$$

Inequality (32) implies after integration in time

$$\mathbf{E}(u^\epsilon(\cdot, t)) \leq \mathbf{E}(u_0^\epsilon), \quad \iint_{Q_T} |\nabla \sqrt{u_k^\epsilon}|^2 \leq C, \quad 1 \leq k \leq N. \quad (34)$$

From the first inequality in (34), using Proposition 1 and Fatou's lemma, we deduce

$$\mathbf{E}(u(\cdot, t)) \leq \mathbf{E}(u_0) \quad \text{a.e. } t. \quad (35)$$

Let us prove that, up to a subsequence,

$$\lim_{\ell \rightarrow \infty} \mathbf{E}(u^{\epsilon_\ell}(\cdot, t)) = \mathbf{E}(u(\cdot, t)) \quad \text{a.e. } t \in (0, \infty), \quad (36)$$

We have

$$\begin{aligned} \frac{\partial}{\partial t} (\tau_i u_i^\epsilon + \tau_j u_j^\epsilon) - \Delta (d_i u_i^\epsilon + d_j u_j^\epsilon) &= 0 \quad \text{in } Q_T \\ \frac{\partial}{\partial \nu} (d_i u_i^\epsilon + d_j u_j^\epsilon) \Big|_{\partial \Omega} &= 0, \quad u_k^\epsilon|_{t=0} = u_{k0}^\epsilon \end{aligned}$$

for $1 \leq i \leq m < j \leq N$, and $1 \leq k \leq N$. Then Lemma 4 of [22] implies

$$\|u^\epsilon\|_{L^2(Q_{\tau,T})} \leq C_{\tau,T} \quad (37)$$

for any $\tau \in (0, T)$ with $C_{\tau,T} > 0$ independent of ϵ , where $Q_{\tau,T} = \Omega \times (\tau, T)$. (See Proposition 6.1 of [21] when $(u_{k0}) \in L^2(\Omega)^N$ in which case we may take $\tau = 0$). Since u^{ϵ_ℓ} tends to u a.e. (see Proposition 1), we classically deduce (36) from Egorov's theorem and the estimate (37). Indeed, given $\alpha > 0$, there exists a compact set $K_\alpha \subset Q_{\tau,T}$ such that $u^{\epsilon_\ell} \rightarrow u$ uniformly on K_α and $|Q_{\tau,T} \setminus K_\alpha| < \alpha$. With $\Phi(s) = s[\log s - 1] + 1$ as in (10), since for some $C_0 \in (0, \infty)$

$$0 \leq \Phi(s)^{3/2} \leq C_0(s^2 + 1), \quad s > 0,$$

125 it holds by (37) that

$$\begin{aligned} \iint_{Q_{\tau,T} \setminus K_\alpha} |\Phi(u^\varepsilon) - \Phi(u)| &\leq |Q_{\tau,T} \setminus K_\alpha|^{1/3} \left(\iint_{Q_{\tau,T} \setminus K_\alpha} |\Phi(u^\varepsilon) - \Phi(u)|^{3/2} \right)^{2/3} \\ &\leq \alpha^{1/3} \left\{ \iint_{Q_{\tau,T}} C_0 \left[((u^\varepsilon)^2 + 1)^{2/3} + (u^2 + 1)^{2/3} \right]^{3/2} \right\}^{2/3} \leq C \alpha^{1/3}. \end{aligned}$$

Hence

$$\limsup_{\ell \rightarrow \infty} \iint_{Q_{\tau,T}} |\Phi(u^{\varepsilon_\ell}) - \Phi(u)| \, dx dt \leq C \alpha^{1/3}.$$

Letting $\alpha \downarrow 0$, we obtain (recall the definition of \mathbf{E} in (11), (12))

$$\lim_{\ell \rightarrow \infty} \int_\tau^T |\mathbf{E}(u^{\varepsilon_\ell}(\cdot, t)) - \mathbf{E}(u(\cdot, t))| \, dt = 0,$$

and therefore (36), up to a subsequence.

Let $\phi \in C_0^\infty[0, T]^+$. It holds that

$$\phi(0)\mathbf{E}(u_0) + \int_0^\infty \phi'(t)\mathbf{E}(u^\varepsilon(\cdot, t)) \, dt = \int_0^\infty \phi(t)D_\varepsilon(u^\varepsilon(\cdot, t)) \, dt \quad (38)$$

by (32). As $\varepsilon = \varepsilon_\ell \downarrow 0$, the left-hand side of (38) converges to

$$\phi(0)\mathbf{E}(u_0) + \int_0^\infty \phi'(t)\mathbf{E}(u(\cdot, t)) \, dt.$$

Here, we used the dominated convergence theorem, recalling (36) with (35) and $(u_{k0} \log u_{k0}) \in L^1(\Omega)^N$.

To treat the right-hand side of (38), we recall the expression of $D_\varepsilon(u^\varepsilon)$ in (33). For its first term, we use (34) to deduce the weak convergence,

$$\nabla \sqrt{u_k^{\varepsilon_\ell}} \rightharpoonup \nabla \sqrt{u_k} \quad \text{in } L^2(Q_T)^N \text{ for } 1 \leq k \leq N,$$

passing to a subsequence. Fatou's lemma is applicable to the second term and it follows that

$$\liminf_{\ell \rightarrow \infty} \int_0^\infty \phi(t)D_{\varepsilon_\ell}(u^{\varepsilon_\ell}(\cdot, t)) \, dt \geq \int_0^\infty \phi(t)D(u(\cdot, t)) \, dt.$$

We thus end up with

$$\phi(0)\mathbf{E}(u_0) + \int_0^\infty \phi'(t)\mathbf{E}(u(\cdot, t)) \, dt \geq \int_0^\infty \phi(t)D(u(\cdot, t)) \, dt$$

which means (31) on $[0, \infty)$ in the sense of distributions, because $T > 0$ and $\phi \in$

130 $C_0^\infty[0, \infty)^+$ are arbitrary. \square

Remark 9. Analyzing the above proof shows that the same result would hold for quite more general approximations f_ϵ of f . For instance, we could choose

$$f_\epsilon(s) = f(s)G_\epsilon(s), \quad 0 \leq G_\epsilon(s) \leq M, \quad |f_\epsilon(s)| \leq 1/\epsilon, \quad \text{for all } s \in [0, \infty)^N,$$

with $f_\epsilon(s) \rightarrow f(s)$ as $\epsilon \rightarrow 0^+$. Then any pointwise limit of the corresponding approximate solution would satisfy the conclusion of Lemma 8 and of Theorem 3 as well.

The following lemma is an adaptation of the classical Csiszár-Kullback inequality
135 to our situation in the spirit of [8, 9, 10, 12, 1].

Lemma 10. *With the notation and assumptions of Theorem 3,*

$$\|u(t) - z\|_{L^1(\Omega)^N} \leq C \mathbf{E}(u(t) \mid z), \quad \forall t \geq 0,$$

for some $C > 0$ depending on u_0, z and the data.

Proof. For $\Phi(s) = s(\log s - 1) + s$ as defined by (10), we have

$$\forall s \in [0, M], \quad |s - 1|^2 \leq C(M) \Phi(s).$$

We deduce

$$|\bar{u}_k(t) - z_k|^2 = z_k^2 \left| \frac{\bar{u}_k(t)}{z_k} - 1 \right|^2 \leq C z_k \Phi\left(\frac{\bar{u}_k(t)}{z_k}\right), \quad 1 \leq k \leq N,$$

where C depends only on $\|u_0\|_{L^1(\Omega)^N}, \|z\|$. It follows that, for some $C_1 > 0$

$$C_1 [\|\bar{u}(t) - z\|_{L^1(\Omega)^N}]^2 \leq \sum_{k=1}^N \tau_k |\bar{u}_k(t) - z_k|^2 \leq C \mathbf{E}(\bar{u}(t) \mid z). \quad (39)$$

Now the classical Csiszár-Kullback-Pinsker inequality says (see e.g. Theorem 31 in [5] or also [6])

$$\left[\int_{\Omega} |u_k(t) - \bar{u}_k(t)| \right]^2 \leq 4 \bar{u}_k(t) E(u_k(t) \mid \bar{u}_k(t)).$$

This implies, for some other constant C

$$\|u(t) - \bar{u}(t)\|_{L^1(\Omega)^N}^2 \leq C \mathbf{E}(u(t) \mid \bar{u}(t)). \quad (40)$$

Using the obvious relation $\mathbf{E}(u(t) \mid z) = \mathbf{E}(u(t) \mid \bar{u}(t)) + \mathbf{E}(\bar{u}(t) \mid z)$ together with (39) and (40), we obtain with another constant C

$$\|u(t) - z\|_{L^1(\Omega)^N}^2 \leq C \mathbf{E}(u(t) \mid z),$$

which is the estimate of Lemma 10. □

Proof of Theorem 3. As proved in Section 2.3, we may assume (25). By Lemmas 8, 7 and 5, we obtain

$$\frac{d}{dt} \mathbf{E}(u \mid z) \leq -2a \mathbf{E}(u \mid z)$$

in the sense of distributions on $(0, \infty)$. This is the statement of Proposition 4 and it implies

$$\mathbf{E}(u(\cdot, t) \mid z) \leq C e^{-2at}, \quad t \geq 0. \quad (41)$$

Together with Lemma 10, this implies Theorem 3. \square

4. Proof of Lemma 5

140 This proof is inspired from those given in [8, 9, 10, 12] for the 4×4 systems, with some significant improvements and simplifying modifications as explained in the introduction.

Here we denote by u_k, u any of the functions $u_k(t), u(t)$ without indicating the t dependence (which is actually not used in this section). Only the conservation laws (see (29))

$$\tau_i \bar{u}_i^k + \tau_j \bar{u}_j^k = U_{ij} := \tau_i \bar{u}_{i0} + \tau_j \bar{u}_{j0}, \quad \forall 1 \leq i \leq m < j \leq N,$$

will be used together with the simplified assumption (25) and $\min_{i,j} U_{ij} > 0$. All constants ' C ' below will depend only on:

$$\min_{i,j} U_{ij}, \bar{u}_{k0}, \tau_k, 1 \leq k \leq N. \quad (42)$$

Lemma 11. *It holds that*

$$\mathbf{E}(\bar{u} \mid z) \leq C \sum_{k=1}^N (\sqrt{\bar{u}_k} - \sqrt{z_k})^2. \quad (43)$$

Proof. It is easily seen that $B(s) := \Phi(s)/(\sqrt{s} - 1)^2$ is continuous on $[0, \infty)$. Thus $B(\bar{u}_k/z_k)$ is bounded above by a constant depending on those in (42). And we have

$$\begin{aligned} \mathbf{E}(\bar{u} \mid z) &= \sum_{k=1}^N \tau_k z_k \Phi\left(\frac{\bar{u}_k}{z_k}\right) = \sum_{k=1}^N \tau_k z_k \left(\frac{\sqrt{\bar{u}_k}}{\sqrt{z_k}} - 1\right)^2 B\left(\frac{\bar{u}_k}{z_k}\right) \\ &\leq C \sum_{k=1}^N (\sqrt{\bar{u}_k} - \sqrt{z_k})^2, \end{aligned}$$

145 whence Lemma 11. \square

Lemma 12. *It holds that*

$$\sum_{k=1}^N (\sqrt{\bar{u}_k} - \sqrt{z_k})^2 \leq C \left[f(\sqrt{\bar{u}}) \right]^2, \quad \sqrt{\bar{u}} = (\sqrt{\bar{u}_k})_{1 \leq k \leq N}. \quad (44)$$

Proof. Recall that, under the assumption (25), $f(u) = \prod_{i=1}^m u_i - \prod_{j=m+1}^N u_j$. According to (30), we have

$$\begin{cases} \bar{u} - z = \theta e, & \theta = \bar{u}_1 - z_1, \quad e = (e_k)_{1 \leq k \leq N}, \\ e_i = \tau_1/\tau_i, \quad e_j = -\tau_1/\tau_j, \quad \forall 1 \leq i \leq m < j \leq N. \end{cases} \quad (45)$$

Therefore

$$f(\bar{u}) - f(z) = \left[\int_0^1 \nabla f((1-s)z + s\bar{u}) ds \right] \cdot (\bar{u} - z) = L(\bar{u})(\bar{u}_1 - z_1), \quad (46)$$

where

$$L(\zeta) = \int_0^1 \nabla f((1-s)z + s\zeta) \cdot e ds, \quad 0 \leq \zeta \in \mathbb{R}^N. \quad (47)$$

We have $\bar{u} = z + (\bar{u}_1 - z_1)e$ where $\bar{u}_1 \in I := [0, \min_{m < j \leq N} U_{1j}]$. But the mapping $\sigma \in I \mapsto L(z + (\sigma - z_1)e)$ is continuous. It does not vanish: indeed, if one had $L(\zeta) = 0$ for some $\zeta = z + (\sigma - z_1)e, \sigma \in I$, then, by the same computation as in (46) with \bar{u} replaced by ζ , we would also have $f(\zeta) = 0$. But the uniqueness property of Proposition 6 would imply $\zeta = z$. And this is impossible since then $L(z) = 0$ and by (47),

$$L(z) = \nabla f(z) \cdot e = \tau_1 \left[\sum_{i=1}^m (\tau_i z_i)^{-1} \prod_{k=1}^m z_k + \sum_{j=m+1}^N (\tau_j z_j)^{-1} \prod_{k=m+1}^N z_k \right],$$

whence a contradiction.

Thus, for

$$\delta = \min_{\sigma \in I} L(z + (\sigma - z_1)e) > 0,$$

it holds that $L(\bar{u}) \geq \delta$, which implies by (46) and (45)

$$f(\bar{u})^2 = (L(\bar{u}))^2 (\bar{u}_1 - z_1)^2 \geq \delta^2 \|\bar{u} - z\|^2 / \|e\|^2,$$

where $\|\cdot\|$ denotes here the euclidean norm in \mathbb{R}^N . We combine this with the identities

$$\begin{aligned} (\bar{u}_k - z_k)^2 &= (\sqrt{\bar{u}_k} - \sqrt{z_k})^2 (\sqrt{\bar{u}_k} + \sqrt{z_k})^2 \\ &\geq \left(\min_{1 \leq k \leq N} z_k \right) \cdot (\sqrt{\bar{u}_k} - \sqrt{z_k})^2, \quad 1 \leq k \leq N \end{aligned}$$

and with

$$\begin{aligned} f(\bar{u})^2 &= \left(\prod_{i=1}^m \bar{u}_i - \prod_{j=m+1}^N \bar{u}_j \right)^2 = f(\sqrt{\bar{u}})^2 \cdot \left(\prod_{i=1}^m \sqrt{\bar{u}_i} + \prod_{j=m+1}^N \sqrt{\bar{u}_j} \right)^2 \\ &\leq C f(\sqrt{\bar{u}})^2 \end{aligned}$$

to deduce (44). \square

Lemma 13. *It holds that*

$$\left[f(\sqrt{\bar{u}}) \right]^2 \leq C \int_{\Omega} f(\sqrt{u})^2 + \sum_{k=1}^N |\nabla \sqrt{u_k}|^2 \quad (48)$$

150 for $\sqrt{u} = (\sqrt{u_k})_{1 \leq k \leq N}$.

Proof. All constant C in this proof may again differ from each other but will depend only on the value in (??). Define $\sigma = \sigma(x) \in \mathbb{R}^N$ for $x \in \Omega$ by $\sqrt{u} = \sqrt{\bar{u}} + \sigma$. First, we have

$$f(\sqrt{u})^2 = f(\sqrt{\bar{u}} + \sigma)^2 = \left(f(\sqrt{\bar{u}}) + \nabla f(\sqrt{\bar{u}}) \cdot \sigma + M \right)^2,$$

where $M = \int_0^1 (1-s) D^2 f(\sqrt{\bar{u}} + s\sigma)[\sigma, \sigma] ds$. Using $(\nabla f(\sqrt{\bar{u}}) \cdot \sigma + M)^2 \geq 0$, this implies

$$f(\sqrt{u})^2 \geq f(\sqrt{\bar{u}})^2 + 2f(\sqrt{\bar{u}}) \nabla f(\sqrt{\bar{u}}) \cdot \sigma + 2f(\sqrt{\bar{u}})M.$$

By Young's inequality and the estimate $|\nabla f(\sqrt{\bar{u}}) \cdot \sigma| \leq C\|\sigma\|$, we have

$$2f(\sqrt{\bar{u}}) \nabla f(\sqrt{\bar{u}}) \cdot \sigma \geq -\frac{1}{2}f(\sqrt{\bar{u}})^2 - 2(\nabla f(\sqrt{\bar{u}}) \cdot \sigma)^2 \geq -\frac{1}{2}f(\sqrt{\bar{u}})^2 - C\|\sigma\|^2.$$

It follows from the two previous inequalities and $|f(\sqrt{\bar{u}})| \leq C$ that

$$f(\sqrt{u})^2 \geq \frac{1}{2}f(\sqrt{\bar{u}})^2 - C(\|\sigma\|^2 + |M|). \quad (49)$$

Next, since $\sqrt{u} \geq 0$ implies $\sigma \geq -\sqrt{\bar{u}}$ in \mathbb{R}^N , we have the partition $\Omega = \Omega_1 \cup \Omega_2$ where

$$\Omega_1 = \{x \in \Omega \mid -\sqrt{\bar{u}_k} \leq \sigma_k(x) \leq 1, \forall 1 \leq k \leq N\},$$

$$\Omega_2 = \cup_{1 \leq k \leq N} \{x \in \Omega \mid \sigma_k(x) > 1\}.$$

For $x \in \Omega_1$, $s \in [0, 1]$, one has: $0 \leq \sqrt{\bar{u}_k} + s\sigma_k \leq 1 + \sqrt{\bar{u}_k}$, so that

$$|M| \leq \int_0^1 (1-s) \|D^2 f(\sqrt{\bar{u}} + s\sigma)\| ds \cdot \|\sigma\|^2 \leq C\|\sigma\|^2, \quad x \in \Omega_1.$$

Together with (49), we deduce

$$\int_{\Omega_1} f(\sqrt{u})^2 dx \geq \int_{\Omega_1} \left[\frac{1}{2}f(\sqrt{\bar{u}})^2 - C\|\sigma\|^2 \right] dx. \quad (50)$$

We also have

$$\int_{\Omega_2} f(\sqrt{u})^2 dx = |\Omega_2| f(\sqrt{u})^2 \leq f(\sqrt{u})^2 \sum_{k=1}^N |\{\sigma_k^2 > 1\}|$$

with

$$|\{\sigma_k^2 > 1\}| = \int_{\{\sigma_k^2 > 1\}} dx \leq \int_{\{\sigma_k^2 > 1\}} \sigma_k^2 dx \leq \int_{\Omega} \sigma_k^2 dx,$$

which implies

$$\int_{\Omega_2} f(\sqrt{u})^2 dx \leq f(\sqrt{u})^2 \int_{\Omega} \|\sigma\|^2 dx \leq C \int_{\Omega} \|\sigma\|^2 dx. \quad (51)$$

By (50)-(51), we obtain

$$f(\sqrt{u})^2 = \int_{\Omega} f(\sqrt{u})^2 dx \leq C \int_{\Omega} [f(\sqrt{u})^2 + \|\sigma\|^2] dx. \quad (52)$$

Then, using in particular Schwarz inequality: $\sqrt{u_k} \geq \int_{\Omega} \sqrt{u_k}$, we have

$$\int_{\Omega} \sigma_k^2 = \int_{\Omega} u_k - 2\sqrt{u_k} \int_{\Omega} \sqrt{u_k} + \int_{\Omega} u_k \leq 2 \left\{ \int_{\Omega} u_k - \left(\int_{\Omega} \sqrt{u_k} \right)^2 \right\} = 2 \int_{\Omega} \left(\sqrt{u_k} - \int_{\Omega} \sqrt{u_k} \right)^2.$$

Using now Poincaré-Wirtinger's inequality implies that

$$\int_{\Omega} \sigma_k^2 = 2 \int_{\Omega} \left(\sqrt{u_k} - \int_{\Omega} \sqrt{u_k} \right)^2 \leq C \int_{\Omega} |\nabla \sqrt{u_k}|^2.$$

Whence (48) by plugging this inequality for all $k = 1, \dots, N$ into (52). \square

Proof of Lemma 5. Combining Lemmas 11, 12, and 13, we obtain

$$\mathbf{E}(\bar{u} | z) \leq C \int_{\Omega} f(\sqrt{u})^2 + \sum_{k=1}^N |\nabla \sqrt{u_k}|^2. \quad (53)$$

Here, the elementary inequality

$$\left(\sqrt{Y} - \sqrt{X} \right)^2 \leq (Y - X) \log \frac{Y}{X}, \quad X, Y \geq 0,$$

applied to $Y = \prod_{i=1}^m u_i$, $X = \prod_{j=m+1}^N u_j$, implies that

$$f(\sqrt{u})^2 \leq f(u) \left(\log \prod_{i=1}^m u_i - \log \prod_{j=m+1}^N u_j \right)$$

and hence

$$\int_{\Omega} f(\sqrt{u})^2 \leq \int_{\Omega} f(u) \left(\log \prod_{i=1}^m u_i - \log \prod_{j=m+1}^N u_j \right) \left(\prod_{i=1}^m u_i - \prod_{j=m+1}^N u_j \right).$$

From this inequality and (53), we obtain

$$\mathbf{E}(\bar{u} | z) \leq CD(u). \quad (54)$$

Finally, we use the additivity property $\mathbf{E}(u \mid z) = \mathbf{E}(u \mid \bar{u}) + \mathbf{E}(\bar{u} \mid z)$ and the logarithmic Sobolev inequality (see e.g. Theorem 17 in [5])

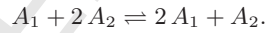
$$E(u_k \mid \bar{u}_k) \leq C \int_{\Omega} |\nabla \sqrt{u_k}|^2, \quad 1 \leq k \leq N,$$

to deduce the statement of Lemma 5. \square

5. Concluding remarks

The main result of Theorem 3 is proved under the positivity assumption (7). This is actually not a restriction. Indeed, if one has $f_{\Omega} u_{i0} + u_{j0} = 0$ for some $1 \leq i \leq m < j \leq N$, in other words if $u_{i0} \equiv 0 \equiv u_{j0}$, then by uniqueness, $u_i^{\epsilon}(t) \equiv 0 \equiv u_j^{\epsilon}(t)$, $f(u^{\epsilon}) \equiv 0$ and System (2) is reduced to the heat equation for each u_k . It is well known in this case that $u_k(t)$ converges exponentially as $t \rightarrow \infty$ to the average $f_{\Omega} u_{k0}$.

On the other hand, Theorem 3 does not handle the interesting case when the chemical species are not separated, contrary to the reversible reaction (1). Then, the system has boundary equilibria and it is known that the standard entropy method does not work (see for instance [13], [7] and their references). This is the case for instance with the typical following reaction



The corresponding system writes

$$\begin{cases} \frac{\partial u_1}{\partial t} - d_1 \Delta u_1 = u_1 u_2^2 - u_1^2 u_2 = - \left[\frac{\partial u_2}{\partial t} - d_2 \Delta u_2 \right], \\ \frac{\partial u_1}{\partial \nu} = 0 = \frac{\partial u_2}{\partial \nu}, \quad (u, v)|_{t=0} = (u_0(x), v_0(x)) \geq 0. \end{cases} \quad (55)$$

Here, the only positive solution of System (22), namely of

$$z_1 z_2^2 = z_1^2 z_2, \quad z_1 + z_2 = \bar{u}_{10} + \bar{u}_{20} := U_{12},$$

is given by $z = (U_{12}/2, U_{12}/2)$. But the situation is quite different from Theorem 3. Indeed if $U_{12} > 0$, the solution does not always converge to this z . If we chose for instance, $u_{10} \equiv 0, u_{20} \equiv a > 0$, then, by uniqueness, the solution is independent of the space variable x and is given by $(u_1(t), u_2(t)) = (0, a)$. Actually, the solution of the spatially homogeneous part of this system is given by $(u_1(t), u_2(t)) = (v(t), a - v(t))$ where v is solution of

$$v' = v(a - v)(a - 2v).$$

And this equation has three stationary states, 0 , $a/2$, a . The second one is stable,
 while the first and the third ones are unstable. Such a behavior probably holds for
 System (55) and more generally, for systems corresponding to general reversible chem-
 ical reactions with all A_1, \dots, A_N appearing on both sides so that boundary equilibria
 appear. We refer to [7] for an extension of the entropy method applied to a specific
 situation with such boundary equilibria.

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- [1] A. Arnold, P. Markowich, G. Toscani and A. Unterreiter, *On generalized Csiszr-Kullback inequalities*, Monatsh. Math., **131** (2000), 235-253.
- [2] D. Bothe, A. Fischer, M. Pierre and G. Rolland, *Global Wellposedness for a Class of Reaction-Advection-Anisotropic-Diffusion Systems*, J. Evol. Equ., (2016), to appear.
- [3] C. Caputo, A. Vasseur, *Global regularity of solutions to systems of reaction-diffusion with sub-quadratic growth in any dimension*, Commun. Partial Differential Equations, **34** (2009), 1228-1250.
- [4] J.A. Canizo, L. Desvillettes and K. Fellner, *Improved duality estimates and applications to reaction-diffusion equations*, Comm. Partial Differential Equations, **39** 6 (2014), 1185-1204.
- [5] J.A. Carrillo, A. Jüngel, P.A. Markowich, G. Toscani, and A. Unterreiter, *Entropy dissipation methods for degenerate parabolic problems and generalized Sobolev inequalities*, Monatsh. Math. **133** (2001), 1-82.
- [6] I. Csiszár, *Eine informationstheoretische Ungleichung und ihre Anwendung auf den Beweis von Markoschen Ketten*, Magyar Tud. Akad. Mat. Kutató Int. Közl. **8** (1963), 85-108.
- [7] L. Desvillettes, K. Fellner and B.Q. Tang, *Trend to equilibrium for reaction-diffusion systems arising from complex balanced chemical reaction networks*, arXiv:1604.04536

- [8] L. Desvillettes and K. Fellner, *Entropy methods for reaction-diffusion equations: slowly growing a priori bounds*, Rev. Mat. Ibero Am. **24** (2008), 407-431.
- 190 [9] L. Desvillettes and K. Fellner, *Duality-Entropy Methods for Reaction-Diffusion Equations Arising in Reversible Chemistry*, System Modelling and Optimization, IFIP AICT, **443** (2014), 96-104.
- [10] L. Desvillettes and K. Fellner, *Exponential Decay toward Equilibrium via Entropy Methods for Reaction-Diffusion Equations*, J. Math. Anal. Appl. **319**, (2006),
195 157-176.
- [11] L. Desvillettes, K. Fellner, M. Pierre and J. Vovelle, *Global existence for quadratic systems of reaction-diffusion*, Adv. Nonlinear Stud. **7** (2007), 491-511.
- [12] K. Fellner and El-Haj Laamri, *Exponential decay towards equilibrium and global classical solutions for nonlinear reaction-diffusion systems*, J. Evol. Equ., (2016),
200 to appear.
- [13] K. Fellner and B.Q. Tang, *Explicit exponential convergence to equilibrium for mass action reaction-diffusion systems with detailed balance condition*, arXiv:1601.05992.
- [14] K. Fellner, E. Latos and T. Suzuki, *Global classical solutions for mass- conserving, (super)-quadratic reaction-diffusion systems in three and higher space dimensions*,
205 to appear in Discrete Contin. Dyn. Syst. Ser. B.
- [15] J. Fischer, *Global existence of renormalized solutions to entropy-dissipating reaction-diffusion systems*, Arch. Rational. Mech. Anal. **218** (2015), 553-587.
- [16] T. Goudon and A. Vasseur, *Regularity analysis for systems of reaction-diffusion equations*, Ann. Sci. Ec. Norm. Sup., **43** (2010), 117-142.
210
- [17] F.J.M. Horn, R. Jackson, *General mass action kinetics*, Arch. Rational Mech. Anal., **47** (1972), 81-116.
- [18] E-H Laamri, *Global existence of classical solutions for a class of reaction-diffusion systems*, Acta Appli. Math. **115** 2 (2011), 153-165.
- 215 [19] A. Mielke, J. Haskovec, P. A. Markowich, *On uniform decay of the entropy for reaction-diffusion systems*, J. Dynam. Differential Equations, **27** (2015), 897-928.

- [20] M. Pierre, *Weak solutions and supersolutions in L^1 for reaction diffusion systems*, J. Evolution Equations **3** (2003), 153-168.
- [21] M. Pierre, *Global existence in reaction-diffusion system with control of mass: a survey*, Milan J. Math. **78** (2010), 417-455.
- [22] M. Pierre and G. Rolland, *Global existence for a class of quadratic reaction-diffusion systems with nonlinear diffusions and L^1 data*, Nonlinear Analysis TMA, **138** (2016), 369-387.
- [23] J. Prüss, *Maximal regularity for evolution equations in L^p -spaces*, Conf. Semin. Mat. Univ. Bari, **285** (2003), 1-39.