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Positive nonlinear CVFE scheme for degenerate anisotropic Keller-Segel system

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Abstract. In this paper, a nonlinear control volume finite element (CVFE) scheme for a degenerate Keller–Segel model with anisotropic and heterogeneous diffusion tensors is proposed and analyzed. In this scheme, degrees of freedom are assigned to vertices of a primal triangular mesh, as in finite element methods. The diffusion term which involves an anisotropic and heterogeneous tensor is discretized on a dual mesh (Donald mesh) using the diffusion fluxes provided by the conforming finite element reconstruction on the primal mesh. The other terms are discretized using a nonclassical upwind finite volume scheme on the dual mesh. The scheme ensures the validity of the discrete maximum principle without any restriction on the transmissibility coefficients. The convergence of the scheme is proved under very general assumptions. Finally, some numerical experiments are carried out to prove the ability of the scheme to tackle degenerate anisotropic and heterogeneous diffusion problems over general meshes.

Math. classification. 65N08, 65N30.

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1. Introduction and model

In this paper, we are interested in degenerate nonlinear parabolic reaction–convection–diffusion systems modeling the chemotaxis process over general mesh, with anisotropic and heterogeneous diffusion tensors. From the numerical point of view, the convergence analysis of the finite volume scheme for this type of systems is carried out in [4] for the isotropic case (i.e. the diffusion tensor is considered to be proportional to the identity matrix) and under the “admissibility” assumption on the mesh used for the space discretization in the sense of satisfying the orthogonality condition (see e.g. [21]). Although its ability to ensure stability, the classical upwind finite volume method does not permit to handle anisotropic diffusion even if the mesh verifies the orthogonality condition. Various “multi-point” schemes, where the approximation of the flux through an edge involves several scalar unknowns, have been proposed for anisotropic diffusion problems, see for example [22, 18, 14, 2, 15] for a detailed review of modern finite volume methods for diffusion equations. However, nonlinear corrections have been proposed in [11] in order to enforce the monotony, but no complete convergence proof have been provided for such methods yet.

Let us introduce the chemotaxis model. For that, let Ω be a connected open bounded polygonal domain of \mathbb{R}^2 , and $t_f > 0$ be a fixed time. The modified Keller–Segel system (e.g., see [26, 27]) modeling

the chemotaxis process is given by the following set of equations

$$\begin{aligned} \partial_t u - \operatorname{div}(\Lambda(\mathbf{x})a(u) - u - \Lambda(\mathbf{x}) - (u) - v) &= f(u) & \text{in } Q_{t_f} = \Omega \times (0, t_f), \\ \partial_t v - \operatorname{div}(D(\mathbf{x}) - v) &= g(u, v) & \text{in } Q_{t_f} = \Omega \times (0, t_f). \end{aligned} \quad (1.1)$$

The system is complemented with zeros-flux boundary conditions on $\Sigma_{t_f} := \Omega \times (0, t_f)$ given by

$$(\Lambda(\mathbf{x})a(u) - u - \Lambda(\mathbf{x}) - (u) - v) \cdot \mathbf{n} = 0, \quad D(\mathbf{x}) - v \cdot \mathbf{n} = 0, \quad (1.2)$$

and the initial conditions on Ω :

$$u(\mathbf{x}, 0) = u_0(\mathbf{x}), \quad v(\mathbf{x}, 0) = v_0(\mathbf{x}). \quad (1.3)$$

In the above model, the density of the cell-population and the chemoattractant concentration are represented by $u = u(\mathbf{x}, t)$ and $v = v(\mathbf{x}, t)$ respectively. Next, $a(u)$ is a density-dependent diffusion coefficient, and $\Lambda(\mathbf{x})$ is the diffusion tensor in a heterogeneous medium. Furthermore, the function f is the chemoattractant sensitivity, and $D(\mathbf{x})$ is the diffusion tensor for v . The function f describes the cell density proliferation and the cell density death. The function g describes the production and the degradation of the chemoattractant concentration; for simplicity, we assume that it is a linear function given by

$$g(u, v) = \mu(u) - \nu(v), \quad \mu, \nu \geq 0. \quad (1.4)$$

and μ represent respectively the production and the degradation rate of the chemical concentration. Let us state the main assumptions made about system (1.1)–(1.3):

- (A1) The cell-density diffusion coefficient $a : [0, 1] \rightarrow \mathbb{R}^+$ is a continuous function such that, $a(0) = a(1) = 0$, and $a(u) > 0$ for $0 < u < 1$.
- (A2) The chemosensitivity $\mu : [0, 1] \rightarrow \mathbb{R}^+$ is a continuous function such that, $\mu(0) = \mu(1) = 0$. Furthermore, we assume that there exists a function $\nu \in C([0, 1]; \mathbb{R}^+)$, such that $\mu(u) = \frac{\nu(u)}{a(u)}$ for all $u \in (0, 1)$ and $\mu(0) = \mu(1) = 0$.
- (A3) The diffusion tensors Λ and D are two bounded, uniformly positive symmetric tensors on Ω , that is: $\Lambda \mathbf{w} = 0, 0 < T_- |\mathbf{w}|^2 \leq T(\mathbf{x}) \mathbf{w}, \mathbf{w} \leq T_+ |\mathbf{w}|^2 < \infty$, $T = \Lambda$ or D .
- (A4) The cell density proliferation f is a continuous function such that $f(0) \geq 0$ and $f(1) \leq 0$.
- (A5) The initial function u_0 and v_0 are two functions in $L^2(\Omega)$ such that, $0 \leq u_0 \leq 1$ and $v_0 \geq 0$.

In the sequel, we use the Lipschitz continuous nondecreasing function $\Phi : \mathbb{R} \rightarrow \mathbb{R}$ defined by

$$\Phi(u) := \int_0^u \frac{1}{a(s)} ds, \quad u \in \mathbb{R}. \quad (1.5)$$

We recall the definition of a weak solution of system (1.1)–(1.3).

Definition 1.1 (weak solution). Under the assumptions (A1)–(A5), we say that the couple of measurable functions (u, v) is a weak solution of system (1.1)–(1.3) if

$$\begin{aligned} 0 \leq u(\mathbf{x}, t) \leq 1, \quad 0 \leq v(\mathbf{x}, t) & \text{ for a.e. in } Q_{t_f}, \\ (u) & \in L^2(0, t_f; H^1(\Omega)), \\ v & \in L^2(Q_{t_f}) \cap L^2(0, t_f; H^1(\Omega)), \end{aligned}$$

and for all $(\mathbf{x}, t) \in D \times [0, t_f]$, one has

$$\begin{aligned}
 - \int_{Q_{t_f}} u_0(\mathbf{x}) \, d\mathbf{x} - \int_{Q_{t_f}} u_t \, d\mathbf{x} \, dt + \int_{Q_{t_f}} \overline{a(u)\Lambda(\mathbf{x})} \cdot \nabla u \, d\mathbf{x} \, dt \\
 - \int_{Q_{t_f}} \Lambda(\mathbf{x}) \cdot \nabla v \, d\mathbf{x} \, dt = \int_{Q_{t_f}} f(u) \, d\mathbf{x} \, dt, \quad (1.6)
 \end{aligned}$$

$$- \int_{Q_{t_f}} v_0(\mathbf{x}) \, d\mathbf{x} - \int_{Q_{t_f}} v_t \, d\mathbf{x} \, dt + \int_{Q_{t_f}} D(\mathbf{x}) \cdot \nabla v \, d\mathbf{x} \, dt = \int_{Q_{t_f}} g(u, v) \, d\mathbf{x} \, dt. \quad (1.7)$$

A standard weak formulation uses the Kirchhoff transform $\overline{a(u)}$ as a primitive of the function $a(u)$. According to [8, 9], we approximate the degenerate diffusion term in its original form in (1.1). Next, we use the specific form of the chemoattractant function to propose a new scheme preserving the positivity of solutions and convergent.

Schemes with mixed conforming piecewise linear finite elements on triangles for the diffusion term and finite volume on dual elements were proposed and analyzed in [7, 13, 1] for fluid mechanics equations, and in [25] for a degenerate nonlinear chemotaxis model. The convergence analysis for these schemes is carried out for the case of anisotropic and heterogeneous diffusion problems under an essential assumption that all the transmissibility coefficients are nonnegative. However, there is no sufficient conditions for nonnegativity of transmissibility coefficients and therefore the schemes do not permit to tackle general anisotropic diffusion problems. Nevertheless, in [12] the authors propose a combined nonconforming finite elements finite volumes scheme for which they add a monotone regularization permitting positiveness of discrete solution; the convergence of the scheme, introduced in [11], is ensured under a numerical condition depending on the mesh size and on the discrete solutions.

Recently, Cancès and Guichard proposed and analyzed in [9] a nonlinear *Control Volume Finite Element* (CVFE) scheme for solving degenerate anisotropic parabolic diffusion equations modeling flows in porous media. The convergence analysis is carried out without any restriction on the transmissibility coefficients, and the efficiency of the scheme is tested using anisotropic diffusion tensors over an unstructured mesh.

Our aim is to elaborate a general approach, inspired from [9] and [25], to approximate a nonlinear degenerate parabolic system modeling the chemotaxis process over general mesh, with anisotropic and heterogeneous diffusion tensors. Especially, the diffusion terms are discretized by means of a conforming piecewise linear finite element method on a primal triangular mesh and using the Godunov scheme to approximate the diffusion fluxes provided by the conforming finite element reconstruction. The others terms are discretized by means of a nonclassical upwind finite volume method on a dual mesh (Donald mesh or Median dual mesh).

The rest of this paper is organized as follows. In section 2, we define a primal triangular mesh and its corresponding Donald dual mesh, next, we define standard P_1 finite element and finite volume reconstructions. Then, we introduce the nonlinear CVFE scheme and specify the discretization of the degenerate diffusion and convection terms. In Section 3, we prove the existence of a discrete solution to the CVFE scheme based on the establishment of *a priori* estimates on the discrete solution as well as the discrete maximum principle. In Section 4, we give estimates on differences of time and space translates for the approximate solutions. In Section 5, using the Kolmogorov relative compactness criterion, we prove the convergence of a subsequence of discrete solutions to the weak solution (Definition 1.1). Finally, some numerical simulations are carried out, in Section 6, to show the effectiveness of the scheme to tackle degenerate anisotropic and heterogeneous diffusion problems over general unstructured mesh.

2. The numerical scheme and main result

In this section, we describe the space and time discretizations of Q_t , define the approximate spaces, introduce useful properties on discrete H^1 -norms stemming from finite elements discretizations as well as the *nonlinear CVFE* scheme, and state the main result.

2.1. Space-time discretization and notations

2.1.1. Space discretizations of Ω .

In order to discretize problem (1.1)–(1.3), we perform a finite element triangulation \mathcal{T} of the polygonal domain Ω , consisting of open bounded triangles such that $\bar{\Omega} = \bigcup_{T \in \mathcal{T}} \bar{T}$ and such that for all $T, T' \in \mathcal{T}$, $\bar{T} \cap \bar{T}'$ is either an empty set or a common vertex or edge of T and T' . We denote by V the set of vertices of the discretization \mathcal{T} , located at positions $(\mathbf{x}_K)_{K \in V}$, and by E the set of edges of \mathcal{T} joining two vertices of V . The edge joining two vertices K and L is denoted by KL .

For a given triangle $T \in \mathcal{T}$, we denote by \mathbf{x}_T the centre of gravity of T , by E_T the set of the edges of T , by h_T the diameter of T , and by ρ_T the diameter of the largest ball inscribed in the triangle T . We denote by h the size of the triangulation \mathcal{T} defined by $h := \max_{T \in \mathcal{T}} h_T$ and by $\sigma_{\mathcal{T}}$ the shape regularity of the triangulation \mathcal{T} , defined by $\sigma_{\mathcal{T}} := \max_{T \in \mathcal{T}} h_T / \rho_T$.

For $K \in V$, we denote by E_K the set of the edges having K as an extremity, and by \mathcal{T}_K the subset of \mathcal{T} including the triangles having K as a vertex. We also define a barycentric dual mesh \mathcal{M} (known as

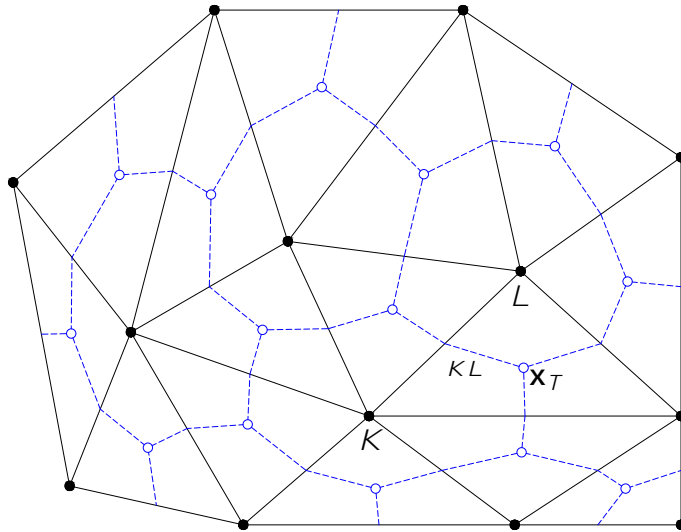


FIGURE 2.1. Triangular mesh \mathcal{T} and Donald dual mesh \mathcal{M} : dual volumes, vertices, interfaces.

Donald dual or Median dual mesh) generated by the triangulation mesh \mathcal{T} . There is one dual element κ_K associated with each vertex $K \in V$. We construct it around the vertex K by connecting the barycenter \mathbf{x}_T of each surrounding triangle $T \in \mathcal{T}_K$ with the barycenters \mathbf{x} of the edges $KL \in E_K$. We refer to Fig. 2.1 for an illustration of the primal and the barycentric dual mesh in a two-dimensional space. Note that $\bar{\Omega} = \bigcup_{K \in V} \bar{\kappa}_K$. The 2-dimensional Lebesgue measure of κ_K is denoted by m_K .

2.2. Discrete finite elements space H_T , control volumes space X_M .

We define two discrete functional spaces associated with each mesh of the above meshes. The first one, denoted by H_T , is the usual P_1 -finite element space corresponding to the triangular mesh T , consisting of piecewise affine finite elements.

$$H_T := \{ u \in C^0(\bar{\Omega}) ; \int_T P_1(\mathbb{R}), \quad T \in \mathcal{T} \quad H^1(\Omega) \}.$$

The canonical basis of H_T is spanned by the shape functions $(\varphi_K)_{K \in \mathcal{V}}$, such that

$$\varphi_K(\mathbf{x}_K) = 1, \quad \varphi_K(\mathbf{x}_L) = 0 \text{ if } L \neq K, \quad K \in \mathcal{V}.$$

On the other hand, we denote by X_M the discrete control volumes space consisting of piecewise constant functions on the dual mesh \mathcal{M} .

$$X_M = \{ v : \Omega \rightarrow \mathbb{R} \text{ measurable; } \int_K v \text{ is constant, } K \in \mathcal{V} \}.$$

Given a vector $(u_K)_{K \in \mathcal{V}} \in \mathbb{R}^{\#\mathcal{V}}$ (resp. $(v_K)_{K \in \mathcal{V}} \in \mathbb{R}^{\#\mathcal{V}}$), there exists a unique function $u_T \in H_T$ (resp. $v_T \in H_T$) and a unique $u_M \in X_M$ (resp. $v_M \in X_M$) such that

$$\begin{aligned} u_T(\mathbf{x}_K) &= u_M(\mathbf{x}_K) = u_K, & K \in \mathcal{V}, \\ v_T(\mathbf{x}_K) &= v_M(\mathbf{x}_K) = v_K, & K \in \mathcal{V}. \end{aligned} \quad (2.1)$$

For all $(K, L) \in \mathcal{V}^2$, we define the transmissibility coefficient T_{KL} by

$$T_{KL} = - \int_T T(\mathbf{x}) \cdot \nabla (\varphi_K(\mathbf{x}) - \varphi_L(\mathbf{x})) d\mathbf{x} = T_{LK}, \quad T = \Lambda \text{ or } D. \quad (2.2)$$

We have $T_{KK} = - \sum_{L \in \mathcal{V}} T_{KL}$, since $\int_K \varphi_K = 1$. As a consequence, one has

$$\int_T T(\mathbf{x}) \cdot \nabla v_T d\mathbf{x} = \sum_{K, L \in \mathcal{V}} T_{KL} (u_K - u_L) (v_K - v_L), \quad T = \Lambda \text{ or } D.$$

2.3. Time discretization of $(0, t_f)$.

For the time discretization of the interval $(0, t_f)$, we consider a uniform time discretization, and we do not impose any restriction on the time step. In addition, we assume that the spatial meshes do not change with the time step. We note that all the results presented in this paper can be extended to the case of general time discretization.

Let N be a nonnegative integer, we define the uniform time step $\Delta t = t_f / (N + 1)$, and $t^n = n\Delta t$ for all $n \in \{0, \dots, N + 1\}$, so that $t^0 = 0$, and $t^{N+1} = t_f$.

2.4. Space-time discretization of Q_{t_f} .

Here, we define the space and time discrete spaces $H_{T, t}$ and $X_{M, t}$ as the set of piecewise constant functions in time with values in H_T and X_M respectively.

$$\begin{aligned} H_{T, t} &= \{ u \in L^2(0, t_f; H^1(\Omega)) \text{ , } (\mathbf{x}, t) \in \mathcal{E} \times [0, t_f] \text{ , } u(\mathbf{x}, t) \in H_T, \quad t \in (t^n, t^{n+1}] \}, \\ X_{M, t} &= \{ v : Q_{t_f} \rightarrow \mathbb{R} \text{ measurable, } (\mathbf{x}, t) \in \mathcal{E} \times [0, t_f] \text{ , } v(\mathbf{x}, t) \in X_M, \quad t \in (t^n, t^{n+1}] \}. \end{aligned}$$

For a given $(u_K^n)_{n \in \{0, \dots, N+1\}, K \in \mathcal{V}} \in \mathbb{R}^{(N+2)\#\mathcal{V}}$ (resp. $(v_K^n)_{n \in \{0, \dots, N+1\}, K \in \mathcal{V}} \in \mathbb{R}^{(N+2)\#\mathcal{V}}$), there exists a unique function $u_{T, t} \in H_{T, t}$ (resp. $v_{T, t} \in H_{T, t}$) and a unique $u_{M, t} \in X_{M, t}$ (resp. $v_{M, t} \in X_{M, t}$)

such that

$$\begin{aligned} u_{T, t}(\mathbf{x}_K, t) &= u_{M, t}(\mathbf{x}_K, t) = u_K^{n+1}, & K \in V, t \in (t^n, t^{n+1}], \\ v_{T, t}(\mathbf{x}_K, t) &= v_{M, t}(\mathbf{x}_K, t) = v_K^{n+1}, & K \in V, t \in (t^n, t^{n+1}]. \end{aligned} \quad (2.3)$$

2.5. The nonlinear CVFE scheme

The discretizations of the initial data u_K^0 and v_K^0 , $K \in V$ are defined by

$$u_M^0(\mathbf{x}) = u_K^0 = \frac{1}{m_K} \int_K u_0(\mathbf{y}) \, d\mathbf{y}, \quad \mathbf{x} \in K, \quad (2.4)$$

$$v_M^0(\mathbf{x}) = v_K^0 = \frac{1}{m_K} \int_K v_0(\mathbf{y}) \, d\mathbf{y}, \quad \mathbf{x} \in K, \quad (2.5)$$

2.5.1. Discretization of the first equation of system (1.1)

For all $K \in V$, and $n \in \{0, \dots, N\}$, we define the discretization of the diffusion term by

$$a_{KL}^{n+1} \Lambda_{KL} (u_K^{n+1} - u_L^{n+1}), \quad \text{with } \Lambda_{KL} = \frac{1}{|E_K|} \int_{E_K} \Lambda(\mathbf{y}) \, d\mathbf{y},$$

where,

$$a_{KL}^{n+1} = \begin{cases} \max_{u \in I_{KL}^{n+1}} a(u) & \text{if } \Lambda_{KL} \geq 0, \\ \min_{u \in I_{KL}^{n+1}} a(u) & \text{if } \Lambda_{KL} < 0, \end{cases} \quad (2.6)$$

and I_{KL}^{n+1} denotes the interval defined by

$$I_{KL}^{n+1} = [\min(u_K^{n+1}, u_L^{n+1}), \max(u_K^{n+1}, u_L^{n+1})]$$

Let us focus on the discretization of the convection term, and recall that the function $\mu(u)$ is defined to be the product of the continuous functions $\mu(u)$ and $a(u)$. To handle the discretization of the convection term in order to obtain a robust and stable scheme, we perform a nonclassical upwind finite volume scheme which consists of considering an upwind scheme for the function $\mu(u)$ according to the discrete gradient of v , and an upwind finite volume scheme for the function $a(u)$ with respect to u . These choices of discretization are crucial to ensure the discrete maximum principle as well as the energy estimates on the approximate solutions.

Definition 2.1. Consider system (1.1) and the notations given in §2.2. We say that the function $\mu_{KL}^{n+1} = \mathcal{Z}(u_K^{n+1}, u_L^{n+1})$ is an approximation of the function $\mu(u)$ on the interfaces of K with respect to the discrete gradient of v if it is nonincreasing (resp. nondecreasing) with respect to the first variable u_K^{n+1} and nondecreasing (resp. nonincreasing) with respect to the other variable u_L^{n+1} when $\Lambda_{KL} (v_K^{n+1} - v_L^{n+1}) \geq 0$ (resp. $\Lambda_{KL} (v_K^{n+1} - v_L^{n+1}) < 0$). Furthermore, we have $\mathcal{Z}(u_K^{n+1}, u_K^{n+1}) = \mu(u_K^{n+1})$.

We give here two examples on the construction of μ_{KL}^{n+1} . The first example consists of taking the Engquist-Osher scheme and the second example consists of taking the Godunov scheme (see e.g. [24, 28]).

Engquist-Osher scheme

$$\bullet \mu_{KL}^{n+1} = \begin{cases} \mu^+(u_K^{n+1}, u_L^{n+1}) + \mu^-(u_L^{n+1}, u_K^{n+1}), & \text{if } \Lambda_{KL} (v_K^{n+1} - v_L^{n+1}) \geq 0, \\ \mu^-(u_K^{n+1}, u_L^{n+1}) + \mu^+(u_L^{n+1}, u_K^{n+1}), & \text{if } \Lambda_{KL} (v_K^{n+1} - v_L^{n+1}) < 0. \end{cases}$$

The functions μ^+ and μ^- are given by

$$\mu^+(z) := \int_0^z \mu(s)^+ ds, \quad \mu^-(z) := - \int_0^z \mu(s)^- ds.$$

Herein, $s^+ = \max(s, 0)$ and $s^- = \max(-s, 0)$.

Godunov scheme

$$\bullet \mu_{KL}^{n+1} = \begin{cases} \max_{[u_K^{n+1}, u_L^{n+1}]} \mu(u), & \text{if } \Lambda_{KL} (v_K^{n+1} - v_L^{n+1}) \geq 0, \text{ and } u_K^{n+1} \leq u_L^{n+1}, \\ \min_{[u_L^{n+1}, u_K^{n+1}]} \mu(u), & \text{if } \Lambda_{KL} (v_K^{n+1} - v_L^{n+1}) \geq 0, \text{ and } u_K^{n+1} > u_L^{n+1}, \\ \max_{[u_L^{n+1}, u_K^{n+1}]} \mu(u), & \text{if } \Lambda_{KL} (v_K^{n+1} - v_L^{n+1}) < 0, \text{ and } u_K^{n+1} > u_L^{n+1}, \\ \min_{[u_K^{n+1}, u_L^{n+1}]} \mu(u), & \text{if } \Lambda_{KL} (v_K^{n+1} - v_L^{n+1}) < 0, \text{ and } u_K^{n+1} \leq u_L^{n+1}. \end{cases}$$

We are now in a position to introduce what we call *nonlinear control volume finite element (CVFE) scheme*. For all $K \in V$, and all $n \in \{0, \dots, N\}$,

$$\frac{u_K^{n+1} - u_K^n}{\Delta t} m_K + \sum_{KL \in E_K} \Lambda_{KL} a_{KL}^{n+1} (u_K^{n+1} - u_L^{n+1}) - \sum_{KL \in E_K} \Lambda_{KL} \mu_{KL}^{n+1} a_{KL}^{n+1} (v_K^{n+1} - v_L^{n+1}) = f(u_K^{n+1}) m_K, \quad (2.7)$$

where, the transmissibility coefficients Λ_{KL} and D_{KL} are given in equality (2.2).

2.5.2. Discretization of the second equation of system (1.1)–(1.3)

Here, we focus on the discretization of the second equation of system (1.1)–(1.3). We note that a classical discretization of this equation is given by the following form

$$m_K \frac{v_K^{n+1} - v_K^n}{\Delta t} + \sum_{KL \in E_K} D_{KL} (v_K^{n+1} - v_L^{n+1}) = m_K (u_K^n - v_K^{n+1}). \quad (2.8)$$

However, this discretization does not guaranty the positivity of the discrete solutions without any restriction on the transmissibility coefficients, for instance, one can get the discrete maximum principle by assuming that all the transmissibility coefficients D_{KL} are nonnegative (see [25]).

Here, we propose a numerical discretization in order to ensure the discrete maximum principle without any restriction on the transmissibility coefficients. To do this, we introduce the following set of

functions: $\chi(v)$, $\rho(v)$, $\Gamma(v)$ and $\bar{\chi}(v)$ defined by

$$\chi(v) = \max(0, \min(v, 1)), \quad (2.9)$$

$$\rho(v) = \int_1^v \frac{1}{(s)} ds = \begin{cases} \ln(v) & \text{if } v \in (0, 1), \\ v - 1 & \text{if } v \geq 1, \end{cases} \quad (2.10)$$

$$\Gamma(v) = \int_1^v \rho(s) ds = \begin{cases} v \ln(v) - v + 1 & \text{if } v \in [0, 1), \\ \frac{(v-1)^2}{2} & \text{if } v \geq 1, \end{cases} \quad (2.11)$$

$$\bar{\chi}(v) = \int_0^v \frac{1}{(s)} ds = \begin{cases} 2 - \bar{v} & \text{if } v \in [0, 1), \\ v + 1 & \text{if } v \geq 1. \end{cases} \quad (2.12)$$

In the sequel, we adopt the convention

$$\chi(v)\rho(v) = 0 \quad \text{if } v = 0. \quad (2.13)$$

We give the discretization of the second equation of system (1.1)–(1.3); specifically, we have

$$m_K \frac{v_K^{n+1} - v_K^n}{\Delta t} + \sum_{\kappa L \in E_K} D_{\kappa L} \frac{n+1}{\kappa L} \rho(v_K^{n+1}) - \rho(v_L^{n+1}) = m_K (u_K^n - v_K^{n+1}), \quad (2.14)$$

where, denoting by $J_{\kappa L}^{n+1} = [\min(v_K^{n+1}, v_L^{n+1}), \max(v_K^{n+1}, v_L^{n+1})]$, we have set

$$\frac{n+1}{\kappa L} = \begin{cases} \max_s J_{\kappa L}^{n+1}(s) & \text{if } D_{\kappa L} = 0, \\ \min_s J_{\kappa L}^{n+1}(s) & \text{if } D_{\kappa L} < 0. \end{cases} \quad (2.15)$$

Note that because of the use of the function ρ in the scheme, the scheme (2.14) only makes sense if

$$v_K^{n+1} > 0 \quad \forall K \in \mathcal{V}, \quad n \geq 0. \quad (2.16)$$

This will be assumed in the *a priori* estimates and rigorously proved later on (cf. Lemma 3.11).

We can show that the scheme (2.7)–(2.14), whose construction is based on finite elements for the diffusion term and a nonclassical upwind finite volume for the convection term, can be interpreted as a finite volume scheme. Indeed, denoting by

$$\begin{aligned} F_{\kappa L}^{n+1} &= \Lambda_{\kappa L} a_{\kappa L}^{n+1} (u_K^{n+1} - u_L^{n+1}) - \Lambda_{\kappa L} \mu_{\kappa L}^{n+1} a_{\kappa L}^{n+1} (v_K^{n+1} - v_L^{n+1}), \\ \Phi_{\kappa L}^{n+1} &= D_{\kappa L} \frac{n+1}{\kappa L} \rho(v_K^{n+1}) - \rho(v_L^{n+1}). \end{aligned}$$

Then the scheme (2.7)–(2.14) rewrites

$$\begin{aligned} F_{\kappa L}^{n+1} + F_{L\kappa}^{n+1} &= 0 = \Phi_{\kappa L}^{n+1} + \Phi_{L\kappa}^{n+1}, & \text{for all } \kappa L \in E, \\ m_K \frac{v_K^{n+1} - v_K^n}{\Delta t} + \sum_{\kappa L \in E_K} F_{\kappa L}^{n+1} &= f(v_K^{n+1}) m_K, & \text{for all } K \in \mathcal{V}, \\ m_K \frac{v_K^{n+1} - v_K^n}{\Delta t} + \sum_{\kappa L \in E_K} \Phi_{\kappa L}^{n+1} &= g(v_K^n, v_K^{n+1}) m_K, & \text{for all } K \in \mathcal{V}. \end{aligned}$$

2.6. Main result

Let $(T_m)_{m \geq 1}$ be a sequence of triangulations of Ω such that

$$h_m = \max_T \text{diam}(T) \rightarrow 0 \text{ as } m \rightarrow \infty.$$

We assume that the sequence of triangulations has a bounded regularity, i.e., there exists a constant $\tau > 0$ such that

$$\tau_m \geq \tau, \quad m \geq 1.$$

As before, a sequence of dual meshes $(M_m)_{m \geq 1}$ is given.

Let $(N_m)_m$ be an increasing sequence of integers, then we define the corresponding sequence of time steps $(\Delta t_m)_m$ such that $\Delta t_m \rightarrow 0$ as $m \rightarrow \infty$. The intention of this paper is to prove the following main result.

Theorem 2.2. *Let $(u_{M_m, t_m}, v_{M_m, t_m})_m$ be a sequence of solutions to the scheme (2.7)–(2.14), such that $0 \leq u_{M_m, t_m} \leq 1$ and $0 \leq v_{M_m, t_m}$ for almost everywhere in Q_T , then*

$$u_{M_m, t_m} \rightharpoonup u \text{ and } v_{M_m, t_m} \rightharpoonup v \text{ a.e. in } Q_T \text{ as } m \rightarrow \infty,$$

where the couple (u, v) is a weak solution to the system (1.1)–(1.3) in the sense of Definition 1.1.

3. Discrete properties, a priori estimates and existence of a discrete solution

In this section, we first bring up some technical lemmas presented by Cancès and Guichard [9], that we reproduce here for clarity. Then, we establish the a priori estimates necessary to prove later the existence of a solution to the discrete problem.

Lemma 3.1. *Let $u_K^{n+1} \in \mathbb{R}^{(N+1)\#V}$ (resp. $v_K^{n+1} \in \mathbb{R}^{(N+1)\#V}$), then denoting by T, t (resp. T, t) the unique function of $H_{T, t}$ with nodal values $u_K^{n+1} \in \mathbb{R}^{(N+1)\#V}$ (resp. $v_K^{n+1} \in \mathbb{R}^{(N+1)\#V}$), one has*

$$\begin{aligned} \sum_{n=0}^N \Delta t \sum_{K,L \in E} \Lambda_{KL} a_{KL}^{n+1} (u_K^{n+1} - u_L^{n+1})^2 \\ \sum_{n=0}^N \Delta t \sum_{K,L \in E} \Lambda_{KL} (u_K^{n+1} - u_L^{n+1})^2 = \int_{Q_T} \Lambda(T, t) \cdot T, t \, d\mathbf{x} dt, \end{aligned} \quad (3.1)$$

and

$$\begin{aligned} \sum_{n=0}^N \Delta t \sum_{K,L \in E} D_{KL} \frac{v_K^{n+1}}{K_L} (\rho(v_K^{n+1}) - \rho(v_L^{n+1}))^2 \\ \sum_{n=0}^N \Delta t \sum_{K,L \in E} D_{KL} (v_K^{n+1} - v_L^{n+1})^2 = \int_{Q_T} D(T, t) \cdot T, t \, d\mathbf{x} dt. \end{aligned} \quad (3.2)$$

Proof. We refer to [9, Lemma 3.1], for the proof of this lemma. ■

Let $T \in \mathcal{T}$, and let $(K, L) \in V^2$, we denote by

$$\begin{aligned} \bar{T}_{KL} &:= - \int_T \Lambda(K) \cdot L \, d\mathbf{x} = \bar{T}_{LK}. \\ \bar{T}_{KL} &:= - \int_T D(K) \cdot L \, d\mathbf{x} = \bar{T}_{LK}. \end{aligned}$$

As a consequence, $\Lambda_{KL} = \frac{\bar{T}_{KL}}{T \cdot T}$ and $D_{KL} = \frac{\bar{T}_{KL}}{T \cdot T}$ for all $K, L \in E$.

Lemma 3.2. *Let $\Psi_T = \int_{\mathcal{K} \cup \mathcal{V}} \Psi_T \cdot \Psi_T d\mathbf{x}$, then there exists a quantity C_0 depending only on Λ , D , and τ such that*

$$\int_{\mathcal{K} \cup \mathcal{V}} \Psi_T \cdot \Psi_T d\mathbf{x} \leq C_0 \int_{\mathcal{K} \cup \mathcal{V}} \Psi_T \cdot \Psi_T d\mathbf{x}, \quad (3.3)$$

and

$$\int_{\mathcal{K} \cup \mathcal{V}} \Psi_T \cdot \Psi_T d\mathbf{x} \leq C_0 \int_{\mathcal{K} \cup \mathcal{V}} \Psi_T \cdot \Psi_T d\mathbf{x}. \quad (3.4)$$

Proof. We refer to [9, Lemma 3.2] for the proof of this lemma. \blacksquare

Lemma 3.3. *There exists a quantity C_1 depending only on Λ , D , and τ such that*

$$\sum_{n=0}^N \Delta t \int_{\mathcal{K} \cup \mathcal{E}} |\Lambda_{KL}| a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2 \leq C_1 \sum_{n=0}^N \Delta t \int_{\mathcal{K} \cup \mathcal{E}} \Lambda_{KL} a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2. \quad (3.5)$$

and

$$\sum_{n=0}^N \Delta t \int_{\mathcal{K} \cup \mathcal{E}} |D_{KL}| \frac{1}{\rho} (\rho(v_K^{n+1}) - \rho(v_L^{n+1}))^2 \leq C_1 \sum_{n=0}^N \Delta t \int_{\mathcal{K} \cup \mathcal{E}} D_{KL} \frac{1}{\rho} (\rho(v_K^{n+1}) - \rho(v_L^{n+1}))^2. \quad (3.6)$$

Proof. We denote by $E^- := \{KL \in \mathcal{E}; \Lambda_{KL} < 0\}$, then since $|\mathbf{x}| = \mathbf{x} + 2\mathbf{x}^-$, $\mathbf{x}^- = \max(-\mathbf{x}, 0)$, one has

$$\begin{aligned} \sum_{n=0}^N \Delta t \int_{\mathcal{K} \cup \mathcal{E}} |\Lambda_{KL}| a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2 &= \sum_{n=0}^N \Delta t \int_{\mathcal{K} \cup \mathcal{E}} \Lambda_{KL} a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2 \\ &\quad + 2 \sum_{n=0}^N \Delta t \int_{\mathcal{K} \cup \mathcal{E}^-} |\Lambda_{KL}| a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2. \end{aligned}$$

Now, from the definition (2.6) of a_{KL}^{n+1} , there exists $c \in [0, 1]$ such that

$$|u_K^{n+1} - u_L^{n+1}|^2 = a(c) |u_K^{n+1} - u_L^{n+1}|^2 + a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2, \quad KL \in \mathcal{E}^-$$

Therefore,

$$\begin{aligned} \sum_{n=0}^N \Delta t \int_{\mathcal{K} \cup \mathcal{E}} |\Lambda_{KL}| a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2 &\leq \sum_{n=0}^N \Delta t \int_{\mathcal{K} \cup \mathcal{E}} \Lambda_{KL} a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2 \\ &\quad + 2 \sum_{n=0}^N \Delta t \int_{\mathcal{K} \cup \mathcal{E}^-} |\Lambda_{KL}| |u_K^{n+1} - u_L^{n+1}|^2. \end{aligned} \quad (3.7)$$

Lemma 3.2 ensures the existence of a quantity $C_0 > 0 (= C_0(\Lambda, \tau))$ such that

$$\begin{aligned} \sum_{n=0}^N \Delta t \int_{\mathcal{K} \cup \mathcal{E}} |\Lambda_{KL}| |u_K^{n+1} - u_L^{n+1}|^2 &\leq \sum_{n=0}^N \Delta t \int_{\mathcal{K} \cup \mathcal{E} \cup \mathcal{T}} |\Lambda_{KL}| |u_K^{n+1} - u_L^{n+1}|^2 \\ &\leq C_0 \int_{\Omega} \Lambda_{\tau} \cdot \Lambda_{\tau} d\mathbf{x} dt, \end{aligned}$$

and from Lemma 3.1, we deduce that

$$\sum_{n=0}^N \Delta t \int_{\mathcal{K} \cup \mathcal{E}} |\Lambda_{KL}| |u_K^{n+1} - u_L^{n+1}|^2 \leq C_0 \sum_{n=0}^N \Delta t \int_{\mathcal{K} \cup \mathcal{E}} \Lambda_{KL} a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2. \quad (3.8)$$

Plugging estimate (3.8) into estimate (3.7), then estimate (3.5) holds with $C_1 = 1 + 2C_0$. The proof of estimate (3.6) is similar. \blacksquare

3.1. Discrete maximum principle

Lemma 3.4. *Let u_K^{n+1}, v_K^{n+1} $_{K \in V, n \in \{0, \dots, N\}}$ be a solution to the CVFE scheme (2.7)–(2.14). Then, for all $K \in V$, and all $n \in \{0, \dots, N+1\}$, we have $0 \leq u_K^n \leq 1$.*

Proof. We show this property using an induction on n . The property is true for $n = 0$ thanks to the definitions (2.4) and (2.5) of u_K^0 and v_K^0 and to the assumptions on u_0 and v_0 . Now, assume that the claim is true up to time step n . Consider a dual control volume κ such that $u_K^{n+1} = \min_{L \in V} \{u_L^{n+1}\}$, we want to show that $u_K^{n+1} \geq 0$ i.e. $u_K^{n+1} \bar{=} 0$. Multiplying equation (2.7) by $-u_K^{n+1} \bar{=}$, one has

$$\begin{aligned} -m_K \frac{u_K^{n+1} - u_K^n}{\Delta t} u_K^{n+1} \bar{=} - \sum_{K_L \in E_K} \Lambda_{KL} a_{KL}^{n+1} (u_K^{n+1} - u_L^{n+1}) u_K^{n+1} \bar{=} \\ + \sum_{K_L \in E_K} \Lambda_{KL} \mu_{KL}^{n+1} a_{KL}^{n+1} (v_K^{n+1} - v_L^{n+1}) u_K^{n+1} \bar{=} = -m_K f(u_K^{n+1}) u_K^{n+1} \bar{=} \leq 0, \end{aligned} \quad (3.9)$$

to which, we have used the extension by $f(0) \geq 0$ (see assumption (A4)) of the continuous function f for $u \leq 0$.

In view of the definition (2.6) of a_{KL}^{n+1} , and of the fact that $a(u) = 0$ if $u \leq 0$, one has $a_{KL}^{n+1} = 0$, if $\Lambda_{KL} \leq 0$. Therefore, the second term in the left hand side of equation (3.9) reads to

$$- \sum_{K_L \in E_K} a_{KL}^{n+1} (\Lambda_{KL})^+ (u_K^{n+1} - u_L^{n+1}) u_K^{n+1} \bar{=} \leq 0,$$

Let us now focus on the third term of equation (3.9), and denote by A this term. Since $a_{KL}^{n+1} = 0$ for $\Lambda_{KL} \leq 0$, then A rewrites

$$A = \sum_{K_L \in E_K} \Lambda_{KL}^+ \mu_{KL}^{n+1} a_{KL}^{n+1} (v_K^{n+1} - v_L^{n+1})^+ u_K^{n+1} \bar{=} - \sum_{K_L \in E_K} \Lambda_{KL}^+ \mu_{KL}^{n+1} a_{KL}^{n+1} (v_K^{n+1} - v_L^{n+1})^- u_K^{n+1} \bar{=}.$$

The second term of A is nonpositive, but in view of Definition 2.1 on the approximation μ_{KL}^{n+1} and in view of the extension by zero of the function μ for $u \leq 0$ since $\mu(0) = 0$, one can deduce that

$$\mu_{KL}^{n+1} \Lambda_{KL}^+ (v_K^{n+1} - v_L^{n+1})^- u_K^{n+1} \bar{=} \mu(u_K^{n+1}) \Lambda_{KL}^+ (v_K^{n+1} - v_L^{n+1})^- u_K^{n+1} \bar{=} = 0,$$

thus, the second term of A is equal to zero and consequently $A \geq 0$ since the first term of A is nonnegative.

Finally, we use the identity $u_K^{n+1} = u_K^{n+1} \bar{=} - u_K^{n+1} \bar{=}$ and the nonnegativity of u_K^n , one can deduce from equation (3.9) that $u_K^{n+1} \bar{=} = 0$. According to the choice of the dual control volume κ , then $\min_{L \in V} \{u_L^{n+1}\}$ is non-negative. Consequently, $u_K^n \geq 0$, $K \in V$, and all $n \in \{0, \dots, N+1\}$.

In order to prove by induction that $u_K^n \leq 1$, $K \in V$, $n \in \{0, \dots, N+1\}$, we proceed in the same way as before, so that we consider a dual control volume κ such that $u_K^{n+1} = \max_{L \in V} \{u_L^{n+1}\}$. We get up the result using Remark 2.1, the extension by zero of each of the function a , and μ for $u \leq 1$, and the extension by $\bar{f}(1) \leq 0$ of the continuous function f for $u \geq 1$. \blacksquare

3.2. Entropy estimates on $v_{M, t}$

In the following, C denotes a “generic” constant, that may vary throughout the proofs. We prove now an entropy estimate on $v_{M, t}$.

Lemma 3.5. *There exists $C > 0$ depending only on $v_0 \in L^2(\cdot)$, Ω , t_f , and \cdot such that, for all $n \in \{0, \dots, N\}$, one has*

$$m_K \Gamma(v_K^{n+1}) + \sum_{n=0}^n \Delta t \int_{K \in \mathcal{V}} D_{KL} \int_{K \in \mathcal{E}} \rho(v_K^{n+1}) - \rho(v_L^{n+1})^2 \leq C.$$

Proof. It follows from Jensen’s inequality – recall that Γ is convex – that

$$m_K \Gamma(v_K^0) \leq \int_{K \in \mathcal{V}} \Gamma(v_0(\mathbf{x})) \, d\mathbf{x}.$$

Since $\Gamma(v) = (v-1)^2$ for all $v \geq 0$, we obtain that

$$m_K \Gamma(v_K^0) \leq \int_{K \in \mathcal{V}} (v_0(\mathbf{x}) - 1)^2 \, d\mathbf{x} \leq C. \quad (3.10)$$

Multiplying the scheme (2.14) by $\rho(v_K^{n+1}) \Delta t$ and summing over $K \in \mathcal{V}$ and $n = 0, \dots, n$ provides

$$A + B = C, \quad (3.11)$$

where we have set

$$\begin{aligned} A &= \sum_{n=0}^n \sum_{K \in \mathcal{V}} m_K (v_K^{n+1} - v_K^n) \rho(v_K^{n+1}), \\ B &= \sum_{n=0}^n \Delta t \int_{K \in \mathcal{E}} D_{KL} \int_{K \in \mathcal{E}} \rho(v_K^{n+1}) - \rho(v_L^{n+1})^2, \\ C &= \sum_{n=0}^n \sum_{K \in \mathcal{V}} \Delta t \int_{K \in \mathcal{V}} m_K (u_K^n - v_K^{n+1}) \rho(v_K^{n+1}). \end{aligned}$$

Since, thanks to Lemma 3.4, u_K^n is non-negative for all $K \in \mathcal{V}$ and all $n \geq 0$, and since $\rho(v) = (v-1)^2$ for all $v \geq 0$ (with the convention $\rho(0) = -$), one has

$$u_K^n \rho(v_K^{n+1}) \leq u_K^n (v_K^{n+1} - 1).$$

On the other hand, there exists an absolute constant c such that $v \rho(v) = (v-1)^2 - c$ for all $v \geq 0$. Therefore,

$$v_K^{n+1} \rho(v_K^{n+1}) \leq (v_K^{n+1} - 1)^2 - c.$$

As a consequence, we obtain that

$$C \leq t_f / \Omega / c + \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{V}} m_K \int_{K \in \mathcal{V}} u_K^n (v_K^{n+1} - 1) - (v_K^{n+1} - 1)^2.$$

Using the weighted Young’s inequality $ab \leq b^2 + \frac{a^2}{4}$ for all $(a, b) \in \mathbb{R}^2$ provides

$$u_K^n (v_K^{n+1} - 1) - (v_K^{n+1} - 1)^2 \leq \frac{2}{4} u_K^n - \frac{2}{4}$$

thanks to Lemma 3.4. Hence, we obtain that

$$C \leq t_f / \Omega / c + \frac{2}{4}. \quad (3.12)$$

The function ρ being increasing, an elementary convexity inequality provides that

$$(a-b)\rho(a) \leq \Gamma(a) - \Gamma(b), \quad (a, b) \in (\mathbb{R}_+)^2,$$

ensuring that

$$A \sum_{n=0}^n \sum_{K \in \mathcal{V}} m_K \left(\Gamma(v_K^{n+1}) - \Gamma(v_K^n) \right) = \sum_{K \in \mathcal{V}} m_K \left(\Gamma(v_K^{n+1}) - \Gamma(v_K^0) \right). \quad (3.13)$$

Using (3.12), (3.13) and (3.10) in (3.11) concludes the proof of Lemma 3.5. \blacksquare

As a second step, we propose to derive a classical energy estimate on $v_{M, t}$. Even though the convergence analysis of the scheme can be performed without this estimate, it is interesting to check that our nonlinear scheme also allows to recover the classical estimates one expects from the classical scheme (2.8).

Lemma 3.6. *There exists C depending only on Ω , $v_0 \in L^2(\cdot)$, ρ , ρ' , and t_f such that, for all $n \in \{0, \dots, N\}$, one has*

$$\frac{1}{2} \sum_{K \in \mathcal{V}} m_K |v_K^{n+1}|^2 + \sum_{n=0}^n \Delta t \sum_{K, L \in E} D_{KL} |v_K^{n+1} - v_L^{n+1}|^2 \leq C.$$

Proof. Let $n \in \{0, \dots, n\}$, then multiplying the scheme (2.14) by $v_K^{n+1} \Delta t$ and summing over $K \in \mathcal{V}$ yields

$$A^{n+1} + B^{n+1} = C^{n+1} \quad (3.14)$$

where

$$\begin{aligned} A^{n+1} &= \sum_{K \in \mathcal{V}} m_K v_K^{n+1} |v_K^{n+1} - v_K^n|^2, \\ B^{n+1} &= \Delta t \sum_{K, L \in E} D_{KL} \left(\rho(v_K^{n+1}) - \rho(v_L^{n+1}) \right) |v_K^{n+1} - v_L^{n+1}|^2, \\ C^{n+1} &= \Delta t \sum_{K \in \mathcal{V}} m_K |u_K^{n+1} - v_K^{n+1}|^2. \end{aligned}$$

It follows from the simple inequality $a(a-b) \geq \frac{a^2}{2} - \frac{b^2}{2}$ that

$$A^{n+1} \geq \frac{1}{2} \sum_{K \in \mathcal{V}} m_K |v_K^{n+1}|^2 - \frac{1}{2} \sum_{K \in \mathcal{V}} m_K |v_K^n|^2. \quad (3.15)$$

The definition (2.15) of ρ_{KL}^{n+1} and the relation (2.10) between ρ and ρ' implies that

$$D_{KL} \rho_{KL}^{n+1} \left(\rho(v_K^{n+1}) - \rho(v_L^{n+1}) \right) |v_K^{n+1} - v_L^{n+1}|^2 \geq D_{KL} |v_K^{n+1} - v_L^{n+1}|^2, \quad K, L \in E.$$

Therefore,

$$B^{n+1} \geq \Delta t \sum_{K, L \in E} D_{KL} |v_K^{n+1} - v_L^{n+1}|^2. \quad (3.16)$$

Let us now focus on the term C^{n+1} . Thanks to the simple inequality $ab \geq \frac{a^2}{4} + b^2$, one gets that

$$C^{n+1} \geq \Delta t \sum_{K \in \mathcal{V}} m_K \frac{1}{4} |u_K^{n+1}|^2.$$

Using now the fact that $0 \leq u_K^{n+1} \leq 1$ (cf. Lemma 3.4), we obtain that

$$C^{n+1} \geq \frac{2 \Delta t |\Omega|}{4}. \quad (3.17)$$

Combining (3.15)–(3.17) in (3.14) and summing over $n \in \{0, \dots, N\}$ provides that

$$\frac{1}{2} \sum_{K \in \mathcal{V}} m_K |v_K^{n+1}|^2 + \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{L}, E} D_{KL} |v_K^{n+1} - v_L^{n+1}|^2 \leq \frac{1}{2} \sum_{K \in \mathcal{V}} m_K |v_K^0|^2 + \frac{2n \Delta t |\Omega|}{4}.$$

In order to conclude the proof of Lemma 3.6, it only remains to check that

$$\sum_{K \in \mathcal{V}} m_K |v_K^0|^2 \leq v_0^2 L^2(\cdot)$$

as a consequence of Jensen's inequality. \blacksquare

3.3. Energy estimates on $u_{M, t}$

Proposition 3.7. *There exists a constant $C > 0$ depending only on $v_0 \in L^2(\cdot)$, Ω , t_f , μ , Λ , D , and τ such that, for all $n \in \{0, \dots, N\}$, one has*

$$\sum_{K \in \mathcal{V}} m_K |u_K^{n+1}|^2 + \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{L}, E} \Lambda_{KL} a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2 \leq C. \quad (3.18)$$

Proof. We multiply equation (2.7) by $\Delta t u_K^{n+1}$ and sum over $K \in \mathcal{V}$ and $n \in \{0, \dots, n\}$. This yields

$$E_1 + E_2 + E_3 = E_4, \quad (3.19)$$

where

$$E_1 = \sum_{n=0}^n \sum_{K \in \mathcal{V}} m_K |u_K^{n+1} - u_K^n|^2, \quad E_2 = \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{V}, K \in \mathcal{L}, E_K} \Lambda_{KL} a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2 |u_K^{n+1}|^2,$$

$$E_4 = \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{V}} m_K f |u_K^{n+1}|^2 |u_K^{n+1}|^2, \quad E_3 = - \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{V}, K \in \mathcal{L}, E_K} \Lambda_{KL} \mu_{KL}^{n+1} a_{KL}^{n+1} |v_K^{n+1} - v_L^{n+1}|^2 |u_K^{n+1}|^2.$$

For the time evolution term, we use the following inequality: $(a - b) a \leq \frac{1}{2} a^2 - b^2$, $a, b \in \mathbb{R}$, to get

$$E_1 \leq \frac{1}{2} \sum_{n=0}^n \sum_{K \in \mathcal{V}} m_K |u_K^{n+1}|^2 - (u_K^n)^2 = \frac{1}{2} \sum_{K \in \mathcal{V}} m_K |u_K^{n+1}|^2 - |u_K^0|^2. \quad (3.20)$$

Next, for the diffusion term, we reorganize the sum over the edges, we find

$$E_2 = \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{V}, K \in \mathcal{L}, E_K} \Lambda_{KL} a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2 |u_K^{n+1}|^2 = \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{L}, E} \Lambda_{KL} a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2. \quad (3.21)$$

Similarly, we reorganize the sum over the edges for the convection term. We obtain

$$E_3 = - \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{V}, K \in \mathcal{L}, E_K} \Lambda_{KL} \mu_{KL}^{n+1} a_{KL}^{n+1} |v_K^{n+1} - v_L^{n+1}|^2 |u_K^{n+1}|^2$$

$$= - \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{L}, E} \Lambda_{KL} \mu_{KL}^{n+1} a_{KL}^{n+1} |v_K^{n+1} - v_L^{n+1}|^2 |u_K^{n+1} - u_L^{n+1}|^2.$$

Using the weighted Young inequality and the uniform boundedness of the function μ , we deduce

$$\begin{aligned}
 |E_3| &\leq C \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{K}} \sum_{V \in \mathcal{V}_K} \sum_{K_L \in \mathcal{K}_L} \sum_{E_K \in \mathcal{E}_K} |\Lambda_{KL}| a_{KL}^{n+1} |v_K^{n+1} - v_L^{n+1}| |u_K^{n+1} - u_L^{n+1}| \\
 &\leq C \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{K}} \sum_{V \in \mathcal{V}_K} \sum_{K_L \in \mathcal{K}_L} \sum_{E_K \in \mathcal{E}_K} |\Lambda_{KL}| |v_K^{n+1} - v_L^{n+1}|^2 \\
 &\quad + \frac{1}{2C_1} \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{K}} \sum_{V \in \mathcal{V}_K} \sum_{K_L \in \mathcal{K}_L} \sum_{E_K \in \mathcal{E}_K} |\Lambda_{KL}| a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2,
 \end{aligned}$$

where C_1 is the same constant introduced in Lemma 3.3.

Thanks to estimates (3.3) and (3.5), one has

$$|E_3| \leq C \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{K}} \sum_{V \in \mathcal{V}_K} \sum_{K_L \in \mathcal{K}_L} \sum_{E_K \in \mathcal{E}_K} \Lambda_{KL} |v_K^{n+1} - v_L^{n+1}|^2 + \frac{1}{2} \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{K}} \sum_{V \in \mathcal{V}_K} \sum_{K_L \in \mathcal{K}_L} \sum_{E_K \in \mathcal{E}_K} \Lambda_{KL} a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2.$$

Therefore, Lemma 3.6 provides

$$|E_3| \leq C + \frac{1}{2} \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{K}} \sum_{V \in \mathcal{V}_K} \sum_{K_L \in \mathcal{K}_L} \sum_{E_K \in \mathcal{E}_K} \Lambda_{KL} a_{KL}^{n+1} |u_K^{n+1} - u_L^{n+1}|^2. \quad (3.22)$$

Finally, for the reaction term, since $0 \leq u_K^{n+1} \leq 1$ thanks to Lemma 3.4, one has

$$E_4 = \sum_{n=0}^n \Delta t \sum_{K \in \mathcal{K}} \sum_{V \in \mathcal{V}_K} m_K f |u_K^{n+1} - u_L^{n+1}| \leq |\Omega| f_{L(0,1)} t_f. \quad (3.23)$$

Plugging estimates (3.20)–(3.23) into equation (3.19), one deduces that estimate (3.18) holds. \blacksquare

3.4. Enhanced estimate on $v_{M,t}$

The goal of this section is to prove a refined estimate on $v_{M,t}$ inspired from [9, Lemma 3.10], claiming that either $v_{M,t}$ is constant equal to 0, or $v_{M,t} \geq r_h > 0$ for some r_h depending on the discretization parameters. The first step consists of bounding from below the $L^1((0, t_f); L^1(\Omega))$ norm of $v_{M,t}$.

Lemma 3.8. *Assume that $\int_{\Omega} u_0(\mathbf{x}) d\mathbf{x} > 0$ or $\int_{\Omega} v_0(\mathbf{x}) d\mathbf{x} > 0$, then there exists $r_h > 0$ depending on the discretization and on the data such that*

$$\int_{\Omega} v_{M,t}(\mathbf{x}, t) d\mathbf{x} \geq r_h, \quad t \in [0, t_f].$$

Proof. Summing equation (2.14) over $K \in \mathcal{K}$ ensures that

$$m_K (1 + \Delta t) v_K^{n+1} = m_K v_K^n + \Delta t \sum_{K \in \mathcal{K}} m_K u_K^n, \quad n \in \{0, \dots, N\}. \quad (3.24)$$

Assume that $v_{K^n}^n > 0$ or $u_{K^n}^n > 0$ for some $K^n \in \mathcal{K}$, as this is the case for $n = 0$ because of the assumption on the initial data u_0 and v_0 , then we deduce from (3.24) and from the non-negativity of v_K^n and u_K^n proved in Lemma 3.4 that

$$m_K (1 + \Delta t) v_K^{n+1} > 0.$$

In particular, there exists $K^{n+1} \in \mathcal{K}$ such that $v_{K^{n+1}}^{n+1}$ is (strictly) positive and

$$m_{K^{n+1}} v_{K^{n+1}}^{n+1} := v_{n+1} > 0.$$

One concludes the proof by setting $v = \min_{n=1, \dots, N+1} v_n$. \blacksquare

We give now the definition of D -transmissive path, which was introduced in [9, Definition 3.4].

Definition 3.9. A D -transmissive path w joining $K_i \in V$ to $K_f \in V$ consists in a list of vertices $(K_q)_{0 \leq q \leq M}$ such that $K_i = K_0$, $K_f = K_M$, with $K_q = K$ if $q = 0$, and such that $K_q K_{q+1} \in E$ with $D_{K_q K_{q+1}} > 0$ for all $q \in \{0, \dots, M-1\}$. We denote by $W(K_i, K_f)$ the set of the transmissive path joining $K_i \in V$ to $K_f \in V$.

We now state a result which is proved in [9, Lemma 3.5].

Lemma 3.10. For all $(K_i, K_f) \in V^2$ there exists a transmissive path $w \in W(K_i, K_f)$.

We have now introduced all the necessary tools for proving the main result of this section.

Lemma 3.11. Assume that $\int u_0(\mathbf{x})d\mathbf{x} > 0$ or $\int v_0(\mathbf{x})d\mathbf{x} > 0$, then there exists $r_h > 0$ depending on the data as well as on the mesh T and Δt such that

$$v_K^{n+1} \geq r_h, \quad K \in V, \quad n \in \{0, \dots, N\}. \quad (3.25)$$

Proof. Thanks to Lemma 3.8, we know that there exists K_i such that $v_{K_i}^{n+1} > 0$. Let $K_f \in V$, then there exists a D -transmissive path $w = (K_q)_{0 \leq q \leq M} \in W(K_i, K_f)$ thanks to Lemma 3.10, with $K_0 = K_i$ and $K_M = K_f$.

Thanks to Lemmas 3.3 and 3.5, we know that there exists C such that

$$\sum_{n=0}^N \Delta t \sum_{K \sim L \in E} |D_{KL}| \frac{v_K^{n+1} - v_L^{n+1}}{K_L} \leq C.$$

In particular, this ensures that

$$D_{K_q K_{q+1}} \frac{v_{K_q}^{n+1} - v_{K_{q+1}}^{n+1}}{K_q K_{q+1}} \leq \frac{C}{\Delta t}, \quad q \in \{0, \dots, M-1\}.$$

Assume now that $v_{K_q}^{n+1} > 0$, as this is the case for $q = 0$, then $\frac{v_{K_q}^{n+1}}{K_q K_{q+1}} - \frac{v_{K_{q+1}}^{n+1}}{K_q K_{q+1}} > 0$. Then one has

$$\frac{v_{K_q}^{n+1} - v_{K_{q+1}}^{n+1}}{K_q K_{q+1}} \leq \frac{C}{\Delta t D_{K_q K_{q+1}} \frac{v_{K_q}^{n+1}}{K_q K_{q+1}}} < \dots \quad (3.26)$$

We deduce from (3.26) that $v_{K_{q+1}}^{n+1} > 0$ and, since $\lim_{v \rightarrow 0} \rho(v) = 0$ hence $v_{K_{q+1}}^{n+1} > 0$. A straightforward induction provides that $v_{K_f}^{n+1} > 0$, and since K_f was chosen arbitrarily, we obtain that $v_K^{n+1} > 0, \quad K \in V$.

Since the set $V \times \{0, \dots, N\}$ is finite, we can conclude that there exists r_h such that (3.25) holds. ■

3.5. Existence of a discrete solution

Proposition 3.12. Given $(u_K^n, v_K^n)_{K \in V}$ such that $u_{M, t}(\cdot, n\Delta t)$ and $v_{M, t}(\cdot, n\Delta t)$ are non-negative, then there exists (at least) one solution $(u_K^{n+1}, v_K^{n+1})_{K \in V}$ of the scheme (2.7),(2.14). Moreover, $u_{M, t}(\cdot, n\Delta t)$ and $v_{M, t}(\cdot, n\Delta t)$ are non-negative.

Proof. The case where $(u_K^n, v_K^n)_{K \in V} = 0$ has to be treated apart. In this very particular case, it is easy to check that $(u_K^{n+1}, v_K^{n+1})_{K \in V} = 0$ is a solution to the scheme.

Let us now focus on the case where u_K^n or v_K^n is strictly positive for some $K \in V$. Because of the weak coupling on the numerical scheme, we can first solve (2.14), and afterwards (2.7). The existence of a solution $(u_K^{n+1}, v_K^{n+1})_{K \in V}$ can be proved by slightly adapting the proof of [9, Proposition 3.11], which

relies on a topological argument. The main difficulty comes from the fact the scheme (2.14) is not continuous w.r.t. v_K^{n+1} on $(\mathbb{R}_+)^{\#V}$, but Lemma 3.11 ensures that no component v_K^{n+1} of the discrete solution can go close to 0. Let us detail now the proof.

Let $\tau \in [0, 1]$, we denote by $v_{K,V}^{n+1}$ the solution (if it exists) to the numerical scheme

$$\frac{v_{K,V}^{n+1} - v_K^n}{\Delta t} m_K + \sum_{K,L \in E_K} D_{KL} \frac{v_{K,L}^{n+1}}{v_{K,L}^{n+1} + v_{K,V}^{n+1}} (\rho(v_{K,V}^{n+1}) - \rho(v_{K,L}^{n+1})) \\ (1 - \tau) \sum_{K,L \in E_K} |D_{KL}| (\rho(v_{K,V}^{n+1}) - \rho(v_{K,L}^{n+1})) = u_K^n m_K - v_{K,V}^{n+1} m_K. \quad (3.27)$$

In the above scheme, we have set

$$v_{K,L}^{n+1} = \begin{cases} \max_v J_{K,L}^{n+1}(v) & \text{if } D_{KL} \geq 0, \\ \min_v J_{K,L}^{n+1}(v) & \text{if } D_{KL} < 0, \end{cases}$$

where $J_{K,L}^{n+1} = \min(v_{K,V}^{n+1}, v_{L,V}^{n+1}), \max(v_{K,V}^{n+1}, v_{L,V}^{n+1})$. Reproducing the analysis carried out in §3.2 and §3.4, we get that for all $\tau \in [0, 1]$,

$$\sum_{K,L \in E} D_{KL} (v_{K,V}^{n+1} - v_{L,V}^{n+1})^2 \leq \sum_{K,L \in E} D_{KL} \frac{v_{K,L}^{n+1}}{v_{K,L}^{n+1} + v_{K,V}^{n+1}} (\rho(v_{K,V}^{n+1}) - \rho(v_{L,V}^{n+1}))^2 \leq C \quad (3.28)$$

and, that there exists $\delta > 0$ such that

$$v_{K,V}^{n+1} \geq \delta, \quad \forall K \in V. \quad (3.29)$$

This ensures in particular that for all $\tau \in [0, 1]$, the solutions of equation (3.27) stay in the interior of a compact subset K of $\mathbb{R}^{\#V}$ such that

$$\text{dist}(K, (\mathbb{R}_-)^{\#V}) \geq \frac{\delta}{2}.$$

Define the function $\Upsilon : K \times [0, 1] \rightarrow \mathbb{R}^{\#V}$ by: $\forall K \in V$,

$$\Upsilon_K((w_K)_{K \in V}) = \frac{w_K - v_K^n}{\Delta t} m_K + \sum_{K,L \in E_K} D_{KL} \frac{v_{K,L}^{n+1}}{v_{K,L}^{n+1} + v_{K,V}^{n+1}} (\rho(w_K) - \rho(w_L)) \\ + (1 - \tau) \sum_{K,L \in E_K} |D_{KL}| (\rho(w_K) - \rho(w_L)) - u_K^n m_K + w_K m_K.$$

The function Υ is uniformly continuous on $K \times [0, 1]$, and for all $\tau \in [0, 1]$ the solution $v_{K,V}^{n+1}$ of the nonlinear system

$$\Upsilon(v_{K,V}^{n+1}) = 0 \quad (3.30)$$

cannot reach K . For $\tau = 0$, the system is monotone, so that the system (3.30) admits a unique solution, whose topological degree is equal to 1 (we refer to [19, Proposition 3.1] for a proof of this property). The topological degree being constant w.r.t. $\tau \in [0, 1]$, the system (3.30) admits at least one solution for $\tau = 1$, concluding the proof of the existence of $v_{K,V}^{n+1}$.

The existence proof for $u_{K,V}^{n+1}$ is similar but simpler since

- i. the *a priori estimate* $0 \leq u_{K,V}^{n+1} \leq 1$ is sufficient for the claim, and no energy estimate is needed here;
- ii. the scheme (2.7) depends in a uniformly continuous way on $u_{K,V}^{n+1}$ on the compact subset $[-1, 2]^{\#V}$ of $\mathbb{R}^{\#V}$.

Therefore, we let to the reader the care of checking the proof for self-conviction. \blacksquare

4. Compactness estimates on the family of discrete solutions.

As a consequence of Lemmas 3.4 and 3.6, the sequences $u_{M_{m, t_m}}$ and $v_{M_{m, t_m}}$ are uniformly bounded w.r.t. m in $L^2(Q_{t_f})$ and $L^2(0, t_f; L^2(\Omega))$ respectively. Moreover, as a consequence of Lemma 3.6, the sequence $v_{T_{m, t_m}}$ is uniformly bounded in $L^2(0, t_f; H^1(\Omega))$. Therefore, there exists $v \in L^2(0, t_f; H^1(\Omega))$ such that, up to an unlabeled subsequence,

$$v_{T_{m, t_m}} \rightharpoonup v \text{ weakly in } L^2(0, t_f; H^1(\Omega)).$$

we deduce from the following inequality (see for instance [6, Lemma 3.4] or [10, Lemma 6.5])

$$|w_{T_{m, t_m}} - w_{M_{m, t_m}}|_{L^2(Q_{t_f})} \leq Ch |w_{T_{m, t_m}}|_{L^2(Q_{t_f})} + |w_{T_{m, t_m}} - H_{T_{m, t_m}}|_{L^2(Q_{t_f})}, \quad (4.1)$$

that $v_{T_{m, t_m}}$ and $v_{M_{m, t_m}}$ have the same limit, so that, up to an unlabeled subsequence,

$$v_{M_{m, t_m}} \rightharpoonup v \text{ in the } L^2(0, t_f; L^2(\Omega))\text{-weak- sense.}$$

On the other hand, the combination of Lemma 3.1 with Proposition 3.7 provides that

$$\int_{Q_{t_f}} |T_{m, t_m}|^2 dx dt \leq C$$

for some C not depending on m , where T_{m, t_m} is the piecewise linear function with nodal values $\frac{n}{K} = (u_K^n)$ for all $K \in \mathcal{V}_m$ and all $n \in \{0, \dots, N_m + 1\}$. Therefore, there exists $T \in L^2(0, t_f; H^1(\Omega))$ such that, up to an unlabeled subsequence,

$$T_{m, t_m} \rightharpoonup T \text{ weakly in } L^2(0, t_f; H^1(\Omega)).$$

It follows from inequality (4.1) that T_{m, t_m} and M_{m, t_m} share the same limit, therefore, up to an unlabeled subsequence,

$$M_{m, t_m} \rightharpoonup T \text{ in the } L^2(Q_{t_f})\text{-weak- sense.}$$

Finally, since $u_{M_{m, t_m}}$ is uniformly bounded in $L^2(Q_{t_f})$, then there exists $u \in L^2(Q_{t_f})$ such that, up to an unlabeled subsequence,

$$u_{M_{m, t_m}} \rightharpoonup u \text{ in the } L^2(Q_{t_f})\text{-weak- sense.}$$

The goal of this section is to show that $v = (u)$, and that

$$v_{M_{m, t_m}} \rightharpoonup v \text{ a.e. in } Q_{t_f} \quad \text{and} \quad u_{M_{m, t_m}} \rightharpoonup u \text{ a.e. in } Q_{t_f},$$

As an alternative to the lengthy and technical proof that consists in estimating the time- and space-translates of the discrete functions (see [3] for the continuous framework and [21] for the discrete setting), we make use of the technical blackbox proposed in [5, Theorem 3.9]. We refer to [16, Lemmas 4.4 and 6.6], [17, §4.2, §C.1.6], and [23] for alternative but very close approaches.

Let $m \geq 1$ be fixed, then let us denote by $\frac{n+1}{K} = (u_K^{n+1})_{K \in \mathcal{V}_{m,0}}^{n=N_m}$ a set a nodal values such that $\frac{n+1}{K} = 0$ if $\mathbf{x}_K \in \partial\Omega$. We deduce the functions T_{m, t_m} and M_{m, t_m} . We state now discrete $L^1(0, t_f; H^1(\Omega))$ estimates on the finite differences w.r.t. time of $u_{M_{m, t_m}}$ and $v_{M_{m, t_m}}$.

Lemma 4.1. *There exists C not depending on m such that*

$$\sum_{n=0}^{N_m} \sum_{K \in \mathcal{V}_m} m_K |u_K^{n+1} - u_K^n|_{K}^{n+1} \leq C \tau_m, \quad (4.2)$$

$$\sum_{n=0}^{N_m} \sum_{K \in \mathcal{V}_m} m_K |v_K^{n+1} - v_K^n|_{K}^{n+1} \leq C \tau_m, \quad (4.3)$$

Proof. We only establish (4.3) since the proof of (4.2) is similar. Multiplying (2.14) by $\Delta t |u_K^{n+1}|$ and summing over $n \in \{0, \dots, N_m\}$ and $K \in \mathcal{V}_m$ yields

$$\sum_{n=0}^{N_m} \sum_{K \in \mathcal{V}_m} m_K |v_K^{n+1} - v_K^n|_{K}^{n+1} = A_m + B_m, \quad (4.4)$$

where

$$A_m = - \sum_{n=0}^{N_m} \Delta t \sum_{K, L \in E} |D_{KL}|_{K, L} |p(v_K^{n+1}) - p(v_L^{n+1})|_{K, L}^{n+1},$$

$$B_m = \sum_{n=0}^{N_m} \Delta t \sum_{K \in \mathcal{V}_m} m_K |u_K^{n+1} - v_K^{n+1}|_{K}^{n+1}.$$

It follows from Cauchy-Schwarz inequality and from $\sum_{K, L \in E} |D_{KL}|_{K, L} = 1$ that

$$|A_m|^2 \leq \sum_{n=0}^{N_m} \Delta t \sum_{K, L \in E} |D_{KL}|_{K, L} |p(v_K^{n+1}) - p(v_L^{n+1})|_{K, L}^2 \leq \sum_{n=0}^{N_m} \Delta t \sum_{K, L \in E} |D_{KL}|_{K, L} |v_K^{n+1} - v_L^{n+1}|_{K, L}^2.$$

Combining Lemmas 3.3 and 3.5 provides

$$\sum_{n=0}^{N_m} \Delta t \sum_{K, L \in E} |D_{KL}|_{K, L} |p(v_K^{n+1}) - p(v_L^{n+1})|_{K, L}^2 \leq C,$$

whereas Lemma 3.2 implies that

$$\sum_{n=0}^{N_m} \Delta t \sum_{K, L \in E} |D_{KL}|_{K, L} |v_K^{n+1} - v_L^{n+1}|_{K, L}^2 \leq C \tau_m, \quad (4.5)$$

Therefore, we obtain that

$$|A_m| \leq C \tau_m, \quad (4.5)$$

On the other hand, Cauchy-Schwarz inequality provides

$$|B_m| \leq \sum_{M \in \mathcal{M}_m} u_{M, t_m} - \sum_{V \in \mathcal{V}_m} v_{M, t_m} \leq C \tau_m.$$

It results from Proposition 3.7 and Lemma 3.6 that

$$\sum_{M \in \mathcal{M}_m} u_{M, t_m} - \sum_{V \in \mathcal{V}_m} v_{M, t_m} \leq C,$$

whereas the discrete Poincaré's inequality [6, Lemma 3.3] ensures that

$$\sum_{M \in \mathcal{M}_m} u_{M, t_m} \leq C \tau_m.$$

Gathering the previous inequalities, one gets that

$$|B_m| \leq C \tau_m. \quad (4.6)$$

Putting (4.4), (4.5) and (4.6) together provides (4.3). \blacksquare

We have all the necessary estimates at hand to make use of [5, Theorem 3.9]. It allows us to claim directly that $\varphi = \varphi(u)$, and that

$$v_{M_m; t_m} \rightharpoonup v \text{ a.e. in } Q_{t_f} \quad \text{and} \quad u_{M_m; t_m} \rightharpoonup u \text{ a.e. in } Q_{t_f}:$$

5. Identification as a weak solution

It remains to be shown that $(u; v)$ satisfies the weak formulation (1.6)–(1.7). To do this, we consider a test function $\varphi \in C_c^\infty([0; t_f])$, and denote by $\varphi_K^n = \varphi(x_K; t^n)$, for all $K \in V_m$ and all $n \in \{0; \dots; N_m\}$. Let us focus on the convergence of the first equation of scheme (2.7)–(2.14), i.e., we show that equation (1.6) is verified when $m \rightarrow \infty$. We note that the convergence of the second equation of the scheme is similar and major difficulties that we can encounter are discussed hereafter.

Multiplying the first equation (2.7) by φ_K^n and summing over $n \in \{0; \dots; N_m\}$ and $K \in V_m$ yields, after a reorganization of the sum,

$$A_m + B_m + C_m + D_m = F_m; \tag{5.1}$$

where

$$\begin{aligned} A_m &= \sum_{n=0}^{N_m} \sum_{K \in V_m} u_K^{n+1} u_K^n \varphi_K^n m_K; & F_m &= \sum_{n=0}^{N_m} \sum_{K \in V_m} f u_K^{n+1} \varphi_K^n m_K; \\ B_m &= \sum_{n=0}^{N_m} \sum_{KL \in 2E_m} \int_{KL} a_{KL}^{n+1} u_K^{n+1} u_L^{n+1} \varphi_K^n - a_{KL}^{n+1} u_K^{n+1} u_L^{n+1} \varphi_L^n \, dx; \\ C_m &= \sum_{n=0}^{N_m} \sum_{KL \in 2E_m} \int_{KL} a_{KL}^{n+1} u_K^{n+1} u_L^{n+1} \varphi_K^n - a_{KL}^{n+1} u_K^{n+1} u_L^{n+1} \varphi_L^n \, dx; \\ D_m &= \sum_{n=0}^{N_m} \sum_{KL \in 2E_m} \int_{KL} a_{KL}^{n+1} v_K^{n+1} v_L^{n+1} \varphi_K^n - a_{KL}^{n+1} v_K^{n+1} v_L^{n+1} \varphi_L^n \, dx; \end{aligned}$$

Accumulation term

Note that $\varphi_K^{N_m+1} = 0$ for all $K \in V_m$, then, performing summation by parts in time, the term A_m can be rewritten

$$\begin{aligned} A_m &= \sum_{n=0}^{N_m} \sum_{K \in V_m} u_K^{n+1} \varphi_K^n m_K - \sum_{n=1}^{N_m} \sum_{K \in V_m} u_K^n \varphi_K^n m_K - \sum_{K \in V_m} u_K^0 \varphi_K^0 m_K \\ &= \sum_{n=0}^{N_m} \sum_{K \in V_m} u_K^{n+1} \frac{\varphi_K^{n+1} - \varphi_K^n}{t_m} m_K + \sum_{K \in V_m} u_K^0 \varphi_K^0 m_K \\ &= \int_{Q_{t_f}} u_{M_m; t_m}(x; t) \varphi(x; t) \, dx \, dt - \int_{M_m; t_m} u(x; 0) \varphi(x; 0) \, dx; \end{aligned}$$

Thanks to the regularity of φ , and the convergence in $L^1(Q_{t_f})$ of the sequence $u_{M_m; t_m}$ towards u , it follows that (see e.g. [20])

$$A_m \rightarrow \int_{Q_{t_f}} u(x; t) \varphi(x; t) \, dx \, dt - \int_{M_m; t_m} u(x; 0) \varphi(x; 0) \, dx; \quad \text{as } m \rightarrow \infty;$$

Positive nonlinear CVFE scheme

Diffusion term

Let us first prove that $\lim_{m \rightarrow \infty} B_m = 0$.

For all $K, L \in E_m$ and all $n \in \{0, \dots, N_m\}$, we denote by \bar{a}_{KL}^{n+1} the quantity defined by

$$\bar{a}_{KL}^{n+1} = \begin{cases} \frac{(u_K^{n+1})^q (u_L^{n+1})^{1-q}}{u_K^{n+1} u_L^{n+1}} & \text{if } u_K^{n+1} \neq u_L^{n+1}; \\ a & \text{if } u_K^{n+1} = u_L^{n+1}; \end{cases}$$

Then, the term B_m rewrites

$$B_m = \sum_{n=0}^{N_m} \tau_m \sum_{K, L \in E_m} \frac{q}{a_{KL}^{n+1}} \frac{q}{a_{KL}^{n+1}} \frac{q}{\bar{a}_{KL}^{n+1}} u_K^{n+1} u_L^{n+1} \left(\frac{n}{K} - \frac{n}{L} \right):$$

Now, using the Cauchy-Schwarz inequality, we get

$$|B_m| \leq \sum_{n=0}^{N_m} \tau_m \sum_{K, L \in E_m} \left(\frac{q}{a_{KL}^{n+1}} u_K^{n+1} \right)^2 \left(\frac{q}{\bar{a}_{KL}^{n+1}} u_L^{n+1} \right)^2 A_{KL}^{-1} R_m^{\frac{1}{2}};$$

where, R_m is given by

$$R_m = \sum_{n=0}^{N_m} \tau_m \sum_{K, L \in E_m} \left(\frac{q}{a_{KL}^{n+1}} \right)^2 \left(\frac{q}{\bar{a}_{KL}^{n+1}} \right)^2 \left(\frac{n}{K} - \frac{n}{L} \right)^2:$$

Using Lemma 3.3 and Proposition 3.7, one has $|B_m| \leq C R_m^{\frac{1}{2}}$. Hence, in order to prove that $\lim_{m \rightarrow \infty} B_m = 0$, it suffices to prove that $\lim_{m \rightarrow \infty} R_m = 0$.

For all $T \in T_m$, we denote by

$$a_T^{-n+1} = \max_{x \in T} (p)_{T_m; t_m}(x; t^{n+1}); \quad a_T^{n+1} = \min_{x \in T} (p)_{T_m; t_m}(x; t^{n+1});$$

and for all $(x; t) \in T$, $t^n; t^{n+1}$, by

$$a_T^{-n+1}(x; t) = a_T^{-n+1}; \quad a_T^{n+1}(x; t) = a_T^{n+1};$$

Consider the uniform continuous function a^{-1} defined on the closed bounded interval $[0; 1]$, and let ω be its modulus of continuity, then we have

$$\frac{q}{a_{KL}^{n+1}} \frac{q}{\bar{a}_{KL}^{n+1}} \leq \omega_T^{-n+1} \omega_T^{n+1}; \quad \text{for all } K, L \in E_T: \tag{5.2}$$

Therefore, using this inequality in the definition of R_m , we get

$$0 \leq R_m \leq Q_m \tag{5.3}$$

where,

$$Q_m = \sum_{n=0}^{N_m} \tau_m \sum_{T \in T_m} \omega_T^{-n+1} \omega_T^{n+1} \sum_{K, L \in E_T} \left(\frac{n}{K} - \frac{n}{L} \right)^2; \tag{5.4}$$

and ω_T is the constant defined by (3.3).

Thanks to Lemma 3.2, one can deduce that the inequality (5.3) implies that

$$0 \leq R_m \leq C \int_{Q_T} \omega_{T_m; t_m}^{-n+1}(x; t) \omega_{T_m; t_m}^{n+1}(x; t) dx dt;$$

where C is independent of h_m , and t_m . Therefore, it suffices to show that $\int_{T_m; t_m} \bar{u}_m(x;t) - \int_{T_m; t_m} u_m(x;t) \leq 0$ a.e. in Q_{t_f} to consequently prove that $\lim_{m \rightarrow \infty} R_m = 0$. By a simple generalization of [9, Lemma A.1] and by the help of Lemma 3.1 and Proposition 3.7, it follows that

$$\int_{Q_{t_f}} \int_{T_m; t_m} \bar{u}_m(x;t) - \int_{T_m; t_m} u_m(x;t) dx dt \leq Ch \int_{Q_{t_f}} \int_{T_m; t_m} |r(u) - r(u_m)|^2 dx dt \leq Ch \int_{Q_{t_f}} |r(u) - r(u_m)|^2 dx dt \leq Ch \int_{Q_{t_f}} |u - u_m|^{1/2} dx dt$$

As a consequence, up to a subsequence, one has

$$\lim_{m \rightarrow \infty} B_m = \lim_{m \rightarrow \infty} R_m = \lim_{m \rightarrow \infty} Q_m = 0:$$

We now focus on the term C_m and prove that

$$\lim_{m \rightarrow \infty} C_m = \int_{Q_{t_f}} \int_{T_m; t_m} \frac{q}{a(u)} (u - u_m) r(u) - r(u_m) dx dt:$$

To do this, we introduce the term C_m^0 defined by

$$C_m^0 := \int_{Q_{t_f}} \int_{T_m; t_m} (u - u_m) r(u) - r(u_m) dx dt;$$

where \bar{u}_m is a piecewise constant function (on the triangular mesh) function given by

$$\bar{u}_m(x;t) = \frac{q}{a(u)} \bar{u}_m(x;t); \quad 8x^2 T; 8t^2 (t^n; t^{n+1}); 8T^2 T_m;$$

where \bar{u}_m is defined by

$$\bar{u}_m(x;t) = (u)_{T_m; t_m}(x_T; t); \quad 8x^2 T; 8t^2 (t^n; t^{n+1}); 8T^2 T_m:$$

Using again a slight generalization of [9, Lemma A.1] as well as the boundedness of the continuous function $\frac{q}{a(u)}$, we obtain

$$\begin{aligned} \bar{u}_m &\leq \frac{q}{a(u)} \quad \text{in } L^2(Q_{t_f}) \text{ as } m \rightarrow \infty; \\ \bar{u}_m &\leq \frac{q}{a(u)} \quad \text{in } L^2(Q_{t_f}) \text{ as } m \rightarrow \infty; \end{aligned} \tag{5.5}$$

It remains to verify that $\int C_m - C_m^0 \rightarrow 0$, when m tends to infinity.

We denote by

$$a_T^{n+1} = \int_{T_m; t_m} x_T; t^{n+1}^2; \quad 8T^2 T_m; 8n^2 f_0; \dots; N_m g:$$

The discretization of the term C_m^0 is written as

$$C_m^0 = \sum_{n=0}^{N_m} \int_{T_m} \int_{T_m} \frac{q}{a_T^{n+1}} \int_{KL \in E_T} u_K^{n+1} - u_L^{n+1} \left(\frac{n}{K} - \frac{n}{L} \right):$$

Similar arguments as for obtaining inequality (5.2) yield

$$\frac{q}{a_{KL}^{n+1}} - \frac{q}{a_T^{n+1}} \leq \frac{-n+1}{T} - \frac{n+1}{-T}; \quad \text{for all } KL \in E_T:$$

Therefore, using the Cauchy-Schwarz inequality, Lemma 3.1, Lemma 3.2, and Proposition 3.7, we deduce that there exists a constant C does not depend on h_m such that

$$\begin{aligned} C_m &\leq C_m^0 + \sum_{n=0}^{N_m} \int_{T_m} \int_{T_m} \frac{q}{a_T^{n+1}} \int_{KL \in E_T} u_K^{n+1} - u_L^{n+1} \left(\frac{n}{K} - \frac{n}{L} \right) \\ &\leq C_m^0 + \sum_{n=0}^{N_m} \int_{T_m} \int_{T_m} \frac{q}{a_T^{n+1}} \int_{KL \in E_T} u_K^{n+1} - u_L^{n+1}^2 \leq C Q_m \rightarrow 0 \text{ as } m \rightarrow \infty; \end{aligned}$$

Positive nonlinear CVFE scheme

Convection term

For all $T \geq 2T_m$, we define the piecewise constant function $\chi_{T_m; t_m}$ by

$$\chi_{T_m; t_m}(x; t) = \begin{cases} 1 & \text{if } (x, t) \in T_m; t_m \\ 0 & \text{otherwise} \end{cases}$$

Using the same guidelines as for the convergence results (5.5), one has

$$\chi_{T_m; t_m} \rightharpoonup^* (u) \quad \text{in } L^2(Q_{t_f}) \text{ as } m \rightarrow \infty :$$

We introduce the term

$$D_m^0 := \int_{Q_{t_f}} \chi_{T_m; t_m}(x) r v_{T_m; t_m} r \chi_{T_m; t_m}(x; t) dx dt$$

Thanks to the weak convergence in $L^2(Q_{t_f})$ of the sequence $v_{T_m; t_m}$ towards $r v$, and to the uniform convergence of $\chi_{T_m; t_m}$ towards r , we obtain

$$D_m^0 \rightarrow \int_{Q_{t_f}} (u) (x) r v r dx dt \quad \text{as } m \rightarrow \infty :$$

Let us prove, using the same guidelines as before, that $D_m - D_m^0 \rightarrow 0$, when m tends to infinity. We denote by

$$\begin{aligned} \chi_T^{n+1} &= \chi_{T_m; t_m}(x; t) \chi_{T; t^{n+1}}; & \chi_{T; t^{n+1}} &= \chi_{T; t^{n+1}}; \\ \chi_T^{n+1} &= \chi_{T_m; t_m}(x; t) \chi_{T; t^{n+1}}; & \chi_{T; t^{n+1}} &= \chi_{T; t^{n+1}} \end{aligned}$$

Therefore,

$$D_m - D_m^0 = \sum_{n=0}^{N_m} \int_{T \times T_m} \int_{K_L \times E_T} a_T^{n+1} \chi_T^{n+1} a_{KL}^{n+1} \chi_{KL}^{n+1} v_K^{n+1} v_L^{n+1} \left(\frac{n}{K} \frac{n}{L} \right) dx dt$$

Thanks to the triangle inequality and to the existence of a continuity modulus and of the continuous functions $\frac{1}{a} \chi_T^{n+1}$ and χ_T^{n+1} respectively, one has

$$\begin{aligned} a_{KL}^{n+1} \chi_{KL}^{n+1} a_T^{n+1} \chi_T^{n+1} &= \chi_{KL}^{n+1} a_{KL}^{n+1} a_T^{n+1} + a_T^{n+1} \chi_{KL}^{n+1} \chi_T^{n+1} \\ C \chi_T^{n+1} \chi_T^{n+1} &+ \chi_T^{n+1} \chi_T^{n+1}; \end{aligned}$$

where the constant C does not depend on h_m . Therefore, using the Cauchy-Schwarz inequality, Lemma 3.1, Lemma 3.2, and Proposition 3.7, we deduce that there exists a constant α independent of h_m such that

$$D_m - D_m^0 \leq C (Q_m + W_m) \sum_{n=0}^{N_m} \int_{T \times T_m} \int_{K_L \times E_T} \chi_{KL}^{n+1} v_K^{n+1} v_L^{n+1} dx dt;$$

where Q_m is given by equation (5.4), and W_m is given by

$$W_m = \sum_{n=0}^{N_m} \int_{T \times T_m} \int_{K_L \times E_T} \chi_T^{n+1} \chi_T^{n+1} \chi_{KL}^{n+1} \left(\frac{n}{K} \frac{n}{L} \right)^2 dx dt$$

Now, using the same proof as for the diffusion term, one can deduce that $W_m \rightarrow 0$. Therefore

$$\lim_{m \rightarrow \infty} (D_m - D_m^0) = 0;$$

and consequently,

$$\lim_{m \rightarrow \infty} D_m = \int_{Q_{t_f}} (u) (x) r v r dx dt$$

Reaction term

We would now like to show that

$$F_m \leq \iint_{Q_{t_f}} f(u(x;t)) \phi(x;t) dx dt \quad \text{as } m \rightarrow 1 \quad (2.13)$$

For this purpose, we denote, for all $K \in \mathcal{V}_m$ and for all $n \geq 1$, by $f_K^n = f(u_K^n)$, and by $f_{M_m; t_m}$ the piecewise constant reconstruction in $X_{M_m; t_m}$. Thus we have

$$F_m = \iint_{Q_{t_f}} f_{M_m; t_m}(M_m; t_m)(\cdot; t) \phi(x;t) dx dt \leq \iint_{Q_{t_f}} f(u(x;t)) \phi(x;t) dx dt \quad \text{as } m \rightarrow 1 \quad (2.14)$$

since $(u)_{M_m; t_m}$ converges strongly in $L^2(Q_{t_f})$ towards $f(u)$, and as $(\phi)_{M_m; t_m}$ converges uniformly towards ϕ . This ends the proof of Theorem 2.2.

6. Numerical results

In this section, we establish various 2D numerical results provided by the nonlinear CVFE scheme (2.7), (2.14). Newton's algorithm is carried out for the implementation of the scheme, coupled with a biconjugate gradient method to solve linear systems arising from the Newton algorithm. We provide three tests to show the effectiveness of the nonlinear CVFE scheme (2.7), (2.14). For these tests, we consider the following data: $L_x = 1$, $L_y = 1$ (the length and the width of the domain). We set:

$\tau = 0.002$, $\alpha = 0.01$, $\beta = 0.05$, $a(u) = d_u u(1-u)$, $d_u = 0.0005$, $\phi(u) = (u(1-u))^2$, $\gamma = 0.05$.
By definition, we have $\bar{u}(u) = \frac{1}{\alpha} u(1-u)$ then, the numerical flux function \bar{u}_K^{n+1} is given using the following functions:

$$\bar{u}_K(z) = \min\{z; \frac{1}{2}g\}; \quad \text{and} \quad \bar{u}_K^\#(z) = \max\{z; \frac{1}{2}g - \frac{1}{2}\}; \quad \forall z \in (0; 1) \quad (0; 1):$$

Unless stated otherwise and throughout the tests, we assume that $\bar{u}(u) = 0$, that the initial conditions are defined by regions, and we assume zero-flux boundary conditions. For instance, the cell density is initially defined by $u_0(x;y) = 1$ in the square region given by $(x;y) \in [0.45; 0.55] \times [0.45; 0.55]$ and 0 otherwise. The initial chemoattractant concentration is defined by $v_0(x;y) = 5$ in the space region given by $(x;y) \in [0.2; 0.3] \times [0.45; 0.55] \cup [0.45; 0.55] \times [0.2; 0.3] \cup [0.45; 0.55] \times [0.7; 0.8] \cup [0.7; 0.8] \times [0.45; 0.55]$.

Test 1 (Weak anisotropic case). In this test, we assume that the diffusion tensors are given by

$$D(x) = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}; \quad D(x) = d \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}; \quad d = 0.0001:$$

Further, we consider an admissible triangular primary mesh made of 14 336 triangles, the corresponding Donald dual mesh consists of 7 297 dual control volumes. In an admissible triangular mesh, all the angles of triangles are acute, then one can deduce that the maximum principle is verified for u since the transmissibility coefficients are nonnegative, which it is not the case for u . In Tab. 6.1, we present minimum and maximum values obtained with each of the scheme (2.7) (2.8), the nonlinear CVFE scheme (2.7), (2.14), and the finite volume scheme.

Positive nonlinear CVFE scheme

		scheme(2.7) (2.8)	scheme (2.7),(2.14)	FV scheme
After 1 iteration = 1	Min. Val. u	0.0	0.0	0.0
	Max. Val. u	1.0	1.0	1.0
After 10 iterations = 1	Min. Val. u	0.0	0.0	0.0
	Max. Val. u	0.971110	1.0	1.0
After 1 iteration = 5	Min. Val. u	$1.73001 \cdot 10^{-3}$	$8.68789 \cdot 10^{-20}$	
	Max. Val. u	0.99722922	1.0	
After 10 iterations = 5	Min. Val. u	$1.62500 \cdot 10^{-2}$	0.00	
	Max. Val. u	0.9715705	1.0	
After 1 iteration = 10	Min. Val. u	$4.46953 \cdot 10^{-3}$	$6.30555 \cdot 10^{-16}$	
	Max. Val. u	1.00018368	1.0	
After 10 iterations = 10	Min. Val. u	$3.91245 \cdot 10^{-2}$	$6.30554 \cdot 10^{-16}$	
	Max. Val. u	0.98342428	0.9999999	

Table 6.1. Numerical results after 1 and 10 iterations.

Figure 6.1. Meshes: admissible mesh for Test 1(left), initial primal mesh for Test 2 and 3 (center) and barycentric dual mesh for Test 2 and 3 (right).

Test 2 (Weak anisotropic case/obtuse angles) . In this test, we consider a general unstructured mesh that contains obtuse angles, this mesh is made of 5 193 triangles and 2 665 dual control volumes. The discrete maximum principle is not guaranteed for v , hence we cannot expect the maximum principle for u since the computation of u depends on the values of v , for that we consider the nonlinear discretization (2.14) of v .

Figure 6.2. Initial condition for the cell density u (left) with $0 \leq u \leq 1$ and for the chemoattractant concentration v (right) with $0 \leq v \leq 5$.

The diffusion tensors are defined, for all $x \in (0; 1) \times (0; 1)$, by

$$D(x) = \begin{pmatrix} 7 & 2 \\ 2 & 10 \end{pmatrix}; \quad D(x) = d \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}; \quad d = 0.0001.$$

Figure 6.2 represents initial distributions of the cell density u and the chemoattractant concentration v over the initial triangular mesh as well as the corresponding dual mesh.

Figure 6.3. Evolution of the cell density u at time $t = 0.4$ with $\int_{\Omega} u = 0.667$ (left), and at time $t = 1.4$ with $\int_{\Omega} u = 0.632$ (right).

Figure 6.4. Evolution of the cell density u at time $t = 2.4$ with $\int_{\Omega} u = 0.972$ (left), and at time $t = 4$ with $\int_{\Omega} u = 0.987$ (right).

Figures 6.3-6.4 represent the evolution of the cell density at time $t = 0.4$, $t = 1.4$, $t = 2.4$, and $t = 4$. At moment $t = 0.4$, it is clear that the cell density diffuses uniformly in the space without any interactions with the chemoattractant. Then, after a while, and when the chemoattractant diffusion reaches the cell density location, we see that the latter changes its direction to be absorbed by the chemoattractant located vertically. This process continues and the cells accumulate into the location of the chemoattractant and finally we obtain the cell density aggregations as shown at $t = 4$.

Test 3 (Anisotropic case/obtuse angles). In this test, we consider an unstructured mesh consisting of 15 568 primal triangles and 7 912 dual control dual volumes. Further, we assume that the diffusion tensors are anisotropic and are given by:

$$D(x) = \begin{pmatrix} 8 & 7 \\ 7 & 20 \end{pmatrix}; \quad D(x) = d \begin{pmatrix} 1 & 0 \\ 0 & 3 \end{pmatrix}; \quad d = 0.0001.$$

Table 6.2 provides a comparison between the nonlinear CVFE scheme coupled on the one hand with the discretization (2.8) of v and with the discretization (2.14) of v on the other hand. We see that the discretization (2.14) carries out a better approximation than the discretization (2.8) in terms of ensuring the discrete maximum principle property.

Positive nonlinear CVFE scheme

		CVFE scheme: (2.7) (2.8)	CVFE scheme: (2.7),(2.14)
After 1 iteration	Min. Val. u	0.0	0.0
	Max. Val. u	1.0	1.0
	Min. Val. v	-1.141912E-002	1.922764E-051
	Max. Val. v	5.012383	4.999982
After 200 iterations	Min. Val. u	0.0	0.0
	Max. Val. u	0.5298226	0.5312562
	Min. Val. v	-1.731068E-003	1.297192E-080
	Max. Val. v	4.8053827	4.8018742
After 1000 iterations	Min. Val. u	0.0	0.0
	Max. Val. u	0.9957580	0.9974757
	Min. Val. v	6.265859E-023	3.171769E-080
	Max. Val. v	2.961761	2.910828

Table 6.2. Numerical results after 1, 200 and 1000 iterations over an unstructured mesh with obtuse angles.

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