UNCONDITIONALLY ENERGY STABLE DISCONTINUOUS GALERKIN SCHEMES FOR THE CAHN-HILLIARD EQUATION

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Abstract. In this paper, we introduce novel discontinuous Galerkin (DG) schemes for the Cahn-Hilliard equation to produce free-energy-dissipating and mass conservative discrete solutions, irrespective of the time step and the mesh size. We integrate the mixed DG method for the spatial discretization with the Energy Quadratization (EQ) approach for the time discretization. Coupled with a spatial projection, the resulting EQ-DG schemes can be efficiently solved without resorting to any iterative method. The schemes are shown to be unconditionally energy dissipative and mass conservative. Both one and two dimensional numerical examples verify our theoretical results, and demonstrate the good performance of EQ-DG on efficiency, accuracy, and preservation of the desired solution properties.

1. Introduction

The Cahn-Hilliard (CH) equation, originally introduced in [7] as a model of phase separation in binary alloys, has become a fundamental equation as well as a building block in the phase field methodology for moving interface problems arising from various applications (see, e.g., [28] for the references therein).

This work is concerned with high order numerical approximations to the Cahn-Hilliard problem: find \( \{u(x,t), w(x,t)\} \) for \( x \in \Omega \) and \( t > 0 \) such that

\[
\begin{align*}
\frac{du}{dt} &= \nabla \cdot (M(u) \nabla w), \\
% \nabla w &= -\epsilon^2 \Delta u + F'(u), \\
u(x,0) &= u_0(x), \quad x \in \Omega,
\end{align*}
\]

(1.1)

where \( \Omega \subseteq \mathbb{R}^d (d = 1, 2, 3) \) is a bounded domain, \( \epsilon \) is a positive parameter, \( M(u) \geq 0 \) is the mobility function, \( F(u) \) is the nonlinear bulk potential, and \( u_0(x) \) is the initial data.

We consider in this paper either of the two types of boundary conditions below:

(i) \( u \) is periodic; \( \text{or} \) (ii) \( \partial_n u = M(u) \partial_n w = 0, \quad x \in \partial \Omega. \) (1.2)

Here \( n \) stands for the unit outward normal to the boundary \( \partial \Omega. \)

With boundary condition \( \text{[1.2]} \), the model equation follows the dissipative energy law

\[
\frac{d}{dt} \mathcal{E}(u) = -\int_{\Omega} M(u)|\nabla w|^2 \leq 0,
\]

(1.3)
where the total free energy is defined by
\[ \mathcal{E}(u) = \int_\Omega \left( \frac{\epsilon^2}{2} |\nabla u|^2 + F(u) \right) \, dx. \] (1.4)

The solution of the CH problem (1.1)-(1.2) also conserves the total mass
\[ \int_\Omega u(x,t) \, dx = \int_\Omega u_0(x) \, dx. \] (1.5)

The CH model is nonlinear, so that its analytical solutions are intractable. Also, the CH equation as a gradient flow requires very long time simulations to reach steady states. Hence, designing accurate, efficient, and stable algorithms to solve it becomes essential. Keeping the energy dissipation (1.3) and mass conservation (1.5) has been a major concern in the design of various schemes, see, e.g. [6, 15, 19, 33, 31, 18, 34, 41, 8]. The goal of this work is to design novel energy stable and mass conservative schemes to solve the above model problem.

The well-posedness study of the Cahn–Hilliard equation has been very rich, and the results may be classified into two types of models, exploiting specific mathematical properties and structures: one is the constant mobility with polynomial potentials ([14]), and another is the degenerate mobility of form \( M(u) = u(1-u) \) ([12]) with the potential of logarithmic type (see, e.g., [7, 13, 43, 12, 11]). Here we numerically study general model (1.1) with no restrictions on the specific form of the mobility and free energy. For the degenerate CH model, we apply the established scheme to regularized systems as discussed in Section 4. While we also refer the reader to [30] for a new relaxation system to approximate the degenerate CH model. The relaxed system in [30] containing two parabolic/elliptic equations appears more amenable to numerical solvers.

In this paper, we aim to develop unconditionally energy stable discontinuous Galerkin (DG) schemes for solving the CH model. To achieve this, we face two main challenges: (i) how to handle fourth order derivatives in the DG discretization; and (ii) how to handle the nonlinear term associated with the potential \( F \) in time discretization.

For (i), several approaches have been adopted to deal with difficulties caused by the high order solution derivatives. The first one is the local DG (LDG) methods [38, 22, 32], with which the original equation is rewritten into a first order system for further DG discretization. The second one is the mixed symmetric interior penalty DG (SIPG) methods [36, 16, 17, 18], with which the penalty terms are added as interface corrections upon the global solution formulation so that the resulting scheme is stable. The third one is the mixed DG method without interior penalty in [26, 27] for the spatial discretization of fourth order PDEs. It is also possible to apply an ultra-weak DG discretization, such as the DG scheme in [10] for the one-dimensional biharmonic equation.

For (ii), there are several time discretization techniques available in the literature, including the so-called convex splitting approach [37] and the stabilization approach [31, 39]. The former approach (see [2, 15]) is energy stable, however, it produces nonlinear schemes, thus the implementations are often complicated with potentially high computational costs. The later approach by adding a stabilization term to avoid strict time step constraints leads purely to linear schemes, but the nonlinear potential may not satisfy the condition required for the stabilization. A feasible
remedy would be to make a reasonable transform of the given potential. One such remedy is the *Energy Quadratization* (EQ) approach introduced in [40], which generalized the two types of linear energy stable schemes in [20]. In comparison of these, the EQ method provides more flexibilities to treat the complicated nonlinear terms since it only requests that the nonlinear potential be bounded from below. We note that recently a related approach, called the SAV method, has been introduced in [35] with certain advantages over the EQ. Yet efficiently solving the resulting linear system when coupled with a DG spatial discretization appears to be subtle. We refer the reader to the survey paper by Shen et al [34] for a general method applied to the present context.

We therefore only design EQ-DG schemes in this paper. Our strategy is to start with the model satisfying two basic assumptions:

(i) the mobility function $M(u)$ satisfies

$$M(u) \geq M_{\text{min}} > 0;$$

(ii) there exist a constant $B > 0$, such that

$$F(u) > -B,$$

for any $u$ under consideration, and further discuss how to extend the established schemes to more general cases.

The EQ-DG method introduced in [27] has several advantages in numerical performance, such as high order of accuracy, easy to implement and efficient without resorting to any iteration method. For the Swift–Hohenberg equation, the discretization in [27] combines the mixed DG method without interior penalty from [26] with the EQ approach in time discretization. However, the mixed DG method without interior penalty when applied to the CH equation (1.1) does not allow us to prove the energy stability. Therefore, in this paper, we exploit the direct DG (DDG) method [25] coupled with a proper spatial projection. For a special choice of the flux parameters, the DDG scheme can be reformulated as the mixed symmetric interior penalty DG (SIPG) scheme (see, e.g., [17]). The EQ approach for time discretization relies on an auxiliary variable $U = \sqrt{F(u) + B}$, so that

$$U_t = \frac{1}{2} H(u)u_t, \quad H(u) := F'(u)/\sqrt{F(u) + B}.$$

With this transformation we update $U^n$ in two steps: the piecewise $L^2$ projection with $U^n_h = \Pi U^n$, and the update step with

$$\frac{U^{n+1}_h - U^n_h}{\Delta t} = \frac{1}{2} H(u^n_h) u^{n+1}_h - u^n_h.$$

The resulting EQ-DG scheme follows from replacing the nonlinear function $F'(u^{n+1}_h)$ by $H(u^n_h)U^{n+1}$ in the DG discretization (see the scheme formulation in (3.6)). In addition, the resulting discrete systems are linear with scale comparable to that generated by the same DG discretization to the linear problem. As a result, the methods are simple to implement and computationally efficient to achieve high order of spatial accuracy.

Finally, closest to our work is [23], where the authors, building on the EQ formulation with the LDG spatial discretization for phase field problems including the CH equation, proposed energy stable linear schemes combing with the semi-implicit spectral deferred correction to gain higher
order time discretization, while the auxiliary variable had to be computed coupling with other unknowns. In contrast, our algorithms enable a separate update for the auxiliary variable, hence more efficient in computation.

1.1. **Our Contributions.** We summarize the main contributions of this work as follows:

- We propose to solve (1.1) by simple EQ-DG schemes, which integrate the mixed DG method for spatial discretization with the EQ approach for time discretization, coupled with a spatial projection.

- We show that the semi-discrete DG scheme features a discrete energy dissipation law if the penalty parameter is suitably large, and present both first and second order (in time) EQ-DG algorithms. We prove that the EQ-DG schemes are indeed unconditionally energy stable.

- We conduct extensive experiments to evaluate the performance of EQ-DG. First, we present numerical results to show the high order of accuracy of the proposed schemes, the energy dissipating and mass conservative properties of numerical solutions. Second, we conduct experiments on some two dimensional pattern formation problems, all of which demonstrate the good performance of EQ-DG.

1.2. **Organization.** We organize this paper as follows: In Section 2, we formulate a unified semi-discrete DG method for the CH equation (1.1) subject to different boundary conditions. In Section 3, we present fully discrete DG schemes and show the energy dissipation and mass conservation properties. In Section 4, we discuss extensions to the case with degenerate mobility and the logarithmic Flory-Huggin potential. In Section 5, we numerically verify the performance of EQ-DG on different numerical examples. Finally in Section 6 some concluding remarks are given.

### 2. Spatial DG discretization

Let the domain $\Omega$ be a union of rectangular meshes $\mathcal{T}_h = \{K\} := \bigcup_{\alpha=1}^{N} K_{\alpha}$, with $\alpha = (\alpha_1, \cdots, \alpha_d)$, $\mathcal{N} = (\mathcal{N}_1, \cdots, \mathcal{N}_d)$ and $K_{\alpha} = I_{\alpha_1}^{1} \times \cdots \times I_{\alpha_d}^{d}$, where $I_{\alpha_i}^{i} = [x_{\alpha_i}^{i-1/2}, x_{\alpha_i}^{i+1/2}]$ for $\alpha_i = 1, \cdots, \mathcal{N}_i$. Denote by $h_i = \max_{1 \leq \alpha_i \leq \mathcal{N}_i} |I_{\alpha_i}^{i}|$, with $h = \max_{1 \leq i \leq d} h_i$. We denote the set of the interior interfaces by $\Gamma^0$, the set of all boundary faces by $\Gamma^\partial$, and $\Gamma_h = \Gamma^0 \cup \Gamma^\partial$.

The discontinuous Galerkin finite element space can be formulated as

$$V_h = \{ v \in L^2(\Omega) : v|_K \in P^k(K), \ \forall K \in \mathcal{T}_h \},$$

where $P^k(K)$ denotes the set of polynomials of degree no more than $k$ on element $K$. Let $K_1$ and $K_2$ be two neighboring cells. If the unit normal vector $\nu$ on element interfaces $e \in \partial K_1 \cap \partial K_2$ is oriented from $K_1$ to $K_2$, then the average $\{ \cdot \}$ and the jump $[\cdot]$ operator are defined by

$$\{ v \} = \frac{1}{2} (v|_{\partial K_1} + v|_{\partial K_2}), \quad [v] = v|_{\partial K_2} - v|_{\partial K_1},$$

for any function $v \in V_h$, where $v|_{\partial K_i}$ ($i = 1, 2$) is the trace of $v$ on $e$ evaluated from element $K_i$. 
The direct DG discretization of (1.1) is to find \((u_h(\cdot, t), w_h(\cdot, t)) \in V_h \times V_h\) such that for all \(\phi, \psi \in V_h\) and \(K \in T_h\)
\[
\int_K u_h \phi dx = - \int_K M(u_h) \nabla u_h \cdot \nabla \phi dx + \int_{\partial K} M(\tilde{u}_h) \left( \partial_\nu \tilde{w}_h \phi + (w_h - \tilde{w}_h) \partial_\nu \phi \right) ds, \tag{2.1a}
\]
\[
\int_K w_h \psi dx = \epsilon^2 \left( \int_K \nabla u_h \cdot \nabla \psi dx - \int_{\partial K} \partial_\nu \tilde{u}_h \psi + (u_h - \tilde{u}_h) \partial_\nu \psi ds \right) + \int_K F'(u_h) \psi dx, \tag{2.1b}
\]
where \(\nu\) stands for the outward normal direction to \(\partial K\). On each cell interface \(e \in \partial K \cap \Gamma^0\), the numerical flux is taken as
\[
\widehat{\partial_\nu v} = \frac{\beta_0[v]}{h_e} + \{\partial_\nu v\}, \quad \widehat{v} = \{v\}, \tag{2.2}
\]
for \(v = w_h, u_h\), where \(\beta_0 > 0\) is a parameter to be determined. Here \(h_e\) is the characteristic length of interface \(e\). In case of the uniform meshes, we take \(h_e = h_i\) at each interface \(x^i_{\alpha_i+1/2}\) for \(\alpha_i = 0, 1, \ldots, N_i\). The numerical fluxes on \(e \in \partial K \cap \Gamma^0\) depend on the boundary conditions. For periodic boundary conditions, the numerical fluxes can take the same formula as those in (2.2). For homogeneous Neumann boundary conditions, the numerical fluxes on the boundary \(e \in \partial K \cap \Gamma^0\) are defined as
\[
\partial_\nu w_h = 0, \quad \widehat{w}_h = w_h, \quad \partial_\nu u_h = 0, \quad \widehat{u}_h = u_h. \tag{2.3}
\]
Summation of (2.1) over all elements \(K \in T_h\) leads to a global DG formulation
\[
(u_{ht}, \phi) = -A(M(u_h); w_h, \phi), \tag{2.4a}
\]
\[
(w_t, \psi) = A(\epsilon^2; u_h, \psi) + (F'(u_h), \psi), \tag{2.4b}
\]
where the bilinear functional is given by
\[
A(a(x); q, v) = A^0(a(x); q, v) + A^b(a(x); q, v)
\]
with
\[
A^0(a(x); q, v) := \sum_{K \in T_h} \int_K a(x) \nabla q \cdot \nabla v dx + \sum_{e \in \Gamma^0} \int_e a(x) \left( \widehat{\partial_\nu q} + \{q\} \{\partial_\nu v\} \right) ds, \tag{2.5}
\]
and
\[
\text{for (i)} \quad A^b(a(x); q, v) = \frac{1}{2} \sum_{e \in \Gamma^0} \int_e a(x) \left( \widehat{\partial_\nu q} + \{q\} \{\partial_\nu v\} \right) ds, \tag{2.6a}
\]
\[
\text{for (ii)} \quad A^b(a(x); q, v) = 0. \tag{2.6b}
\]
Here \(a(x) = M(u_h)\) in \(K\) but \(M(\tilde{u}_h)\) for \(x \in e\). Note that the factor \(\frac{1}{2}\) in (2.6b) is used to indicate that for periodic boundary conditions only one end in each direction should be counted. Here each respective type of boundary conditions specified in (1.2) has been taken into account. The initial data for \(u_h\) is taken from \(V_h\) so that
\[
\int_{\Omega} (u_0(x) - u_h(x, 0)) \phi dx = 0, \quad \forall \phi \in V_h.
\]
As usual we denote \(u_h(x, 0) = \Pi u_0(x)\), where \(\Pi\) is the piecewise \(L^2\) projection.
We introduce the discrete energy
\[
E(u_h) = \frac{1}{2} A(\epsilon^2; u_h, u_h) + \int_\Omega F(u_h) \, dx,
\] (2.7)
and the notation
\[
\|v\|^2_{DG} := \sum_{K \in \mathcal{T}_h} \int_K |\nabla v|^2 \, dx + \left( \sum_{e \in \Gamma^0} + \frac{1}{2} \sum_{e \in \Gamma^0} \right) \int_e \frac{\beta_0}{h_e} |v|^2 \, ds, \quad \forall v \in V_h,
\] (2.8)
for periodic boundary condition, or
\[
\|v\|^2_{DG} = \sum_{K \in \mathcal{T}_h} \int_K |\nabla v|^2 \, dx + \sum_{e \in \Gamma^0} \int_e \frac{\beta_0}{h_e} |v|^2 \, ds, \quad \forall v \in V_h,
\] (2.9)
for Neumann boundary condition. We can show that if \( \beta_0 \) is suitably large, the semi-discrete DG scheme (2.4) features a discrete energy dissipation law.

**Lemma 2.1.** For \( a(x) > \gamma \), there exists \( \beta_0^* > 0 \) such that if \( \beta_0 > \beta_0^* \), then
\[
A(a(x); v, v) \geq \gamma \|v\|^2_{DG}, \quad \forall v \in V_h.
\] (2.10)
As a result, we have
\[
\frac{d}{dt} E(u_h) = -A(M(u_h); w_h, w_h) \leq 0, \quad \forall t > 0.
\] (2.11)

**Proof.** (i) We only prove the periodic boundary case, the proof for the Neumann boundary case is similar. By the Young’s inequality, we have
\[
A(a(x); v, v) = \sum_{K \in \mathcal{T}_h} \int_K a(x)|\nabla v|^2 \, dx + \left( \sum_{e \in \Gamma^0} + \frac{1}{2} \sum_{e \in \Gamma^0} \right) \int_e a(x)[v] \left( \frac{\beta_0}{h_e} + 2\{\partial_x v\} \right) \, ds
\]
\[
\geq \sum_{K \in \mathcal{T}_h} \int_K a(x)|\nabla v|^2 \, dx + \left( \sum_{e \in \Gamma^0} + \frac{1}{2} \sum_{e \in \Gamma^0} \right) \int_e a(x)\frac{\beta_0}{h_e} |v|^2 \, ds
\]
\[- \left( \sum_{e \in \Gamma^0} + \frac{1}{2} \sum_{e \in \Gamma^0} \right) \left( \frac{\alpha}{h_e} \int_e a(x)|v|^2 \, ds + \frac{h_e}{\alpha} \int_e a(x)\{\partial_x v\}^2 \, ds \right)
\]
\[
= \sum_{K \in \mathcal{T}_h} \int_K a(x)|\nabla v|^2 \, dx - \frac{1}{\alpha} \left( \sum_{e \in \Gamma^0} + \frac{1}{2} \sum_{e \in \Gamma^0} \right) h_e \int_e a(x)\{\partial_x v\}^2 \, ds
\]
\[
+ \left( \sum_{e \in \Gamma^0} + \frac{1}{2} \sum_{e \in \Gamma^0} \right) \left( \frac{\beta_0 - \alpha}{h_e} \right) \int_e a(x)[v]^2 \, ds,
\]
for \( 0 < \alpha < \beta_0 \).

Set
\[
\beta_0^* \geq \sup_{v \in V_h} \frac{\left( \sum_{e \in \Gamma^0} + \frac{1}{2} \sum_{e \in \Gamma^0} \right) h_e \int_e a(x)\{\partial_x v\}^2 \, ds}{\sum_{K \in \mathcal{T}_h} \int_K a(x)|\nabla v|^2 \, dx},
\] (2.12)
then it follows
\[
A(a(x); v, v) \geq \left( 1 - \frac{\beta_0^*}{\alpha} \right) \sum_{K \in \mathcal{T}_h} \int_K a(x)|\nabla v|^2 \, dx + \left( 1 - \frac{\alpha}{\beta_0} \right) \left( \sum_{e \in \Gamma^0} + \frac{1}{2} \sum_{e \in \Gamma^0} \right) \int_e a(x)\frac{\beta_0}{h_e} |v|^2 \, ds.
\]
Set $\alpha = \sqrt{\beta_0 \beta_0^*}$ and $\gamma = \left(1 - \frac{\beta_0}{\beta_0^*}\right) \inf_{x \in \Omega} a(x)$, we obtain (2.10) iff $\beta_0 > \beta_0^*$. 

(ii) Taking $\phi = w_h$, $\psi = u_{ht}$ in (2.4), then (2.11) follows immediately. \hfill \Box

Remark 2.1. For $M(u) = \text{const}$ and rectangular uniform meshes, $\beta_0^*$ can be more precisely estimated as $\beta_0^* = k^2$, see [24, Lemma 3.1] with the parameter $\beta_1 = 0$. 

3. Time Discretization 

3.1. The EQ reformulation. The basic idea of the EQ methodology [42, 41] is to rewrite the energy functional into a quadratic form

$$E(u_h, U) = \frac{1}{2} A(\epsilon^2; u_h, u_h) + \int_{\Omega} U^2 dx = E(u_h) + B|\Omega|,$$ (3.1)

where

$$U = \sqrt{F(u_h) + B}$$

is well-defined when $B$ is chosen so that $F(u_h) + B > 0$. With the EQ approach $U$ is updated by solving

$$U_t = \frac{1}{2} H(u_h) u_{ht},$$

where

$$H(w) = \frac{f(w)}{\sqrt{F(w) + B}}.$$ (3.2)

The semi-discrete DG scheme (2.4) may be expanded as the following system: find $(u_h, w_h, U_h) \in V_h \times V_h \times V_h$ such that

$$(u_{ht}, \phi) = A(M(u_h); w_h, \phi),$$ (3.3a)

$$(w_h, \psi) = A(\epsilon^2; u_h, \psi) + (H(u_h) U_h, \psi),$$ (3.3b)

$$(U_h, \tau) = \frac{1}{2} (H(u_h) u_{ht}, \tau),$$ (3.3c)

for all $\phi, \psi, \tau \in V_h$, from which we find $(u_h^n, w_h^n, U_h^n) \in V_h \times V_h \times V_h$

$$(u_h^{n+1} - u_h^n) = - A(M(u_h^n); w_h^{n+1}, \phi),$$ (3.4a)

$$(w_h^{n+1}, \psi) = A(\epsilon^2; u_h^{n+1}, \psi) + (H(u_h^n) U_h^{n+1}, \psi),$$ (3.4b)

$$\left(\frac{U_h^{n+1} - U_h^n}{\Delta t}, \tau\right) = \frac{1}{2} \left( H(u_h^n) \frac{u_h^{n+1} - u_h^n}{\Delta t}, \tau\right)$$ (3.4c)

for $\forall \phi, \psi, \tau \in V_h$. One can verify that this scheme does satisfy the energy dissipation property as stated in the following

Lemma 3.1. There exists $\beta_0^* > 0$ such that if $\beta_0 > \beta_0^*$, the scheme (3.4) admits a unique solution $(u_h^n, w_h^n, U_h^n)$ for any $\Delta t > 0$. Moreover, for $E^n := E(u_h^n, U_h^n)$, we have

$$E^{n+1} = E^n - \Delta t A(M(u_h^n); w_h^{n+1}, w_h^{n+1}) - \frac{1}{2} A(\epsilon^2; u_h^{n+1} - u_h^n, u_h^{n+1} - u_h^n) - \|U_h^{n+1} - U_h^n\|^2,$$

independent of the size of $\Delta t$. 

One main drawback of the scheme (3.4) is that the auxiliary variable would have to be updated together with \((u_h, w_h)\) by solving the full expanded system, hence less efficient.

Instead, we follow [27] where an EQ-DG method was developed for the Swift-Hohenberg equation, to consider the following system: find \((u_h, w_h) \in V_h \times V_h\) and \(U(x, t)\) such that

\[
U_t = \frac{1}{2} H(u_h)u_{ht},
\]

\[
(u_{ht}, \phi) = A(M(u_h); w_h, \phi),
\]

\[
(w_h, \psi) = A(\epsilon^2; u_h, \psi) + (H(u_h)U, \psi),
\]

for all \(\phi, \psi \in V_h\), subject to initial data

\[
U(x, 0) = \sqrt{F(u_0(x)) + B}, \quad u_h(x, 0) = \Pi u_0(x).
\]

Note that with the modified discrete energy (3.1) we still have the following

\[
dt E(u_h, U) = -A(M(u_h); w_h, w_h) \leq 0.
\]

We proceed to discretize (3.5) in time.

3.2. First order fully discrete EQ-DG scheme. Find \((u^n_h, w^n_h) \in V_h \times V_h\) and \(U^n = U^n(x)\) such that

\[
U^n_h = \Pi U^n,
\]

\[
\frac{U^{n+1} - U^n_h}{\Delta t} = \frac{1}{2} H(u^n_h)u^{n+1}_h - u^n_h,
\]

\[
\left( \frac{u^{n+1}_h - u^n_h}{\Delta t}, \phi \right) = -A(M(u^n_h); w^{n+1}_h, \phi),
\]

\[
(w^{n+1}_h, \psi) = A(\epsilon^2; u^{n+1}_h, \psi) + (H(u^n_h)U^{n+1}, \psi),
\]

for \(\phi, \psi \in V_h\).

This scheme admits the following properties.

Theorem 3.1. There exists \(\beta^*>0\) such that if \(\beta_0 > \beta^*_0\), the scheme (3.6) admits a unique solution \((u^n_h, w^n_h)\) for any \(\Delta t > 0\), and the solution \(u^n_h\) satisfies the mass conservation, i.e.,

\[
\int_{\Omega} u^n_h dx = \int_{\Omega} u^0_h dx,
\]

for any \(n > 0\). Moreover, for \(E^n := E(u^n_h, U^n_h)\) we have

\[
E^{n+1} \leq E(u^{n+1}_h, U^{n+1}) = E^n - \Delta t A(M(u^n_h); w^{n+1}_h, w^{n+1}_h)
- \frac{1}{2} A(\epsilon^2; u^{n+1}_h - u^n_h, u^{n+1}_h - u^n_h) - \|U^{n+1} - U^n_h\|^2,
\]

independent of the size of \(\Delta t\).
Proof. Taking $\phi = 1$ in (3.6b) implies (3.7). We next show the existence and uniqueness of (3.6) at each time step. Substitution of (3.6b) into (3.6c) with (3.6d) gives the following linear system

$$
\begin{align*}
(\frac{u_{h}^{n+1}}{\Delta t}, \phi) + A(M(u_{h}^{n}); w_{h}^{n+1}, \phi) &= (u_{h}^{n}/\Delta t, \phi), \\
A(\epsilon^2; u_{h}^{n+1}, \psi) + (1/2H(u_{h}^{n})^2u_{h}^{n+1}, \phi) - (w_{h}^{n+1}, \psi) &= (1/2H(u_{h}^{n})^2u_{h}^{n}, \phi) - (H(u_{h}^{n})U_{h}^{n}, \psi).
\end{align*}
$$

(3.9a)

(3.9b)

It suffices to prove the uniqueness for this linear system. Denoting $(\bar{u}, \bar{w})$ the difference of two possible solutions of (3.9) for fixed $(u_{h}^{n}, w_{h}^{n})$, so that

$$
(\bar{u}/\Delta t, \phi) + A(M(u_{h}^{n}); \bar{w}, \phi) = 0, \\
A(\epsilon^2; \bar{u}, \psi) + (1/2H(u_{h}^{n})^2\bar{u}, \phi) - (\bar{w}, \psi) = 0.
$$

(3.10a)

(3.10b)

Setting $\phi = \Delta t\bar{w}, \psi = \bar{u}$ and adding the two equations, we have

$$
\Delta tA(M(u_{h}^{n}); \bar{w}, \bar{w}) + A(\epsilon^2; \bar{u}, \bar{u}) + (1/2H(u_{h}^{n})^2\bar{u}, \bar{u}) = 0.
$$

By (2.10), it follows that

$$
0 \geq \Delta tM_{\min}\|\bar{w}\|_{DG}^2 + \epsilon^2\|\bar{u}\|_{DG}^2 + \frac{1}{2}\int_{\Omega}H(u_{h}^{n})^2\bar{u}^2\,dx,
$$

which ensures that $\bar{u} = \text{const}$ and $\bar{w} = \text{const}$. Then it follows $A(M(u_{h}^{n}); \bar{w}, \phi) = A(\epsilon^2; \bar{u}, \psi) = 0$. Thus, (3.10a) is equivalent to

$$
(\bar{u}, \phi) = 0, \quad \forall \phi \in V_h.
$$

We must have $\bar{u} = 0$. In a similar fashion, $\bar{w} = 0$ follows from (3.10b). Hence the uniqueness for (3.9) follows.

We next prove (3.8). Taking $\phi = w_{h}^{n+1}$ in (3.6c), $\psi = \frac{u_{h}^{n+1} - u_{h}^{n}}{\Delta t}$ in (3.6d) gives

$$
-A(M(u_{h}^{n}); w_{h}^{n+1}, w_{h}^{n+1}) = A(\epsilon^2; w_{h}^{n+1}, \frac{u_{h}^{n+1} - u_{h}^{n}}{\Delta t}) + \left( H(u_{h}^{n})U^{n+1}, \frac{u_{h}^{n+1} - u_{h}^{n}}{\Delta t} \right).
$$

By (3.6b) and bilinearity of $A(\epsilon^2; \cdot, \cdot)$, the right hand side of the above equation gives

$$
RHS = \frac{1}{2\Delta t} \left( A(\epsilon^2; u_{h}^{n+1}, u_{h}^{n+1}) - A(\epsilon^2; u_{h}^{n}, u_{h}^{n}) + A(\epsilon^2; u_{h}^{n+1} - u_{h}^{n}, u_{h}^{n+1} - u_{h}^{n}) \right)
\quad + \frac{1}{\Delta t} \left( \|U^{n+1}\|^2 - \|U_{h}^{n}\|^2 + \|U^{n+1} - U_{h}^{n}\|^2 \right).
$$

Hence

$$
E(u_{h}^{n+1}, U^{n+1}) = E(u_{h}^{n}, U_{h}^{n}) - \Delta tA(M(u_{h}^{n}); w_{h}^{n+1}, w_{h}^{n+1})
\quad - \frac{1}{2}A(\epsilon^2; u_{h}^{n+1} - u_{h}^{n}, u_{h}^{n+1} - u_{h}^{n}) - \|U^{n+1} - U_{h}^{n}\|^2.
$$

(3.11)

Implied by the fact that $\Pi$ is a contraction mapping in $L^2$, we have

$$
E(u_{h}^{n+1}, U^{n+1}) \leq E(u_{h}^{n+1}, U^{n+1}),
$$

(3.12)

hence (3.8) as desired. 

□
3.3. Second order fully discrete EQ-DG scheme. We first obtain \( u_h^1, w_h^1 \) and \( U^1 \) from the first order full discrete EQ-DG scheme (3.6). We further use the second order backward differentiation formula (BDF2) for time discretization. In other words, for \( n \geq 1 \), the second order fully discrete EQ-DG scheme is to find \((u_h^{n+1}, w_h^{n+1}) \in V_h \times V_h\) such that for \( \forall \phi, \psi \in V_h \),
\[
U_h^n = \Pi U^n, \quad (3.13a)
\]
\[
\frac{3U^{n+1} - 4U_h^n + U_h^{n-1}}{2\Delta t} = \frac{1}{2} H(u_h^{n*}) \frac{3u_h^{n+1} - 4u_h^n + u_h^{n-1}}{2\Delta t}, \quad (3.13b)
\]
\[
\left( \frac{3u_h^{n+1} - 4u_h^n + u_h^{n-1}}{2\Delta t}, \phi \right) = -A(M(u_h^{n*}); w_h^{n+1}, \phi), \quad (3.13c)
\]
\[
(w_h^{n+1}, \psi) = A(\epsilon^2; u_h^{n+1}, \psi) + \left( H(u_h^{n*})U^{n+1}, \psi \right), \quad (3.13d)
\]
where \( u_h^{n*} \) is obtained using \( u_h^{n-1} \) and \( u_h^n \)
\[
u_h^{n*} = 2u_h^n - u_h^{n-1}. \quad (3.14)
\]
Here instead of \( u_h^{n+1} \) we use \( u_h^{n*} \) to avoid iteration steps in updating the numerical solution, while still maintaining second order accuracy in time.

To show the energy stability, we first present some useful identities.

**Lemma 3.2.** For any symmetric bilinear functional \( \mathcal{A}(\cdot, \cdot) \), it follows
\[
\mathcal{A}(\phi + \psi, \phi - \psi) = \mathcal{A}(\phi, \phi) - \mathcal{A}(\psi, \psi),
\]
\[
2\mathcal{A}(\phi_1, 3\phi_1 - 2\phi_2 - \phi_3) = \mathcal{A}(\phi_1, \phi_1) + \mathcal{A}(2\phi_1 - \phi_2, 2\phi_1 - \phi_2) - \mathcal{A}(\phi_2, \phi_2)
- \mathcal{A}(\phi_3, \phi_3) + \mathcal{A}(\phi_1 - \phi_3, \phi_1 - \phi_3).
\]

**Proof.** The first identity follows from a direct calculation using the symmetry of the bilinear functional \( \mathcal{A}(\cdot, \cdot) \). The second follows from a proper decomposition and using the first identity, that goes as follows:
\[
2\mathcal{A}(\phi_1, 3\phi_1 - 2\phi_2 - \phi_3) = \mathcal{A}(\phi_1, 6\phi_1 - 4\phi_2 - 2\phi_3)
= \mathcal{A}(\phi_1, \phi_1 + 4(\phi_1 - \phi_2) + \phi_1 - 2\phi_3)
= \mathcal{A}(\phi_1, \phi_1) + \mathcal{A}(2\phi_1 - \phi_2, 2\phi_1 - \phi_2) + \mathcal{A}(\phi_1, \phi_1 - 2\phi_3)
= \mathcal{A}(\phi_1, \phi_1) + \mathcal{A}(2\phi_1 - \phi_2, 2\phi_1 - \phi_2) - \mathcal{A}(\phi_2, \phi_2)
+ \mathcal{A}(\phi_1 - \phi_3, \phi_1 - \phi_3) - \mathcal{A}(\phi_3, \phi_3).
\]
\[\square\]

For the scheme (3.13), we have

**Theorem 3.2.** There exists \( \beta_0 > 0 \) such that if \( \beta_0 > \beta_0^* \), the second order fully discrete DG scheme (3.13) admits a unique solution \((u_h^{n+1}, w_h^{n+1})\), and the solution \( u_h^n \) satisfies the mass conservation (3.7) for any \( n > 0 \). Moreover, for any \( \Delta t > 0 \) it follows
\[
\bar{E}^{n+1} - \bar{E}^n \leq -\Delta t A(M(u_h^{n*}); w_h^{n+1}, w_h^{n+1}) \leq 0, \quad (3.15)
\]
where the modified energy is defined by
\[ \tilde{E}^n = \frac{E(u^n_h, U^n_h) + E(u^{n,*}_h, U^{n,*}_h)}{2}, \]
with
\[ U^{n,*}_h = 2U^n_h - U^{n-1}_h. \]

Proof. We first prove \([3.15]\). Taking \( \phi = 2\Delta t w^{n+1}_h \) in \([3.13c]\) gives
\[-2\Delta t A(M(u^{n,*}_h); w^{n+1}_h, u^{n+1}_h) = (u^{n+1}_h, 3u^{n+1}_h - 4u^n_h + u^{-1}_h)\]
using \([3.13d]\)
\[ = A(\epsilon^2; w^{n+1}_h, \psi) + (H(u^{n,*}_h)U^{n+1}_h, \psi), \]
\[ \psi := 3u^{n+1}_h - 4u^n_h + u^{-1}_h \]
using \([3.13b]\)
\[ = A(\epsilon^2; u^{n+1}_h, 3u^{n+1}_h - 4u^n_h + u^{-1}_h) + (3U^{n+1}_h - 4U^n_h + U^{n-1}_h, 2U^{n+1}_h) \]
\[ = A(\epsilon^2; u^{n+1}_h, 3u^{n+1}_h - 2u^n_h - u^{n,*}_h) + (3U^{n+1}_h - 2U^n_h - U^{n,*}_h, 2U^{n+1}_h). \]

Both \( A(\epsilon^2; \cdot, \cdot) \) and \((\cdot, \cdot)\) are symmetric, by Lemma \([3.2]\) we have
\[ A(\epsilon^2; u^{n+1}_h, 3u^{n+1}_h - 2u^n_h - u^{n,*}_h) = \frac{1}{2} \left[ A(\epsilon^2; u^{n+1}_h, u^{n+1}_h) + A(\epsilon^2; u^{n+1,*}_h, u^{n+1,*}_h) - A(\epsilon^2; u^n_h, u^n_h) \right. \]
\[ - A(\epsilon^2; u^{n,*}_h, u^{n,*}_h) + A(\epsilon^2; u^{n+1}_h - u^{n,*}_h, u^{n+1}_h - u^{n,*}_h) \right], \]
\[ (3U^{n+1}_h - 2U^n_h - U^{n,*}_h, 2U^{n+1}_h) = \|U^{n+1}_h\|^2 + \|2U^{n+1}_h - U^n_h\|^2 - \|U^{n,*}_h\|^2 + \|U^{n+1}_h - U^{n,*}_h\|^2. \]

Regrouping, we obtain
\[ \frac{1}{2} \left[ A(\epsilon^2; u^{n+1}_h, u^{n+1}_h) + A(\epsilon^2; u^{n+1,*}_h, u^{n+1,*}_h) \right] + \|U^{n+1}_h\|^2 + \|2U^{n+1}_h - U^n_h\|^2 \]
\[ = 2\tilde{E}^n - 2\Delta t A(M(u^{n,*}_h); w^{n+1}_h, u^{n+1}_h) - \frac{1}{2} A(\epsilon^2; u^{n+1}_h - u^{n,*}_h, u^{n+1}_h - u^{n,*}_h) - \|U^{n+1}_h - U^{n,*}_h\|^2 \]
\[ \leq 2\tilde{E}^n - 2\Delta t A(M(u^{n,*}_h); w^{n+1}_h, u^{n+1}_h). \]

Further use of the fact that \( \Pi \) is a contraction mapping in \( L^2 \), we have
\[ \|U^{n+1}_h\|^2 \leq \|U^{n+1}_h\|^2, \quad \|2U^{n+1}_h - U^n_h\|^2 \leq \|2U^{n+1}_h - U^n_h\|^2. \]

Then the left hand side of \([3.17]\) is bounded below by \( 2\tilde{E}^{n+1} \), thus \([3.15]\) follows.

Similar to the proof of Theorem \([3.1]\) the existence and uniqueness of the scheme \([3.13]\) is equivalent to showing the uniqueness of \( u^{n+1}_h, w^{n+1}_h \) given \( u^i_h, w^i_h, U^i \) with \( i = n, n - 1 \).

Let \((\bar{u}, \bar{w}, \bar{U})\) be the difference of two such solutions, then
\[ \bar{U} = \frac{1}{2} H(u^{n,*}_h)\bar{u}, \]
\[ (3\bar{u}, \phi) = -2\Delta t A(M(u^{n,*}_h); \bar{w}, \phi), \]
\[ (\bar{w}, \psi) = A(\epsilon^2; \bar{u}, \psi) + \left( H(u^{n,*}_h)\bar{U}, \psi \right). \]

Setting \( \phi = \bar{w}, \psi = 3\bar{u} \), and subtracting \([3.18b]\) from \([3.18c]\), it follows
\[ 2\Delta t A(M(u^{n,*}_h); \bar{w}, \bar{w}) + 3A(\epsilon^2; \bar{u}, \bar{u}) + 6\|\bar{U}\|^2 = 0, \]
where \([3.18a]\) has been used to simplify the third term. By \([2.10]\), it follows that
\[ 2\Delta t M_{\min} \|\bar{w}\|_{DG}^2 + 3\epsilon^2 \|\bar{u}\|_{DG}^2 + 6\|\bar{U}\|^2 \leq 0, \]
which ensures that $\tilde{u} = \text{const}$, $\tilde{w} = \text{const}$ and $\tilde{U} = 0$. Thus, using (3.18) again, we must have $\tilde{u} = \tilde{w} = 0$. Thus leads to the existence and uniqueness of the scheme (3.13).

Taking $\phi = 1$ in (3.13), it follows

$$\int_{\Omega} u_{n+1}^h dx = \frac{1}{3} \int_{\Omega} 4u_n^h - u_{n-1}^h dx. \tag{3.19}$$

From Theorem [3.1] we have

$$\int_{\Omega} u_1^h dx = \int_{\Omega} u_0^h dx, \tag{3.20}$$

which when combined with (3.19) gives the mass conservation (3.7). □

3.4. Algorithms. Denote by

$$S = \{ x_\alpha^j \in K_\alpha, \ j = 1, \ldots, Q; \alpha = 1, \ldots, N \}$$

the set of all quadrature points from each element $K_\alpha$ with dimensional point index $j = (j_1, \ldots, j_d)$, $\alpha = (\alpha_1, \ldots, \alpha_d)$, $N = (N_1, \ldots, N_d)$ and $Q = (Q_1, \ldots, Q_d)$, where $Q_j := Q$, $j = 1, \ldots, d$ denote the total number of quadrature points in each direction. In our numerical tests in section 5, we use the Legendre-Gauss quadrature with $Q = k + 1$, when using $P^k$ polynomials in each $K_\alpha$.

For a given function $v$, we define $v_h = \Pi_k^h v \in V_h$ by

$$\sum_{\alpha=1}^N |K_\alpha| \sum_{j=1}^Q \omega_j v_h(x_\alpha^j) \tau(x_\alpha^j) = \sum_{\alpha=1}^N |K_\alpha| \sum_{j=1}^Q \omega_j v(x_\alpha^j) \tau(x_\alpha^j), \quad \forall \tau \in V_h,$$

where $\{\omega_l\}_{l=1}^Q$ denotes the collective quadrature weights. Same quadratures will be used for evaluating integrals in solving the linear systems (3.9) and (3.13), respectively.

The details related to the schemes implementation are summarized in the following algorithms

3.4.1. Algorithm for the first order fully discrete EQ-DG scheme (3.6).

- **Step 1 (Initialization)** From the given initial data $u_0(x)$
  1. generate $u_0^h = \Pi u_0(x) \in V_h$;
  2. generate $U^0 = \sqrt{F(u_0(x)) + B}$ for $\forall x \in S$, where $B$ is a priori chosen so that $\inf(F(v) + B) > 0$.

- **Step 2 (Evolution)**
  1. Lift $U^n(x), x \in S$ onto the DG space, $U^n_h = \Pi_k^h U^n$;
  2. Solve the linear system (3.9) for $u^{n+1}_h, w^{n+1}_h$;
  3. Update $U^{n+1}$ using (3.6b) for $\forall x \in S$, then return to (1) in Step 2.

3.4.2. Algorithm for the second order fully discrete EQ-DG scheme (3.13).

- **Step 1 (Initialization)** From the given initial data $u_0(x)$
  1. generate $u_0^h = \Pi u_0(x) \in V_h$;
  2. generate $U^0 = \sqrt{F(u_0(x)) + B}$ for $\forall x \in S$, where $B$ is a priori chosen so that $\inf(F(v) + B) > 0$; and
  3. solve for $u_1^h, w_1^h$ and $U^1$ for $\forall x \in S$ through Algorithm 3.4.1 for the first order fully discrete EQ-DG scheme (3.6).

- **Step 2 (Evolution)**
(1) Lift $U^n(x), x \in S$ onto the DG space, $U^n_h = \Pi_h^k U^n$;

(2) Solve the linear system for $u_{h}^{n+1}, w_{h}^{n+1},$

$$
\left(\frac{3u_{h}^{n+1}}{2\Delta t}, \phi \right) + A(M(u_{h}^{n,*})/w_{h}^{n+1}, \phi) = \left(\frac{4u_{h}^{n} - u_{h}^{n-1}}{2\Delta t}, \phi \right),
$$

$$
A(\varepsilon^2, u_{h}^{n+1}, \psi) + \frac{1}{2} \left( (H(u_{h}^{n,*}))^2 u_{h}^{n+1}, \psi \right) - (w_{h}^{n+1}, \psi) = RHS,
$$

where $RHS = - \left( (H(u_{h}^{n,*}))^2 u_{h}^{n+1} - \frac{1}{2} (H(u_{h}^{n,*}))^2 \frac{4u_{h}^{n} - u_{h}^{n-1}}{3}, \psi \right)$

(3) Update $U^{n+1}$ through (3.13b) for $\forall x \in S$, i.e.,

$$
U^{n+1} = \frac{1}{2} H(u_{h}^{n,*}) u_{h}^{n+1} + \left( \frac{4U_{h}^{n} - U_{h}^{n-1}}{3} - \frac{1}{2} H(u_{h}^{n,*}) \frac{4u_{h}^{n} - u_{h}^{n-1}}{3} \right),
$$

then return to (1) in Step 2.

Remark 3.1. Higher order (in time) EQ discretization is possible. We omit the details here due to space limitation. Interested readers are referred to [21] for some arbitrarily high-order linear schemes for gradient flow models.

4. Extensions

It is known that solving the Cahn-Hilliard equation with degenerate mobility and/or logarithmic potential is more difficult since it requires a point-wise control of the numerical solution. We discuss how our schemes can be applied by a proper modification.

4.1. Mobility. Though the mobility is often taken as a constant for simplicity, a thermodynamically reasonable choice is actually the degenerate mobility $M(u) = u(1-u)$ (see e.g., [12]). There is hope that solutions which initially take values in the interval $[0, 1]$ will do so for all positive time (which is not true for fourth-order parabolic equations without degeneracy). We remark that only values in the interval $[0, 1]$ are physically meaningful. Such degeneracy leads to numerical difficulties.

Here, we follow [12, 4] by considering the modified mobility

$$
\tilde{M}(u) = \begin{cases} 
M(\sigma) & u \leq \sigma, \\
M(u) & \sigma < u < 1 - \sigma, \\
M(1 - \sigma) & u \geq 1 - \sigma,
\end{cases}
$$

(4.1)

It is obvious that for given $\sigma$,

$$
\tilde{M}(u) \geq M_{\min} > 0,
$$

and it is well-defined for $u \in (-\infty, \infty)$. Numerically, we apply our scheme using this modified mobility with a small $\sigma$. 
4.2. Flory-Huggins potential. A practical choice for the potential is the Logarithmic Flory-Huggins function\[^{[5, 7, 9]}\]

\[
F(v) = \frac{\theta}{2} \left( v \ln v + (1-v) \ln(1-v) \right) + \frac{\theta_c}{2} v(1-v), \quad v \in [0, 1],
\]

(4.2)

where \(\theta, \theta_c > 0\) are physical parameters. This function is non-convex with double wells for \(\theta_c > 2\theta\), and it only has a single well and admits only a single phase for \(\theta_c \leq 2\theta\)\[^{[36]}\].

The domain of the logarithmic potential (4.2) is \((0, 1)\), which requires the numerical solution be strictly inside \((0, 1)\). For some numerical schemes, such solution bounds can be established (see, e.g., \[^{[11, 12, 29, 9, 8]}\]).

For high order DG schemes it is rather difficult to preserve the numerical solution within \((0, 1)\). We choose to regularize the logarithmic Flory-Huggins potential (4.2) by extending its domain from \((0, 1)\) to \((-\infty, \infty)\). Such regularization technique is commonly used to remove the numerical overflow; see, e.g., \[^{[9, 1, 12, 3, 41]}\]. Specifically, it can be replaced by the twice continuously differentiable function

\[
\tilde{F}(v) = \begin{cases} 
\frac{\theta}{2} \left( v \ln v + (1-v) \ln \sigma + \frac{(1-v)^2}{2\sigma} - \frac{\sigma}{2} \right) + \frac{\theta_c}{2} v(1-v), & v \geq 1 - \sigma, \\
\frac{\theta}{2} \left( v \ln v + (1-v) \ln(1-v) \right) + \frac{\theta_c}{2} v(1-v), & \sigma < v < 1 - \sigma, \\
\frac{\theta}{2} \left( (1-v) \ln(1-v) + v \ln \sigma + \frac{v^2}{2\sigma} - \frac{\sigma}{2} \right) + \frac{\theta_c}{2} v(1-v), & v \leq \sigma,
\end{cases}
\]

and thus \(\tilde{F}(v)\) is well defined for \(v \in (-\infty, \infty)\). It was argued in \[^{[12]}\] that the solution with regularized \(M(u)\) and \(\tilde{F}(u)\) converges to the solution to the original problem as \(\sigma \to 0\). This treatment has been applied in numerical simulations, for example in \[^{[4]}\]. In this paper, we apply our EQ-DG schemes to problems formulated with the modified mobility and the regularized potential.

5. Numerical examples

In this section, we will carry out several numerical tests in both 1D and 2D to demonstrate both temporal and spatial accuracy of the numerical scheme (3.6) and (3.13), the mass conservation and energy dissipation properties. In the following numerical examples, the parameter \(\beta_0 = 2k^2 + k\) for problems with constant mobility and \(\beta_0 = 3k^2 + k\) for other cases. The parameter \(B = 1\) as default unless specified.

**Example 5.1.** (1D spatial accuracy test) Consider the Cahn-Hilliard equation (1.1) with \(M = 1\) and double-well potential \(F(u) = \frac{1}{4}(u^2 - 1)^2\) in \(\Omega = [0, 2\pi]\) with periodic boundary conditions. Here, we follow Example 5.2 in \[^{[32]}\] by adding a source term

\[
s(x, t) = -e^{-t} \sin x \left( 3e^{-2t} \cos 2x + 3e^{-2t} \cos^2 x + 1 \right)
\]

(5.1)
to the Cahn-Hilliard equation (1.1), so that the exact solution is

\[
u(x, t) = e^{-t} \sin x.
\]

(5.2)

We use the fully discrete EQ-DG scheme (3.13) with a term \((s(\cdot, t^{n+1}), \phi)\) added to the right hand side of (3.13c), and we test the DG scheme based on \(P^k\) polynomials, with \(k = 1, 2, 3\). Both errors and orders of accuracy at \(T = 1\) are reported in Table 1. These results show that \((k + 1)\)th order of accuracy in both \(L^2\) and \(L^\infty\) norms are obtained.
Table 1. 1D $L^2$, $L^\infty$ errors and orders of accuracy at $T = 1$.

| $k$ | $\Delta t$ | N=10 | N=20 | N=40 | N=80 |
|-----|-------------|------|------|------|------|
|     | error       | error | order| error | order | error | order |
| 1   | 1e-3        | 3.09646e-02 | 8.07876e-03 | 1.94 | 2.03575e-03 | 1.99 | 5.10124e-04 | 2.00 |
|     | $||u - u_h||_{L^2}$ | 1.68270e-02 | 4.58886e-03 | 1.87 | 1.16103e-03 | 1.98 | 2.91198e-04 | 2.00 |
| 2   | 1e-4        | 3.56585e-04 | 4.17179e-05 | 3.10 | 5.12149e-06 | 3.03 | 6.35139e-07 | 3.01 |
|     | $||u - u_h||_{L^\infty}$ | 4.34261e-04 | 5.50274e-05 | 2.98 | 6.89646e-06 | 3.00 | 8.63616e-07 | 3.00 |
| 3   | 5e-5        | 3.95098e-04 | 2.63710e-05 | 3.91 | 1.67970e-06 | 3.97 | 1.05540e-07 | 3.99 |
|     | $||u - u_h||_{L^\infty}$ | 3.08214e-04 | 2.04705e-05 | 3.91 | 1.29411e-06 | 3.98 | 8.23617e-08 | 3.97 |

Example 5.2. (2D spatial accuracy test with constant mobility and double-well potential) For the Cahn-Hilliard equation (1.1) with $M(u) = 1$ and double-well potential $F(u) = \frac{1}{4}(u^2 - 1)^2$ in $\Omega$ with appropriate boundary conditions, we add a source term

$$s(x, y, t) = -\frac{w(x, y, t)}{4} + \frac{e^2w(x, y, t)}{4} - \frac{3w(x, y, t)v(x, y, t)}{2} + \frac{3w(x, y, t)^3}{2} - \frac{w(x, y, t)}{2}$$

to the right hand side of (1.1), where

$$w(x, y, t) = 0.1e^{-t/4} \sin(x/2) \sin(y/2),$$

$$v(x, y, t) = (0.1e^{-t/4} \cos(x/2) \sin(y/2))^2 + (0.1e^{-t/4} \sin(x/2) \cos(y/2))^2,$$

so that the exact solution is

$$u(x, y, t) = w(x, y, t).$$

Here the parameter $\epsilon = 0.1$. We test this example by DG scheme (3.6) with a term $(s(x, y, t_{n+1}), \phi)$ added to the right hand side of (3.6), and the DG scheme is based on polynomials of degree $k$ with $k = 1, 2, 3$ on rectangular meshes.

Test case 1. (Periodic BC) In this test case, we take $\Omega = [0, 4\pi]^2$ and consider periodic boundary conditions. Both errors and orders of accuracy at $T = 0.01$ are reported in Table 2. These results show that $(k + 1)$th order of accuracy in both $L^2$ and $L^\infty$ are obtained.

Table 2. 2D $L^2$, $L^\infty$ errors at $T = 0.01$ with mesh $N \times N$.

| $k$ | $\Delta t$ | N=8 | N=16 | N=32 | N=64 |
|-----|-------------|-----|------|------|------|
|     | error       | error | order| error | order |
| 1   | 1e-3        | 3.16822e-02 | 8.03463e-03 | 1.98 | 2.0336e-03 | 1.99 | 5.04024e-04 | 2.01 |
|     | $||u - u_h||_{L^2}$ | 1.38669e-02 | 3.74776e-03 | 1.89 | 9.5955e-04 | 1.97 | 2.40239e-04 | 2.00 |
| 2   | 1e-4        | 4.52729e-03 | 5.75115e-04 | 2.98 | 7.33589e-05 | 2.97 | 9.21578e-06 | 2.99 |
|     | $||u - u_h||_{L^\infty}$ | 2.32640e-03 | 2.95229e-04 | 2.98 | 4.06866e-05 | 2.86 | 5.26926e-06 | 2.95 |
| 3   | 5e-5        | 4.46670e-04 | 2.97916e-05 | 3.91 | 1.89117e-06 | 3.98 | 1.18585e-07 | 4.00 |
|     | $||u - u_h||_{L^\infty}$ | 3.20555e-04 | 1.80104e-05 | 4.15 | 1.02204e-06 | 4.14 | 6.16224e-08 | 4.05 |
Test case 2. (Neumann BC) Considering $\Omega = [-\pi, 3\pi]^2$ with homogenous Neumann boundary conditions (1.2(ii)), both errors and orders of accuracy at $T = 0.01$ are reported in Table 3. These results also show $(k + 1)$th order of accuracy in both $L^2$ and $L^\infty$.

Table 3. 2D $L^2$, $L^\infty$ errors at $T = 0.01$ with mesh $N \times N$.

| $k$ | $\Delta t$ | $N=8$ | $N=16$ | $N=32$ | $N=64$ |
|-----|------------|-------|--------|--------|--------|
|     |            | error | error  | error  | error  | order | order | order | order |
| 1   | 1e-3       | $\|u - u_h\|_{L^2}$ | 3.16822e-02 | 8.03463e-03 | 1.98 | 2.02336e-03 | 1.99 | 5.04024e-04 | 2.01 |
|     |            | $\|u - u_h\|_{L^\infty}$ | 1.38669e-02 | 3.74776e-03 | 1.89 | 9.59555e-04 | 1.97 | 2.04239e-04 | 2.00 |
| 2   | 1e-4       | $\|u - u_h\|_{L^2}$ | 4.52729e-03 | 5.75115e-04 | 2.98 | 7.33591e-05 | 2.97 | 9.18427e-06 | 3.00 |
|     |            | $\|u - u_h\|_{L^\infty}$ | 2.32640e-03 | 2.95229e-04 | 2.98 | 4.06885e-05 | 2.86 | 5.08342e-06 | 3.00 |
| 3   | 1e-5       | $\|u - u_h\|_{L^2}$ | 4.46670e-04 | 2.97916e-05 | 3.91 | 1.89102e-06 | 3.98 | 1.18133e-07 | 4.00 |
|     |            | $\|u - u_h\|_{L^\infty}$ | 3.20555e-04 | 1.80104e-05 | 4.15 | 1.02406e-06 | 4.14 | 6.40520e-08 | 4.00 |

Example 5.3. (2D spatial accuracy test with constant mobility and logarithmic potential) We consider the Cahn-Hilliard equation (1.1) with constant mobility $M(u) = 1$, the logarithmic Flory-Huggins potential (4.2) with $\theta = \theta_c = 2$, the parameters $\epsilon = 1$ and $B = 10$. We add an appropriate source term $s(x, y, t)$ to the right hand side of (1.1) such that the exact solution is

$$u(x, y, t) = \frac{1}{10} e^{-t/4} \sin(x/4) \sin(y/4) + \frac{1}{2}.$$ 

We test this example by DG scheme (3.13) with a term $(s(x, y, t^{n+1}), \phi)$ added to the right hand side of (3.13c), and the DG scheme is also based on polynomials of degree $k$ with $k = 1, 2, 3$ on rectangular meshes.

Test case 1. (Periodic BC) In this test case, we take $\Omega = [0, 8\pi]^2$ and consider periodic boundary conditions. Both errors and orders of accuracy at $T = 0.01$ are reported in Table 4. These results show that $(k + 1)$th order of accuracy in both $L^2$ and $L^\infty$ are obtained.

Table 4. 2D $L^2$, $L^\infty$ errors at $T = 0.01$ with mesh $N \times N$.

| $k$ | $\Delta t$ | $N=8$ | $N=16$ | $N=32$ | $N=64$ |
|-----|------------|-------|--------|--------|--------|
|     |            | error | error  | error  | error  | order | order | order | order |
| 1   | 1e-3       | $\|u - u_h\|_{L^2}$ | 6.34010e-02 | 1.62047e-02 | 1.97 | 4.04183e-03 | 2.00 | 1.00777e-03 | 2.00 |
|     |            | $\|u - u_h\|_{L^\infty}$ | 1.38744e-02 | 3.74858e-03 | 1.89 | 9.55245e-04 | 1.97 | 2.39967e-04 | 1.99 |
| 2   | 1e-4       | $\|u - u_h\|_{L^2}$ | 9.39224e-03 | 1.18059e-04 | 2.98 | 1.46853e-04 | 3.01 | 1.83323e-05 | 3.00 |
|     |            | $\|u - u_h\|_{L^\infty}$ | 2.45698e-03 | 3.14143e-04 | 2.97 | 3.74571e-05 | 3.07 | 4.54860e-06 | 3.04 |
| 3   | 5e-6       | $\|u - u_h\|_{L^2}$ | 1.09183e-03 | 6.72768e-05 | 4.02 | 4.09870e-06 | 3.99 | 2.54225e-07 | 4.01 |
|     |            | $\|u - u_h\|_{L^\infty}$ | 2.30167e-04 | 1.58541e-05 | 3.86 | 1.02039e-06 | 3.96 | 6.42180e-08 | 3.99 |

Test case 2. (Neumann BC) In this test case, we take $\Omega = [-2\pi, 2\pi]^2$ and consider Neumann boundary conditions. Both errors and orders of accuracy at $T = 0.01$ are reported in Table 5. These results show that $(k + 1)$th order of accuracy in both $L^2$ and $L^\infty$ are obtained.
EQ-DG METHODS FOR THE CAHN-HILLIARD EQUATION

Table 5. 2D $L^2$, $L^\infty$ errors at $T = 0.01$ with mesh $N \times N$.

| $k$ | $\Delta t$ | $N=8$ | $N=16$ | $N=32$ | $N=64$ |
|-----|------------|-------|--------|--------|--------|
|     | $\|u - u_h\|_{L^2}$ | error | error | order  | error | order  | error | order  |
| 1   | $1e-3$     | 1.27997e-01 | 3.55296e-02 | 1.85   | 9.55174e-03 | 1.90   | 2.13203e-03 | 2.16   |
|     | $\|u - u_h\|_{L^\infty}$ | 5.54685e-02 | 1.49970e-02 | 1.89   | 3.92808e-03 | 1.93   | 9.67492e-04 | 2.02   |
| 2   | $1e-4$     | 1.87014e-02 | 2.35480e-03 | 2.99   | 2.94393e-04 | 3.00   | 2.13203e-03 | 2.16   |
|     | $\|u - u_h\|_{L^\infty}$ | 1.05130e-02 | 1.30587e-03 | 3.01   | 1.62919e-04 | 3.00   | 9.67492e-04 | 2.02   |
| 3   | $5e-6$     | 2.23974e-03 | 1.24902e-04 | 4.16   | 7.57937e-06 | 4.04   | 4.99051e-07 | 3.92   |
|     | $\|u - u_h\|_{L^\infty}$ | 1.47731e-03 | 8.27217e-05 | 4.17   | 4.36207e-06 | 4.24   | 3.29965e-07 | 3.72   |

Example 5.4. (2D spatial accuracy test with degenerate mobility and logarithmic potential) We consider the Cahn-Hilliard equation (1.1) with degenerate mobility $M(u) = u(1 - u)$, the logarithmic Flory-Huggins potential (4.2) with $\theta = \theta_c = 2$, the parameters $\epsilon = 1$ and $B = 10$. We add an appropriate source term $s(x,y,t)$ to the right hand side of (1.1) such that the exact solution is

$$u(x,y,t) = \frac{2}{5}e^{-t/4} \sin(x/2) \sin(y/2) + \frac{1}{2}.$$

We test this example by DG scheme (3.6) with a term $(s(x,y,t^n + 1), \phi)$ added to the right hand side of (3.6), and the DG scheme is also based on polynomials of degree $k$ with $k = 1, 2, 3$ on rectangular meshes.

Test case 1. (Periodic BC) In this test case, we take $\Omega = [0, 4\pi]^2$ and consider periodic boundary conditions. Both errors and orders of accuracy at $T = 0.01$ are reported in Table 6. These results show that $(k + 1)$th order of accuracy in both $L^2$ and $L^\infty$ are obtained.

Table 6. 2D $L^2$, $L^\infty$ errors at $T = 0.01$ with mesh $N \times N$.

| $k$ | $\Delta t$ | $N=8$ | $N=16$ | $N=32$ | $N=64$ |
|-----|------------|-------|--------|--------|--------|
|     | $\|u - u_h\|_{L^2}$ | error | error | order  | error | order  | error | order  |
| 1   | $1e-3$     | 1.31235e-01 | 3.29574e-02 | 1.99   | 8.27934e-03 | 1.99   | 2.08160e-03 | 1.99   |
|     | $\|u - u_h\|_{L^\infty}$ | 5.56010e-02 | 1.49372e-02 | 1.90   | 3.81584e-03 | 1.97   | 9.59510e-04 | 1.99   |
| 2   | $1e-4$     | 2.05688e-02 | 2.51806e-03 | 3.03   | 3.05650e-04 | 3.04   | 3.79714e-05 | 3.01   |
|     | $\|u - u_h\|_{L^\infty}$ | 1.13806e-02 | 1.32194e-03 | 3.11   | 1.48147e-04 | 3.16   | 1.77820e-05 | 3.06   |
| 3   | $5e-6$     | 2.82305e-03 | 1.48385e-04 | 4.25   | 8.56909e-06 | 4.11   | 5.53886e-07 | 3.95   |
|     | $\|u - u_h\|_{L^\infty}$ | 1.58906e-03 | 9.24779e-05 | 4.10   | 4.63277e-06 | 4.32   | 3.35743e-07 | 3.79   |

Test case 2. (Neumann BC) In this test case, we take $\Omega = [-\pi, 3\pi]^2$ and consider Neumann boundary conditions. Both errors and orders of accuracy at $T = 0.01$ are reported in Table 7. These results show that $(k + 1)$th order of accuracy in both $L^2$ and $L^\infty$ is obtained.

Example 5.5. (Temporal Accuracy Test) Following the test case II in Example 5.3, we produce numerical solutions at $T = 1$ using DG schemes (3.6) and (3.13) based on $P^2$ polynomials with time steps $\Delta t = 2^{-m}$ with $2 \leq m \leq 5$ and appropriate meshes. The $L^2$, $L^\infty$ errors and orders of
Table 7. 2D $L^2$, $L^\infty$ errors at $T = 0.01$ with mesh $N \times N$.

| $k$ | $\Delta t$ | $N=8$ | $N=16$ | $N=32$ | $N=64$ |
|-----|-------------|-------|--------|--------|--------|
|     |             | error | error  | order  | error  | order  |
|     |             | error | order  | error  | order  | error  | order  |
| 1   | $1 \times 10^{-3}$ | $1.31235 \times 10^{-1}$ | $3.29574 \times 10^{-2}$ | 1.99 | $8.27934 \times 10^{-3}$ | 1.99 | $2.08160 \times 10^{-3}$ | 1.99 |
|     |             | $5.56010 \times 10^{-2}$ | $1.49372 \times 10^{-2}$ | 1.90 | $3.81584 \times 10^{-3}$ | 1.97 | $9.59510 \times 10^{-4}$ | 1.99 |
| 2   | $1 \times 10^{-4}$ | $2.05688 \times 10^{-2}$ | $2.51806 \times 10^{-3}$ | 3.03 | $3.05650 \times 10^{-4}$ | 3.04 | $3.79715 \times 10^{-5}$ | 3.01 |
|     |             | $1.13806 \times 10^{-2}$ | $1.32194 \times 10^{-3}$ | 3.11 | $1.48147 \times 10^{-4}$ | 3.16 | $1.77820 \times 10^{-5}$ | 3.06 |
| 3   | $5 \times 10^{-6}$ | $2.82305 \times 10^{-3}$ | $1.48385 \times 10^{-4}$ | 4.25 | $8.56909 \times 10^{-6}$ | 4.11 | $5.59243 \times 10^{-7}$ | 3.94 |
|     |             | $1.58906 \times 10^{-3}$ | $9.24779 \times 10^{-5}$ | 4.10 | $1.48385 \times 10^{-6}$ | 4.02 | $3.42344 \times 10^{-7}$ | 3.76 |

Example 5.6. Following [36], we consider the Cahn-Hilliard equation (1.1) with constant mobility $M(u) = 1$, the logarithmic Flory-Huggin potential

$$F(u) = 600 \left( u \ln u + (1 - u) \ln(1 - u) \right) + 1800u(1-u),$$

and the parameters $\epsilon = 1$ and $B = 10^2$. The equation is subject to the initial condition

$$u_0(x, y) = \begin{cases} 
0.71, & (x, y) \in \Omega_1, \\
0.69, & (x, y) \in \Omega_2, 
\end{cases}$$

where the square domain

$$\Omega = [-0.5, 0.5] \times [-0.5, 0.5], \quad \Omega_1 = [-0.2, 0.2] \times [-0.2, 0.2], \quad \Omega_2 = \Omega \setminus \Omega_1.$$  

The boundary conditions are taken as Neumann BCs, (ii) in (1.2).

Test case 1. We first solve this problem by the first order fully discrete EQ-DG scheme (3.6) based on $P_1$ and $P_2$ polynomials with time step $\Delta t = 10^{-7}$ and meshes $40 \times 40$ and $80 \times 80$, respectively. The contours at $T = 8 \times 10^{-5}$ are shown in Figure 1 and the corresponding energy and mass evolutions are shown in Figure 2. From Figure 1, we find that the solution structure is well resolved even on coarser mesh and lower order $P_1$ polynomials, and the scheme (3.6) using $P_2$ polynomials gives a better resolution than that using $P_1$ polynomials on coarser meshes $40 \times 40$, but there is no noticeable difference with solution on refined meshes $80 \times 80$ or higher order polynomial.
Figure 1. The contours of numerical solution for the scheme (3.6).

$P^2$ as shown in Figure 1(b)-(d). The pattern structure is well consistent with that obtained in [36]. Figure 2(a) shows that the numerical solution of the scheme (3.6) satisfies the energy dissipation law and Figure 2(b) shows that the numerical solution conserves the total mass $\int_{\Omega} u \, dx = 0.6932$.

**Test case 2.** We solve this problem again by the second order fully discrete EQ-DG scheme (3.13) based on $P^1$ polynomials with mesh $40 \times 40$. The time steps are taken as $\Delta t = 10^{-7}, 8 \times 10^{-8}, 6.4 \times 10^{-8}, 5 \times 10^{-8}$, respectively. The contours at $T = 8 \times 10^{-5}$ are shown in Figure 3, and the corresponding energy and mass evolutions are shown in Figure 4.

From Figure 3, we find the pattern structure is comparable to that in Figure 1(b)-(d) even with time step $\Delta t = 10^{-7}$ and lower order $P^1$ polynomials. Figure 4(a) shows that the numerical solution of the scheme (3.13) satisfies the energy dissipation law (3.15), but we do find that the modified energy (3.16) need a smaller $\Delta t$ to better approximate the original energy. Figure 4(b) implies the numerical solutions with different time steps $\Delta t$ conserve the total mass $\int_{\Omega} u \, dx = 0.6932$. 

Example 5.7. Following [36], we further consider the Cahn-Hilliard equation (1.1) with degenerate mobility $M(u) = u(1 - u)$, the logarithmic Flory-Huggin potential

$$F(u) = 3000 \left( u \ln u + (1 - u) \ln(1 - u) \right) + 9000u(1 - u),$$

and the parameters $\epsilon = 1$ and $B = 10^3$. The initial condition is

$$u_0(x, y) = 0.63 + 0.05 \text{rand}(x, y),$$

where $\text{rand}(x, y)$ is the random perturbation function in $[-1, 1]$ and has zero mean. For the boundary conditions, we take Neumann BCs (ii) in (1.2).

We solve this problem by the scheme (3.13) based on $P^2$ polynomials with meshes $64 \times 64$ and time step $\Delta t = 10^{-8}$. The evolution of the concentration field is shown in Figure 5. The corresponding energy and mass evolutions are shown in Figure 6. Figure 5 clearly shows the two phases of the concentration evolution. The first phase is governed by spinodal decomposition and phase separation, which is roughly corresponding to the first three figures of Figure 5, this period is basically terminated as soon as the local concentration is driven to either value of the two binodal points. The second phase is governed by grain coarsening, approximately from $t = 8 \times 10^{-6}$ onwards the generated patterns cluster and grains tend to coarsen, which is a very slow process. Figure 5 shows statistically similar patterns in the numerical solution as those in [36]. Figure 6 further confirms the numerical solution of the scheme (3.13) satisfies the energy dissipation law and conserves the total mass $\int_{\Omega} u \, dx = 0.63$.

6. Conclusion

In this paper, we integrate the mixed DG method with the EQ method to design both first and second order fully discrete DG schemes that inherit the energy dissipation law and mass conservation of the continuous equation irrespectively of the mesh and time steps. The spatial discretization is based on the mixed DG method, and the temporal discretization is based on the EQ
Figure 3. The contours of numerical solution for the scheme (3.13).

approach introduced in [40] for treating nonlinear potentials. Coupled with a spatial projection, the resulting EQ-DG algorithms are easy to implement without resorting to any iterative method, and proven to be unconditionally energy stable and mass conservative. We have presented numerical examples to verify our theoretical results, and demonstrate the good performance of the scheme in terms of efficiency, accuracy, and preservation of solution properties such as energy dissipation and mass conservation.

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Figure 4. The energy and mass evolution of numerical solution for the scheme (3.6).

Figure 5. The contours evolution of the numerical solution for the scheme (3.13).
Figure 6. The energy and mass evolution of numerical solution for the scheme (3.13).

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