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The degenerate and non-degenerate Stefan problem with inhomogeneous and anisotropic Gibbs–Thomson law

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The Stefan problem is coupled with a spatially inhomogeneous and anisotropic Gibbs–Thomson condition at the phase boundary. We show the long-time existence of weak solutions for the non-degenerate Stefan problem with a spatially inhomogeneous and anisotropic Gibbs–Thomson law and a conditional existence result for the corresponding degenerate Stefan problem. To this end, approximate solutions are constructed by means of variational problems for energy functionals with spatially inhomogeneous and anisotropic interfacial energy. By passing to the limit, we establish solutions of the Stefan problem with a spatially inhomogeneous and anisotropic Gibbs–Thomson law in a weak generalised BV-formulation.

Key words: Stefan problem; Phase transitions; Gibbs–Thomson law; Free boundaries; Variational problems; Geometric measure-theory

1 Introduction

The Stefan problem models phase transitions in materials. To allow for superheating and undercooling, the Stefan problem is coupled with a geometrical condition at the phase boundary, the so-called Gibbs–Thomson law. This condition takes surface tension effects into account such that the temperature may differ from the melting temperature at the phase boundary. The Gibbs–Thomson law states that the system is in thermodynamic equilibrium.

The classical Gibbs–Thomson law accounts for isotropic surface tension effects. In this case, the temperature at the interface is proportional to the mean curvature. In many applications, however, such as the solidification of alloys, the surface energy density is spatially inhomogeneous and anisotropic, i.e. the density depends on the position in space and on the local orientation of the interface. This means that the Stefan problem with a generalised Gibbs–Thomson law has to be considered (see, for instance [21, 22] for a thermodynamic derivation). The temperature at the interface is then related to a spatially inhomogeneous and anisotropic mean curvature.

Heat conduction in materials often takes place on a much faster time scale than the evolution of the interface. Therefore, a quasi-static version of the Stefan problem, the so-called degenerate Stefan problem, is often used to describe melting and solidification processes.

To formulate the Stefan problem with Gibbs–Thomson law, let $(0,T)$ be a given time interval, $\Omega \subset \mathbb{R}^n$ be a bounded domain with Lipschitz boundary and $\Omega_T := (0,T) \times \Omega$. The phase field variables are the temperature

$$u : \Omega_T \to \mathbb{R}$$

and a phase function

$$\chi : \Omega_T \to \mathbb{R},$$

where the liquid phase is represented by the set $\{(t,x) \in \Omega_T : \chi(t,x) = 1\}$ and the solid phase by the set $\{(t,x) \in \Omega_T : \chi(t,x) = 0\}$.

The *(non-degenerate)* Stefan problem with isotropic Gibbs–Thomson law is formally described by

$$\partial_t \big(u + \chi\big) - \triangle u = f \qquad \text{in } \ \Omega_T, \tag{1.1}$$

$$u = H \qquad \text{on } \ \Gamma, \tag{1.2}$$

where $f : \Omega_T \to \mathbb{R}$ is a given heat source, $H : \Gamma \to \mathbb{R}$ is the mean curvature and Γ denotes the phase boundary.

The *degenerate* Stefan problem models an infinite fast heat flow in the material, i.e. (1.1) is replaced by

$$\partial_t \chi - \triangle u = f \qquad \text{in } \ \Omega_T. \tag{1.3}$$

For a general theory of the Stefan problem, we refer to [20, 27, 33]. Global existence results for the non-degenerate Stefan problem with isotropic Gibbs–Thomson law in a weak (generalised) BV-formulation are shown in [25, 26, 29] and with anisotropic Gibbs–Thomson law in [19a]. For the degenerate Stefan problem, existence of classical solutions locally in time has been proven by Chen, Hong and Yi [8] and by Escher and Simonett [11, 12]. An existence result for global solutions of the degenerate problem can be found in [7], where the limit of a modified Cahn–Hilliard model is considered. However, the isotropic Gibbs–Thomson law is only fulfilled in a rather weak and complex formulation. Using the theory of varifolds, Röger [30] established long-time existence of solutions of the degenerate Stefan problem with isotropic Gibbs–Thomson law in a weak generalised BV-formulation. In contrast to the classical Stefan problem, global weak solutions of the Stefan problem with Gibbs–Thomson law have sharp interfaces but are highly non-unique as discussed in [25]. Uniqueness of classical solutions for the degenerate and non-degenerate Stefan problem with Gibbs–Thomson law is established in [8, 10, 23]. In addition, it is shown in [10] that the free boundary is an analytic function in space and time.

The BV-formulation of the degenerate and non-degenerate Stefan problem with isotropic Gibbs–Thomson law was introduced by Luckhaus and considered for the non-degenerate problem in [25, 26] and for the degenerate problem in [24] (see also [19] for a multi-phase version): The temperature and the phase function

$$u \in u_D + L^2(0,T; H^1_0(\Omega)), \quad u_D \in H^1(0,T; H^1(\Omega)), \qquad \text{and} \qquad \chi \in L^\infty(0,T; BV(\Omega; \{0,1\}))$$

satisfy for the non-degenerate problem

$$\int_{\Omega_T}(u+\chi)\partial_t\xi+\int_\Omega\chi(0)\xi(0)=\int_{\Omega_T}\nabla u\nabla\xi-\int_{\Omega_T}f\xi \quad \text{for all } \xi\in C_c^\infty([0,T)\times\Omega), \tag{1.4}$$

for the degenerate problem

$$\int_{\Omega_T}\chi\partial_t\xi+\int_\Omega\chi(0)\xi(0)=\int_{\Omega_T}\nabla u\nabla\xi-\int_{\Omega_T}f\xi \quad \text{for all } \xi\in C_c^\infty([0,T)\times\Omega) \tag{1.5}$$

and for both problems

$$\int_0^T\int_\Omega\left(\nabla\cdot\xi-\frac{\nabla\chi}{|\nabla\chi|}\cdot\nabla\xi\frac{\nabla\chi}{|\nabla\chi|}+u\,\xi\cdot\frac{\nabla\chi}{|\nabla\chi|}\right)|\nabla\chi|\,dt=0 \quad \text{for all } \xi\in C_c^\infty(\Omega_T;\mathbb{R}^n). \tag{1.6}$$

In this BV-setting, global solutions for the non-degenerate case are obtained in [25, 26] by an implicit time discretisation method. The time discrete approximations χ^h and u^h converge to weak solutions of (1.1) and (1.2). In particular, the exclusion of loss of surface area in the limit, i.e.

$$\lim_{h\to 0}\int_{\Omega_T}|\nabla\chi^h|=\int_{\Omega_T}|\nabla\chi|, \tag{1.7}$$

arises in a natural way from the discrete minimum problem.

For the degenerate system, i.e. (1.3) and (1.2), property (1.7) is in general not satisfied. However, assuming (1.7), existence of global solutions can be shown in the BV-setting (see [24]). Conditions of the form as in (1.7) are typical for such kind of geometric problems and have been applied to several other geometric problems (see [4, 5, 19, 24, 28]).

In this paper, we study the degenerate and non-degenerate Stefan problem with *spatially inhomogeneous* and *anisotropic* Gibbs–Thomson law. This generalised Gibbs–Thomson law results from an inhomogeneous and anisotropic surface energy, i.e.

$$\int_\Gamma\sigma(x,\nu)\,d\mathscr{H}^{n-1},$$

where ν is the outer unit normal of the liquid phase, $\mathscr{H}^{(n-1)}$ is the $(n-1)$-dimensional Hausdorff measure and σ is an anisotropy function satisfying Assumption A 2.1 (see Section 2.1). The corresponding generalised Gibbs–Thomson law at the phase boundary reads as

$$u=H_\sigma \qquad \text{on } \Gamma \tag{1.8}$$

with

$$H_\sigma=\nabla_\Gamma\cdot\sigma_{,p}(x,\nu)+\sigma_{,x}(x,\nu)\cdot\nu,$$

where ∇_Γ denotes the tangential gradient of Γ and $\sigma_{,s}$ is the first partial derivative of σ with respect to the variable s.

The aim of this work is to show existence of weak solutions for the Stefan problem with spatially inhomogeneous and anisotropic Gibbs–Thomson law and existence of weak solutions for the corresponding degenerate problem assuming a condition similar to (1.7). The results of [19a, 24–26] are generalised.

Our main results are under suitable assumptions as follows.

Theorem 1.1 *Let $\Omega \subset \mathbb{R}^n$ be a bounded domain with Lipschitz boundary, σ be an anisotropy function satisfying Assumption A 2.1 (see Section 2.1) and $f \in L^2(\Omega_T)$. Furthermore, let $u_D \in H^1(0,T;H^1(\Omega))$ and the initial data $u_0 \in H^1(\Omega) \cap L^\infty(\Omega)$ and $\chi_0 \in BV(\Omega;\{0,1\})$ be given. Then, there exist functions $\chi \in L^\infty(0,T;BV(\Omega;\{0,1\}))$ and $u \in (u_D + L^2(0,T;H_0^1(\Omega))) \cap L^\infty(0,T;L^2(\Omega))$ that are solutions of*

$$\int_{\Omega_T} (u+\chi)\partial_t \xi + \int_\Omega \chi(0)\xi(0) = \int_{\Omega_T} \nabla u \nabla \xi - \int_{\Omega_T} f\xi \quad \textit{for all } \xi \in C_c^1([0,T) \times \Omega), \tag{1.9}$$

and

$$\int_0^T \int_\Omega (\sigma(\cdot, v(t,\cdot))\nabla\cdot\xi(t,\cdot) + \sigma_{,x}(\cdot, v(t,\cdot)) \cdot \xi(t,\cdot) - v(t,\cdot)\cdot\nabla\xi(t,\cdot)\,\sigma_{,p}(\cdot, v(t,\cdot)) \\ - u(t,\cdot)\,\xi(t,\cdot)\cdot v(t,\cdot))|\nabla\chi(t,\cdot)\,dt = 0 \quad \textit{for all } \xi \in C_c^1(\Omega_T;\mathbb{R}^n) \textit{ with } v = -\frac{\nabla\chi}{|\nabla\chi|}. \tag{1.10}$$

If, in addition, Ω is a bounded domain with C^1-boundary then (1.10) even holds for all $\xi \in C^1(\overline{\Omega}_T;\mathbb{R}^n)$ with $\xi \cdot v_\Omega = 0$ on $\partial\Omega$, where v_Ω is the outer unit normal of $\partial\Omega$.

The above existence result for the non-degenerate system is based on an implicit time discretisation method. In this case, we obtain for the time discrete approximations χ^h, $h > 0$, the following generalised property of (1.7):

$$\lim_{h\to 0} \int_{\Omega_T} \sigma(x, v^h)|\nabla\chi^h| = \int_{\Omega_T} \sigma(x,v)|\nabla\chi|, \qquad v^h := -\frac{\nabla\chi^h}{|\nabla\chi^h|}. \tag{1.11}$$

Under this condition, we are also able to show existence of weak solutions for the degenerate problem.

Theorem 1.2 *Let $\Omega \subset \mathbb{R}^n$ be a bounded domain with Lipschitz boundary, σ be an anisotropy function satisfying Assumption A 2.1 (see Section 2.1) and $f \in L^2(\Omega_T)$. Furthermore, let $u_D \in W^{1,1}(0,T;H^1(\Omega))$ and the initial datum $\chi_0 \in BV(\Omega;\{0,1\})$ be given. If condition (1.11) (see Section 4 for the definition of χ^h) is satisfied then there exist functions $\chi \in L^\infty(0,T;BV(\Omega;\{0,1\}))$ and $u \in u_D + L^2(0,T;H_0^1(\Omega))$ that are solutions of*

$$\int_{\Omega_T} \chi\partial_t \xi + \int_\Omega \chi(0)\xi(0) = \int_{\Omega_T} \nabla u \nabla \xi - \int_{\Omega_T} f\xi \quad \textit{for all } \xi \in C_c^1([0,T) \times \Omega), \tag{1.12}$$

and

$$\int_0^T \int_\Omega (\sigma(\cdot, v(t,\cdot))\nabla\cdot\xi(t,\cdot) + \sigma_{,x}(\cdot, v(t,\cdot)) \cdot \xi(t,\cdot) - v(t,\cdot)\cdot\nabla\xi(t,\cdot)\,\sigma_{,p}(\cdot, v(t,\cdot)) \\ - u(t,\cdot)\,\xi(t,\cdot)\cdot v(t,\cdot))|\nabla\chi(t,\cdot)|\,dt = 0 \quad \textit{for all } \xi \in C_c^1(\Omega_T,\mathbb{R}^n) \textit{ with } v = -\frac{\nabla\chi}{|\nabla\chi|}. \tag{1.10}$$

If, in addition, Ω is a bounded domain with C^1-boundary then (1.10) *even holds for all $\xi \in C^1(\overline{\Omega}_T,\mathbb{R}^n)$ with $\xi \cdot v_\Omega = 0$ on $\partial\Omega$, where v_Ω is the outer unit normal of $\partial\Omega$.*

A major task of the proof of the existence results for both problems has been to assure convergence of the approximate terms, which arise from the spatially inhomogeneous character of the interfacial energy. To handle this convergence problem, we work with slicing and indicator measures and methods of geometric measure theory. We choose the notion of a generalised total variation for BV-functions. Our results are based on weak convergence theorems for homogeneous functions of measures, on geometric properties for anisotropic surface energies and on approaches of [18].

The paper is organised as follows: In Sections 2.1–2.2, we introduce some notation and the assumptions. Then, we state some properties for anisotropy functions and slicing and indicator measures (see Sections 2.3–2.4). In Section 3, we establish a suitable weak formulation of the Stefan problem with spatially inhomogeneous and anisotropic Gibbs–Thomson law in a generalised BV-setting. Section 4 is devoted to time-incremental minimisation problems for energy functionals with spatially inhomogeneous and anisotropic interfacial energy. We construct time discretised solutions for (1.9), (1.10) and (1.12), (1.10), respectively. Arguments similarly to [24–26] are only sketched. Finally, we pass to the limit in the time discretised problems, cf. Sections 5.1–5.3, and prove Theorems 1.1 and 1.2 in Section 5.4.

2 Preliminaries

If not otherwise mentioned, we assume that $\Omega \subset \mathbb{R}^n$ is a bounded domain with Lipschitz boundary. The first and second partial derivatives of a function with respect to the variables s and p are abbreviated by $f_{,s}$ and $f_{,sp}$.

We begin with stating the hypotheses for the anisotropy function σ.

2.1 Anisotropy function

Assumption A 2.1 *The anisotropy function* $\sigma : \overline{\Omega} \times \mathbb{R}^n \to [0, +\infty)$ *satisfies the following properties:*

(i) $\sigma \in C(\overline{\Omega} \times \mathbb{R}^n)$,

$\sigma_{,x}, \sigma_{,p} \in C(\overline{\Omega} \times \mathbb{R}^n \backslash \{0\})$,

$\sigma_{,pp} \in C(\overline{\Omega} \times \mathbb{R}^n \backslash \{0\})$.

(ii) σ *is 1-homogeneous in the second variable, i.e.* $\sigma(x, \lambda p) = \lambda \sigma(x, p)$ *for all* $p \in \mathbb{R}^n$ *and any* $\lambda > 0$.

(iii) There exist constants $\lambda_1 > 0$ *and* $\lambda_2 > 0$ *such that*

$$\lambda_1 |p| \leqslant \sigma(x, p) \leqslant \lambda_2 |p| \qquad \text{for all} \quad x \in \overline{\Omega} \text{ and all } p \in \mathbb{R}^n.$$

(iv) σ *is convex as a 1-homogeneous function in the following sense: There exists a constant* $d_0 > 0$ *such that*

$$\sigma_{,pp}(x, p)\, q \cdot q \geqslant d_0 |q|^2$$

for all $x \in \Omega$ *and all* $p, q \in \mathbb{R}^n$ *with* $p \cdot q = 0$, $|p| = 1$.

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Note that σ is not differentiable at $0 \in \mathbb{R}^n$. However, if we set $\sigma\,\sigma_{,p} = 0$ and $g\,\sigma_{,p} = 0$ at $0 \in \mathbb{R}^n$ for $g \in C^1(\Omega)$ with $g = 0$ in some neighbourhood of 0, then the expressions $\sigma\,\sigma_{,p}$ and $g\,\sigma_{,p}$ are well defined and continuous at 0.

2.2 Generalised total variation

To handle the spatially inhomogeneous and anisotropic Gibbs–Thomson law, we use the notion of the generalised total variation of BV-functions introduced in [1].

Let $\sigma : \Omega \times \mathbb{R}^n \to [0, +\infty)$ be a continuous anisotropy function fulfilling (ii) and (iii) of Assumption A 2.1. Then, the dual function $\sigma^* : \Omega \times \mathbb{R}^n \to [0, +\infty)$ is given by

$$\sigma^*(x, q) = \sup\{q \cdot p : p \in \mathbb{R}^n,\ \sigma(x, p) \leqslant 1\} = \sup\left\{\frac{q \cdot p}{\sigma(x, p)} : p \in \mathbb{R}^n \backslash \{0\}\right\}. \tag{2.1}$$

For any $f \in BV(\Omega)$ the *generalised total variation* of f (with respect to σ) in Ω is defined by

$$\int_\Omega |\nabla f|_\sigma = \sup\left\{\int_\Omega f\, \mathrm{div}\eta\, dx : \eta \in K_\sigma(\Omega)\right\},$$

where $K_\sigma(\Omega) = \{\eta \in C_c^1(\Omega, \mathbb{R}^n) : \sigma^*(x, \eta(x)) \leqslant 1 \text{ for a.e. } x \in \Omega\}$. The generalised total variation can be represented by an integral formula in terms of the measure $|\nabla f|$, cf. [1,2]:

$$\int_\Omega |\nabla f|_\sigma = \int_\Omega \sigma(x, \nu_f)\, |\nabla f|, \tag{2.2}$$

where $\nu_f(x) = -\frac{\nabla f}{|\nabla f|}(x)$ for $|\nabla f|$-a.e. $x \in \Omega$.

We remark, $\int_\Omega |\nabla f|_\sigma$ is $L^1(\Omega)$ lower semi-continuous on $BV(\Omega)$.

2.3 Properties of anisotropy functions

In the sequel, we take advantage from the following properties for anisotropy functions, cf. [6,9,16].

Lemma 2.2 *Let σ be an anisotropy function satisfying Assumption A 2.1. Then, there exist constants $C_1 > 0$ and $C_2 > 0$ such that for all $x \in \Omega$, $\nu_1, \nu_2 \in \mathbb{S}^{n-1}$ and all $p, p_1, p_2 \in \mathbb{R}^n \backslash \{0\}$ the following properties are fulfilled:*

(i)

$$\sigma_{,p}(x, p) \cdot p = \sigma(x, p), \qquad \sigma^*_{,p}(x, p) \cdot p = \sigma^*(x, p), \tag{2.3}$$

(ii)

$$\sigma(x, \nu_1) - \sigma_{,p}(x, \nu_2) \cdot \nu_1 \geqslant C_1 |\nu_1 - \nu_2|^2, \tag{2.4}$$

(iii)

$$|\sigma_{,p}(x, \nu_1) - \sigma_{,p}(x, \nu_2)| \leqslant C_2 |\nu_1 - \nu_2|, \tag{2.5}$$

(iv)

$$\sigma_{,p}(x, \lambda p) = \sigma_{,p}(x, p) \quad \textit{for} \ \ \lambda > 0, \tag{2.6}$$

(v)

$$\sigma(x, \sigma^*_{,p}(x, p_1)) = \sigma^*(x, \sigma_{,p}(x, p_2)) = 1. \tag{2.7}$$

(vi)

$$\sigma(x,p)\,\sigma^*_{,p}(x, s, \sigma_{,p}(x,p)) = p, \qquad \sigma^*(x,p)\,\sigma_{,p}(x, s, \sigma^*_{,p}(x,p)) = p. \tag{2.8}$$

Anisotropy can be visualised by the Wulff shape W that varies in our situation with $x \in \Omega$:

$$W(x) = \{q \in \mathbb{R}^n : \sigma^*(x,q) \leqslant 1\}.$$

The Wulff shape W is convex and its boundary can be expressed as follows:

$$\partial W(x) = \{\sigma_{,p}(x, \tilde{v}) : \tilde{v} \in \mathbb{S}^{n-1}\}, \qquad x \in \Omega.$$

The outer unit normal at the point $\sigma_{,p}(x, \tilde{v})$ on $\partial W(x)$ is $\tilde{v}$. For more details on this topic, we refer to [16, 22].

The following lemma is an essential tool for constructing suitable approximations of the Cahn–Hoffman vector $\sigma_{,p}$, cf. [18]. This auxiliary result is utilised to prove convergence of the time discretised solutions.

Lemma 2.3 (cf. [18]) *Let σ be an anisotropy function satisfying Assumption A 2.1. Then, there exists a constant $C > 0$ such that*

$$C\,|\sigma_{,p}(x,v) - p|^2 \leqslant \sigma(x,v) - p \cdot v$$

for all $x \in \Omega$, $v \in \mathbb{S}^{n-1}$ and all $p \in \mathbb{R}^n \setminus \{0\}$ with $\sigma^*(x,p) \leqslant 1$.

2.4 Slicing and indicator measures

We outline some properties on slicing and indicator measures, which are required in the limit process of the discrete spatially inhomogeneous and anisotropic Gibbs–Thomson law. For details we refer to [3, 13–15].

Let Θ be a finite, non-negative Radon measure on $\Omega \times \mathbb{R}^n$. The canonical projection onto Ω is denoted by π, i.e.

$$\pi(E) := \Theta(E \times \mathbb{R}^n)$$

for each Borel set $E \subset \Omega$.

Proposition 2.4 (cf. [3]) *For π-a.e. point $x \in \Omega$, there exists a Radon probability measure λ_x on $\mathbb{R}^n$ such that*

(i) the mapping $x \to \int_{\mathbb{R}^n} f(x,y)\, d\lambda_x(y)$ is π measurable,

(ii) $\int_{\Omega\times\mathbb{R}^n} f(x,y)\, d\Theta(x,y) = \int_\Omega \left(\int_{\mathbb{R}^n} f(x,y) d\lambda_x(y)\right) d\pi(x)$ (Fubini's decomposition)

for every continuous and bounded function $f : \Omega \times \mathbb{R}^n \to \mathbb{R}$.

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Let $\hat{\mu}$ be an $\mathbb{R}^n$-valued measure on Ω with polar decomposition $d\hat{\mu} = \alpha\, d\mu$. Then, the *indicator measure* of $\hat{\mu}$ is the finite, non-negative Radon measure Θ on $\Omega \times \mathbb{S}^{n-1}$ defined by

$$\langle \Theta, f \rangle = \int_\Omega f(x, \alpha(x)) d\mu(x)$$

for every continuous and bounded function $f : \Omega \times \mathbb{R}^n \to \mathbb{R}$. If $E \subset \Omega$ is a set with finite perimeter, i.e.

$$\text{per}(E) = \int_\Omega |\nabla \chi_E| < \infty, \qquad \chi_E : \text{ characteristic function of } E,$$

then the indicator measure of $\nabla \chi_E$ has the form

$$\langle \Theta, f \rangle = \int_{\partial^* E} f(x, -\nu_E(x))\, d\mathscr{H}^{n-1}(x), \qquad \nu_E : \text{ unit outer normal of } E,$$

where $\partial^* E$ is the reduced boundary of E, cf. [3, 17].

Proposition 2.5 (cf. [3, 15]) *Let $\{\hat{\mu}_k\}_{k \in \mathbb{N}}$ be a sequence of $\mathbb{R}^n$-valued measures on Ω with polar decompositions $d\hat{\mu}_k = \alpha_k\, d\mu_k$ and suppose that $\hat{\mu}_k \to \hat{\mu}$ weakly* with $\hat{\mu} = \alpha\mu$. Then, there exists a subsequence $\{k_j\}_{j \in \mathbb{N}}$ and a non-negative Radon measure $\Theta_\infty \equiv \pi_\infty \otimes \lambda_x^\infty$ on $\Omega \times \mathbb{S}^{n-1}$, λ_x^∞ being probability measures, such that*

(i) $\Theta_{k_j} \equiv \mu_{k_j} \otimes \delta_{\alpha_{k_j}(x)} \to \Theta_\infty \equiv \pi_\infty \otimes \lambda_x^\infty$ *weakly*,* $\qquad \delta_y$ *Dirac mass,*
(ii) $\mu_{k_j} \to \pi_\infty$ *weakly*,*
(iii) $\pi_\infty \geqslant \mu$.

Moreover, for every $f \in C_c(\Omega \times \mathbb{R}^n)$

$$\lim_{j \to \infty} \int_\Omega f(x, \alpha_{k_j}(x)) d\mu_{k_j} = \int_{\Omega \times \mathbb{S}^{n-1}} f(x, y)\, d\Theta_\infty(x, y)$$
$$= \int_\Omega \left(\int_{\mathbb{S}^{n-1}} f(x, y) d\lambda_x^\infty(y) \right) d\pi_\infty(x).$$

3 Weak and strong formulations

In this section, we show that (1.10) is in fact a weak formulation of the spatially inhomogeneous and anisotropic Gibbs–Thomson law (see (1.8)). This weak generalised BV-formulation also includes a boundary condition for the interface with the outer boundary.

Theorem 3.1 *Let Ω be a bounded domain with C^1-boundary, Γ be a C^2-hypersurface and let $\partial\Gamma$ consists of a finite number of C^1-$(n-2)$-dimensional surfaces. If (χ, u) is a solution of (1.9) and (1.10) or (1.12) and* (1.10) *then the following conditions are satisfied:*

(i) Inhomogeneous and anisotropic Gibbs–Thomson law

$$\sigma_{,x}(x, \nu(t)) \cdot \nu(t) + \nabla_{\Gamma(t)} \cdot \sigma_{,p}(x, \nu(t)) = u(t) \qquad \text{on } \Gamma(t)\ \mathscr{H}^{(n-1)}\text{-a.e. for a.e. } t \in (0, T),$$

where ∇_Γ denotes the tangential gradient of Γ.

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(ii) Force balance condition

$$\sigma_{,p}(x, \nu(t)) \cdot \nu_\Omega(t) = 0 \qquad \text{on } \partial\Gamma(t) \cap \partial\Omega \ \mathscr{H}^{(n-2)}\text{-a.e. for a.e. } t \in (0, T),$$

where ν_Ω is the outer unit normal of $\partial\Omega$.

Proof We consider (1.10) and take test functions of the structure $\xi = \eta\nu$ on Γ, where η is an arbitrary function of $C_c^1(\Omega_T; \mathbb{R})$. For the first and third summand of the area part of (1.10), we derive

$$\int_0^T \int_{\Gamma(t)} \nu(t) \cdot \nabla\xi(t)\, \sigma_{,p}(x, \nu(t))\, d\mathscr{H}^{n-1}(t)\, dt = \int_0^T \int_{\Gamma(t)} \nabla\eta(t) \cdot \sigma_{,p}(x, \nu(t))\, d\mathscr{H}^{n-1}(t)\, dt$$

and

$$\begin{aligned}
&\int_0^T \int_{\Gamma(t)} \sigma(x, \nu(t)) \nabla\cdot\xi(t)\, d\mathscr{H}^{n-1}(t)\, dt \\
&= \int_0^T \int_{\Gamma(t)} \nu(t) \cdot (\nabla\eta(t) \cdot \nu(t) + \eta(t)\, \nabla\cdot\nu(t))\, \sigma_{,p}(x, \nu(t))\, d\mathscr{H}^{n-1}(t)\, dt \\
&= \int_0^T \int_{\Gamma(t)} (\nabla\eta(t) - \nabla_{\Gamma(t)}\eta(t)) \cdot \sigma_{,p}(x, \nu(t))\, d\mathscr{H}^{n-1}(t)\, dt \\
&\quad + \int_0^T \int_{\Gamma(t)} \eta(t)\, \kappa(t)\, (\sigma_{,p}(x, \nu(t)) \cdot \nu(t))\, d\mathscr{H}^{n-1}(t)\, dt,
\end{aligned}$$

where $\kappa(t) = \nabla_{\Gamma(t)} \cdot \nu(t)$ is the mean curvature. Applying the divergence theorem on manifolds yields

$$\begin{aligned}
&\int_0^T \int_{\Gamma(t)} \nabla_{\Gamma(t)}\eta(t) \cdot \sigma_{,p}(x, \nu(t))\, d\mathscr{H}^{n-1}(t)\, dt + \int_0^T \int_{\Gamma(t)} \eta(t)\ \nabla_{\Gamma(t)} \cdot \sigma_{,p}(x, \nu(t))\, d\mathscr{H}^{n-1}(t)\, dt \\
&= \int_0^T \int_{\Gamma(t)} \nabla_{\Gamma(t)} \cdot (\eta(t)\, \sigma_{,p}(x, \nu(t)))\, d\mathscr{H}^{n-1}(t)\, dt \\
&= \int_0^T \int_{\Gamma(t)} \kappa(t)\, \eta(t)\, (\sigma_{,p}(x, \nu(t)) \cdot \nu(t))\, d\mathscr{H}^{n-1}(t)\, dt.
\end{aligned}$$

We infer

$$\begin{aligned}
&\int_0^T \int_{\Gamma(t)} (\sigma(x, \nu(t)) \nabla\cdot\xi(t) - \nu(t) \cdot \nabla\, \xi(t) \sigma_{,p}(x, \nu(t)))\, d\mathscr{H}^{n-1}(t)\, dt \\
&\quad = \int_0^T \int_{\Gamma(t)} \eta(t)\ \nabla_{\Gamma(t)} \cdot \sigma_{,p}(x, \nu(t))\, d\mathscr{H}^{n-1}(t)\, dt.
\end{aligned}$$

Since $\eta \in C_c^1(\Omega_T)$ was arbitrary, we end up with

$$\sigma_{,x}(x, \nu(t)) \cdot \nu(t) + \nabla_{\Gamma(t)} \cdot \sigma_{,p}(x, \nu(t)) = u(t)$$

on $\Gamma(t)$ $\mathscr{H}^{n-1}$-a.e. for a.e. $t \in (0, T)$.

To (ii): We choose arbitrary functions $\xi \in C^1(\overline{\Omega}_T; \mathbb{R}^n)$ with $\xi(t) \cdot \nu_\Omega(t) = 0$ on $\partial\Omega$ for a.e. $t \in (0, T)$ and an orthonormal basis $\tau_1(t) = \tau_\Gamma(t)$, $\tau_2(t)$, …, $\tau_{n-1}(t)$ of the tangent space $T\Gamma(t)$, where $\tau_\Gamma(t)$ is the outer unit normal of $\partial\Gamma(t)$. Then, using the Einstein sum convention, we may express ξ in the form $\xi = \eta_\nu \nu + \eta_{\tau_j}\tau_j$. Applying the divergence

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theorem on manifolds leads to

$$\int_0^T \int_{\Gamma(t)} \sigma(x, v(t))\nabla\cdot\big(\eta_{\tau_j}(t)\tau_j(t)\big)\, d\mathscr{H}^{n-1}(t)\, dt$$
$$= \int_0^T \int_{\partial\Gamma(t)} \sigma(x, v(t))\eta_{\tau_\Gamma}(t)\, d\mathscr{H}^{n-2}(t)$$
$$- \int_0^T \int_{\Gamma(t)} \nabla_{\Gamma(t)}\sigma(x, v(t)) \cdot \eta_{\tau_j}(t)\tau_j(t)\, d\mathscr{H}^{n-1}(t)\, dt$$
$$+ \int_0^T \int_{\Gamma(t)} \sigma(x, v(t))\eta_{\tau_j}(t)v(t)\nabla\tau_j(t)v(t)\, d\mathscr{H}^{n-1}(t)\ dt.$$

Since $(\nabla(\eta_{\tau_j}\tau_j))^T v = -(\nabla v)^T(\eta_{\tau_j}\tau_j)$, we have

$$\int_0^T \int_{\Gamma(t)} v(t)\cdot\nabla(\eta_{\tau_j}(t)\tau_j(t))\sigma_{,p}(x, v(t))\, d\mathscr{H}^{n-1}(t)\, dt$$
$$= -\int_0^T \int_{\Gamma(t)} \big(\eta_{\tau_j}(t)\tau_j(t)\big)\cdot\nabla v(t)\sigma_{,p}(x, v(t))\, d\mathscr{H}^{n-1}(t)\ dt.$$

Thus, we get for (1.10) the following representation:

$$\int_0^T \int_{\Gamma(t)} (\sigma(x, v(t))\nabla\cdot\xi(t) + \sigma_{,x}(x, v(t))\cdot\xi(t)$$
$$- v(t)\cdot\nabla\xi(t)\,\sigma_{,p}(x, v(t)))d\mathscr{H}^{n-1}(t)\, dt - \int_0^T \int_{\Gamma(t)} u(t)\,\xi(t)\cdot v(t)\, d\mathscr{H}^{n-1}(t)\, dt$$
$$= \int_0^T \int_{\partial\Gamma(t)} (-\eta_v(t)\sigma_{,p}(x, v(t))\cdot\tau_\Gamma(t) + \sigma(x, v(t))\ \eta_{\tau_\Gamma}(t))\, d\mathscr{H}^{n-2}(t)\, dt$$
$$+ \int_0^T \int_{\Gamma(t)} \eta_v(t)\nabla_{\Gamma(t)}\cdot\sigma_{,p}(x, v(t))\, d\mathscr{H}^{n-1}(t)\, dt$$
$$- \int_0^T \int_{\Gamma(t)} (\nabla_{\Gamma(t)}\sigma(x, v(t)) - \nabla v(t)\sigma_{,p}(x, v(t)))\cdot(\eta_{\tau_j}(t)\tau_j(t))\, d\mathscr{H}^{n-1}(t)$$
$$+ \int_0^T \int_{\Gamma(t)} \sigma(x, v(t))\eta_{\tau_j}(t)v(t)\nabla\tau_j(t)v(t)\, d\mathscr{H}^{n-1}(t)\, dt$$
$$+ \int_0^T \int_{\Gamma(t)} \sigma_{,x}(x, v(t))\cdot\xi(t)\, d\mathscr{H}^{n-1}(t)\, dt - \int_0^T \int_{\Gamma(t)} u(t)\,\eta_v(t)d\mathscr{H}^{n-1}(t)\, dt = 0.$$

Since

$$\int_0^T \int_{\partial\Gamma(t)} (\sigma(x, v(t))\ \eta_{\tau_\Gamma}(t) - \eta_v(t)\,\sigma_{,p}(x, v(t))\cdot\tau_\Gamma(t))\, d\mathscr{H}^{n-2}(t)\ dt$$
$$= \int_0^T \int_{\partial\Gamma(t)} \xi(t)((\sigma_{,p}(x, v(t))\cdot v(t))\tau_\Gamma(t) - v(t)(\sigma_{,p}(x, v(t))\cdot\tau_\Gamma(t)))\, d\mathscr{H}^{n-2}(t)\, dt,$$

we obtain by choosing suitable variations in the neighbourhood of points of $\partial\Gamma$

$$(\sigma_{,p}(x, v(t))\cdot v(t))\tau_\Gamma(t) - (\sigma_{,p}(x, v(t))\cdot\tau_\Gamma(t))\, v(t) = l(t)\, v_\Omega(t)$$

with

$$l(t) = |(\sigma_{,p}(x, \nu(t)) \cdot \nu(t))\tau_\Gamma(t) - (\sigma_{,p}(x, \nu(t)) \cdot \tau_\Gamma(t))\,\nu(t)|$$

on $\Gamma(t)$ $\mathscr{H}^{n-1}$-a.e. for a.e. $t \in (0, T)$. It follows

$$l\,\nu_\Omega \cdot \tau_\Gamma = \sigma_{,p}(x, \nu) \cdot \nu, \qquad l\,\nu_\Omega \cdot \nu = -\sigma_{,p}(x, \nu) \cdot \tau_\Gamma, \qquad \nu_\Omega \cdot \tau_j = 0 \quad \text{for } j \in \{2, \ldots, n-1\}$$

on $\Gamma(t)$ $\mathscr{H}^{n-1}$-a.e. for a.e. $t \in (0, T)$. This shows

$$\begin{aligned}\sigma_{,p}(x, \nu) \cdot \nu_\Omega &= (\sigma_{,p}(x, \nu) \cdot \nu)(\nu \cdot \nu_\Omega) + (\sigma_{,p}(x, \nu) \cdot \tau_j)\,(\tau_j \cdot \nu_\Omega)\\ &= (-(\sigma_{,p}(x, \nu) \cdot \nu)(\sigma_{,p}(x, \nu) \cdot \tau_\Gamma) + (\sigma_{,p}(x, \nu) \cdot \tau_\Gamma)\,(\sigma_{,p}(x, \nu) \cdot \nu))/l\\ &= 0\end{aligned}$$

on $\Gamma(t)$ $\mathscr{H}^{n-1}$-a.e. for a.e. $t \in (0, T)$. □

We remark that the dependence of σ on x has no influence on the boundary condition at intersections of the interface with the outer boundary.

4 The discretisation

The proofs of the existence theorems are based on minimisation problems, cf. [19a, 24, 26]. For the degenerate problem, we choose an energy functional, which is similar to [24]. However, for the non-degenerate problem, we introduce an energy functional, which differs from [19a, 26].

Let $(0, T)$ be the time interval of interest with discretisation fineness $h = \frac{T}{M}$, $M \in \mathbb{N}$. For f and u_D in Theorems 1.1 and 1.2, respectively, we choose discretisations f^h and u_D^h such that f^h and u_D^h are constant on the intervals $((k-1)h, kh], k = 1, \ldots, M$, and $f^h \to f$ in $L^2(\Omega_T)$ and $u_D^h \to u_D$ in $L^2(0, T; H^1(\Omega))$ as $h \to 0$. We also may assume that the boundary values of u_D are extended in Ω such that $\triangle u_D(t) = 0$ for a.e. $t \in (0, T)$.

Now, we construct iteratively time discrete solutions χ^h and u^h for time steps $h > 0$. To this end, we consider the following two minimisation problems in each time step:

Degenerate Stefan problem

Minimise $\mathscr{F}_t^h : BV(\Omega; \{0, 1\}) \to \mathbb{R}$,

$$\mathscr{F}_t^h(\chi) = \int_\Omega |\nabla\chi|_\sigma + \frac{h}{2}\int_\Omega \nabla v \nabla(v - u_D^h(t)) - \int_\Omega \chi u_D^h(t), \tag{4.1}$$

where $v \in H^1(\Omega)$ is the weak solution of

$$\chi - \chi^h(t-h) = h(\triangle v + f^h(t)), \qquad v = u_D^h(t)|_{\partial\Omega}. \tag{4.2}$$

Note that (4.2) is the implicit time discretisation of (1.3) for $\chi = \chi^h(t)$ and $v = u^h(t)$.

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Non-degenerate Stefan problem

Minimise $\mathscr{E}_t^h : BV(\Omega;\{0,1\}) \to \mathbb{R}$,

$$\mathscr{E}_t^h(\chi) = \int_\Omega |\nabla\chi|_\sigma + \frac{h}{2}\int_\Omega \nabla v \nabla(v - u_D^h(t)) + \frac{1}{2}\int_\Omega v^2 - \int_\Omega (v+\chi)u_D^h(t), \tag{4.3}$$

where $v \in H^1(\Omega)$ is the weak solution of

$$v + \chi - \chi^h(t-h) - u^h(t-h) = h(\triangle v + f^h(t)), \qquad v = u_D^h(t)|_{\partial\Omega}. \tag{4.4}$$

Note that (4.4) is the implicit time discretisation of (1.1) for $\chi = \chi^h(t)$ and $v = u^h(t)$.

Lemma 4.1 *There exists a minimiser $\chi^h \in BV(\Omega;\{0,1\})$ of $\mathscr{F}_t^h$.*

Proof Let $\{\chi_k\}_{k\in\mathbb{N}}$, $\chi_k \in BV(\Omega;\{0,1\})$, be a minimising sequence and $\{v_k\}_{k\in\mathbb{N}}$ be the corresponding sequence of weak solutions of (4.2). In view of $\triangle u_D^h = 0$, we estimate

$$\mathscr{F}_t^h(\chi_k) \geqslant \int_\Omega |\nabla\chi_k|_\sigma + \frac{h}{2}\int_\Omega \left|\nabla\left(v_k - u_D^h(t)\right)\right|^2 - \int_\Omega \left|u_D^h(t)\right|.$$

The uniform boundedness of $\{\chi_k\}_{\{k\in\mathbb{N}\}}$ in $L^2(\Omega;\{0,1\})$ and the $BV(\Omega)$-compactness imply that there exists a subsequence (still denoted by $\{\chi_k\}_{k\in\mathbb{N}}$) such that

$$\chi_k \to \hat\chi \quad \text{in} \quad L^2(\Omega) \qquad \text{and} \qquad \hat\chi \in BV(\Omega;\{0,1\}).$$

In addition, by the uniform boundedness of $\{v_k\}_{k\in\mathbb{N}}$ in $H^1(\Omega)$ and by (4.2) we derive

$$v_k \to \hat v \qquad \text{in} \quad H^1(\Omega),$$

where $\hat v$ is the weak solution of (4.2) for $\chi = \hat\chi$. From this property and the lower semi-continuity of $\int_\Omega |\nabla\chi_k|_\sigma$, we conclude that $\hat\chi$ is a minimiser of $\mathscr{F}_t^h$. □

Lemma 4.2 *There exists a minimiser $\chi^h \in BV(\Omega;\{0,1\})$ of $\mathscr{E}_t^h$.*

Proof Let $\{\chi_k\}_{k\in\mathbb{N}}$, $\chi_k \in BV(\Omega;\{0,1\})$, be a minimising sequence and $\{v_k\}_{k\in\mathbb{N}}$ be the corresponding sequence of weak solutions of (4.4). Due to $\triangle u_D^h = 0$, we have

$$\mathscr{F}_t^h(\chi_k) \geqslant \int_\Omega |\nabla\chi_k|_\sigma + \frac{h}{2}\int_\Omega |\nabla\left(v_k - u_D^h(t)\right)|^2 + \frac{1}{2}\int_\Omega v_k^2 - \int_\Omega (|v_k|+1)\left|u_D^h(t)\right|.$$

Since $\{\chi_k\}_{\{k\in\mathbb{N}\}}$ is uniformly bounded in $L^2(\Omega;\{0,1\})$ and in $BV(\Omega)$, there exists a subsequence (still denoted by $\{\chi_k\}_{k\in\mathbb{N}}$) with

$$\chi_k \to \hat\chi \quad \text{in} \quad L^2(\Omega) \qquad \text{and} \qquad \hat\chi \in BV(\Omega;\{0,1\}).$$

Moreover, the uniform boundedness of $\{v_k\}_{k\in\mathbb{N}}$ in $H^1(\Omega)$ implies that there exists a subsequence (still denoted by $\{\chi_k\}_{k\in\mathbb{N}}$) with

$$v_k \rightharpoonup \hat v \quad \text{in} \quad H^1(\Omega).$$

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Since

$$\int_\Omega (\chi_k - \chi_l)(v_k - v_l) = -\int_\Omega (v_k - v_l)^2 - h\int_\Omega |\nabla(v_k - v_l)|^2 \to 0, \quad \text{as} \quad k, l \to \infty,$$

we conclude

$$v_k \to \hat{v} \quad \text{in} \quad H^1(\Omega),$$

where $\hat{v}$ is a weak solution of (4.4) for $\chi = \hat{\chi}$. This property and the lower semi-continuity of $\int_\Omega |\nabla\chi|_\sigma$ assures that $\hat{\chi}$ is a minimiser of $\mathscr{E}_t^h$. □

From the minimisation procedure, we obtain iteratively χ^h and u^h (u^h is the weak solution of (4.2) and (4.4), respectively, for $\chi = \chi^h$) at the time steps $t = kh$, $k = 0, \ldots, M$. We extend χ^h and u^h by $\chi^h(t) = \chi^h(kh)$ and $u^h(t) = u^h(kh)$ for $t \in ((k-1)h, kh]$, $k = 1, \ldots, M$, and abbreviate $\partial_t^{-h} g(t) := \frac{g(t)-g(t-h)}{h}$ for a function g.

Next, we establish weak formulations of the Euler–Lagrange equations for $\mathscr{F}_t^h$ and $\mathscr{E}_t^h$, which are connected to (1.8) and (1.10), respectively. To determine the first variation of the spatially inhomogeneous and anisotropic interfacial energy, we fall back on the following variational property, cf. [18]

Lemma 4.3 *Let $\Phi : [-\tau_0, \tau_0] \times G \to G$ be a family of diffeomorphisms of G onto itself with $G = \Omega$ or $G = \overline{\Omega}$. If $g \in BV(\Omega; \{0,1\})$ then*

$$\begin{aligned}
&\frac{d}{d\tau}\int_\Omega |\nabla g(\Phi^{-1}(\tau,\cdot))|_\sigma \Big|_{\tau=0} \\
&\quad = \int_\Omega \Bigg(\sigma(\Phi(\tau,x), \Psi(\tau,x)\nu_g(x))\, tr\left(\frac{\partial \Phi_{,\tau}(\tau,x)}{\partial x}\right) + \sigma_{,x}(\Phi(\tau,x), \Psi(\tau,x)\nu_g(x)) \cdot \frac{d}{d\tau}\Phi(\tau,x) \\
&\qquad + \sigma_{,p}(\Phi(\tau,x), \Psi(\tau,x)\nu_g(x)) \cdot \frac{d}{d\tau}(\Phi_{,x}(\tau,x))^{-T}\nu_g(x) \Bigg)\Bigg|_{\tau=0} |\nabla g(x)|,
\end{aligned}$$

where tr denotes the trace, $\Psi(\tau,x) = |\det \Phi_{,x}(\tau,x)|(\Phi_{,x}(\tau,x))^{-T}$ and $\nu_g = -\frac{\nabla g}{|\nabla g|}$ for $|\nabla g|$-a.e. $x \in \Omega$.

Note that if M is an $n \times n$–matrix then $Id + \eta M$, $\eta \in \mathbb{R}$, is invertible for $|\eta|$ sufficiently small. In addition,

$$\det(Id + \eta M) = 1 + \eta \operatorname{tr}(M) + \tfrac{1}{2}\eta^2((\operatorname{tr} M)^2 - \operatorname{tr}(M^2)) + O(\eta^3),$$

and

$$(Id + \eta M)^{-1} = Id - \eta M + \eta^2 M^2 + O(\eta^3).$$

Theorem 4.4 *Let Ω be a domain with Lipschitz boundary. Further, let Assumption A 2.1 be satisfied. If $\chi^h(t) \in BV(\Omega; \{0,1\})$ is a minimiser of $\mathscr{F}_t^h$ or $\mathscr{E}_t^h$ and $v = u^h(t)$ is the corresponding weak solution of (4.2) and (4.4), respectively, then*

$$\begin{aligned}
&\int_\Omega (\sigma(\cdot, \nu^h(t,\cdot))\nabla\cdot\xi(\cdot) + \sigma_{,x}(\cdot, \nu^h(t,\cdot))\cdot\xi(\cdot) - \nu^h(t,\cdot)\cdot\nabla\xi(\cdot)\,\sigma_{,p}(\cdot,\nu^h(t,\cdot)))|\nabla\chi^h(t,\cdot)| \\
&\quad - \int_\Omega u^h(t,\cdot)\,\xi(\cdot)\cdot\nu^h(t,\cdot)|\nabla\chi^h(t,\cdot)| = 0 \qquad (4.5)
\end{aligned}$$

for all $\xi \in C_c^1(\Omega, \mathbb{R}^n)$, where $\nu^h(t) = -\frac{\nabla\chi^h(t)}{|\nabla\chi^h(t)|}$.

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If, in addition, Ω is a bounded domain with C^1-boundary then (4.5) even holds for all $\xi \in C^\infty(\overline{\Omega};\mathbb{R}^n)$ with $\xi \cdot \nu_\Omega = 0$ on $\partial\Omega$, where ν_Ω is the outer unit normal of $\partial\Omega$.

Proof Let $\xi \in C_c^1(\Omega;\mathbb{R}^n)$ and consider

$$\Phi(x\,;\tau) = x + \tau\,\xi(x) \tag{4.6}$$

for $x \in \Omega$ and $\tau \in \mathbb{R}$. Then, $\Phi(\cdot\,;\tau)$ is a diffeomorphism of Ω onto itself if $|\tau|$ is sufficiently small. Via the above diffeomorphism, we define

$$\chi_\tau^h(t,x) = \chi^h(t,\Phi^{-1}(x\,;\tau)).$$

Furthermore,

$$\nu_\tau^h(t,x) = -\frac{\nabla\chi_\tau^h(t,x)}{|\nabla\chi_\tau^h(t,x)|}.$$

We denote the weak solution of (4.2) and (4.4) for $\chi = \chi_\tau^h(t)$ by $u_\tau^h(t)$. Since $\chi^h(t) = \chi_\tau^h(t)|_{\tau=0}$ is a minimiser of $\mathscr{F}_t^h$ and $\mathscr{E}_t^h$, respectively, we obtain

$$0 = \frac{d}{d\tau}\mathscr{F}_t^h\big(\chi_\tau^h(t)\big)\Big|_{\tau=0} \qquad \text{and} \qquad 0 = \frac{d}{d\tau}\mathscr{E}_t^h\big(\chi_\tau^h(t)\big)\Big|_{\tau=0}, \quad \text{respectively.}$$

Next, we compute the above derivatives. Here, we take advantage from the following properties of Φ:

(i) $|\det \Phi_{,x}(x\,;0)| = 1$,
(ii) $\Phi_{,x}^{-1}(\Phi(x\,;\tau)\,;\tau) = (\Phi_{,x}(x\,;\tau))^{-1}$,
(iii) $\frac{d}{d\tau}(\Phi_{,x}(x\,;\tau))^{-1}|_{\tau=0} = -\nabla\xi(x)$.

Lemma 4.3 gives

$$\begin{aligned}
&\frac{d}{d\tau}\int_\Omega \sigma\left(z, -\frac{\nabla_z\chi^h(t,\Phi^{-1}(z\,;\tau))}{|\nabla_z\chi^h(t,\Phi^{-1}(z\,;\tau))|}\right)|\nabla_z\chi^h(t,\Phi^{-1}(z\,;\tau))|\,\Bigg|_{\tau=0}\\
&\quad= \int_\Omega (\sigma(x,\nu^h(t))\nabla\cdot\xi + \sigma_{,x}(x,\nu^h(t))\cdot\xi - \nu^h(t)\cdot\nabla\xi\,\sigma_{,p}(x,\nu^h(t)))|\nabla\chi^h(t)|.
\end{aligned}$$

We abbreviate $w_\tau^h(t) = u_\tau^h(t) - u_D^h(t)$, $w^h(t) = u^h(t) - u_D^h(t)$ and utilise $\triangle u_D^h(t) = 0$. Hence, the remaining parts of $\mathscr{F}_t^h$ at $\chi = \chi_\tau^h$ can be re-written as

$$\begin{aligned}
&\frac{h}{2}\int_\Omega \nabla u_\tau^h(t)\nabla\big(u_\tau^h(t) - u_D^h(t)\big) - \int_\Omega \chi_\tau^h(t)u_D^h(t)\\
&\quad= \frac{h}{2}\int_\Omega |\nabla w_\tau^h(t)|^2 - \int_\Omega \chi_\tau^h(t)u_D^h(t)\\
&\quad= \frac{h}{2}\int_\Omega |\nabla\big(w_\tau^h(t) - w^h(t)\big)|^2 + h\int_\Omega \nabla\big(w_\tau^h(t) - w^h(t)\big)\nabla w^h(t) + \frac{h}{2}\int_\Omega |\nabla w^h(t)|^2 - \int_\Omega \chi_\tau^h(t)u_D^h(t)
\end{aligned}$$

$$= \frac{h}{2}\int_\Omega |\nabla(w^h_\tau(t) - w^h(t))|^2 - \int_\Omega (\chi^h_\tau(t) - \chi^h(t))w^h(t) + \frac{h}{2}\int_\Omega |\nabla w^h(t)|^2 - \int_\Omega \chi^h_\tau(t)u^h_D(t)$$
$$= \frac{h}{2}\int_\Omega |\nabla(w^h_\tau(t) - w^h(t))|^2 - \int_\Omega \chi^h_\tau(t)u^h(t) + \int_\Omega \chi^h(t)w^h(t) + \frac{h}{2}\int_\Omega |\nabla w^h(t)|^2. \tag{4.7}$$

Next, we compute the τ-derivative of the first term in (4.7).
In the following, we denote by $C > 0$ some constant, which may differ from estimate to estimate. Note that

$$\begin{aligned}
&\frac{h}{\tau}\int_\Omega \left|\nabla\left(w^h_\tau(t,z) - w^h(t,z)\right)\right|^2 dz \\
&\quad = -\int_\Omega \left(\frac{\chi^h(t,\Phi^{-1}(z;\tau)) - \chi^h(t,z)}{\sqrt{\tau}}\right)\left(\frac{w^h_\tau(t,z) - w^h(t,z)}{\sqrt{\tau}}\right) dz \\
&\quad \leqslant C_\delta \int_\Omega \left(\frac{\chi^h(t,\Phi^{-1}(z;\tau)) - \chi^h(t,z)}{\sqrt{\tau}}\right)^2 + \delta\int_\Omega \left(\frac{w^h_\tau(t,z) - w^h(t,z)}{\sqrt{\tau}}\right)^2 dz
\end{aligned}$$

for any $\delta > 0$ and some $C_\delta > 0$. In consequence, by Poincaré's inequality

$$\frac{1}{\tau}\int_\Omega \left|\nabla\left(w^h_\tau(t,z) - w^h(t,z)\right)\right|^2 dz \leqslant C\int_\Omega \left(\frac{\chi^h(t,\Phi^{-1}(z;\tau)) - \chi^h(t,z)}{\sqrt{\tau}}\right)^2 dz \tag{4.8}$$

for some constant $C > 0$.

Now, we show that the term on the right-hand side of (4.8) is uniformly bounded as $\tau \to 0$. Denoting $\Omega_0(t) = \{x \in \Omega : \chi^h(t,x) = 0\}$ and $\Omega_1(t) = \{x \in \Omega : \chi^h(t,x) = 1\}$, we estimate

$$\begin{aligned}
&\int_\Omega (\chi^h(t,\Phi^{-1}(z;\tau)) - \chi^h(t,z))^2 dz \\
&\quad = \int_{\Omega_0(t)} |\chi^h(t,\Phi^{-1}(z;\tau)) - \chi^h(t,z)| dz + \int_{\Omega_1(t)} |\chi^h(t,\Phi^{-1}(z;\tau)) - \chi^h(t,z)| dz \\
&\quad \leqslant |\Phi^{-1}(\Omega_0(t);\tau))\backslash\Omega_0(t)| + |\Phi^{-1}(\Omega_1(t);\tau)\backslash\Omega_1(t)| \\
&\quad \leqslant 2\int_\Omega |\nabla\chi^h(t,z)| \max_{z\in\overline{\Omega}} |\Phi^{-1}(z;\tau) - \Phi^{-1}(z;0)| \\
&\quad \leqslant 2\int_\Omega |\nabla\chi^h(t,z)| \max_{z\in\overline{\Omega}} |x - \Phi(z;\tau)| \\
&\quad \leqslant 2\int_\Omega |\nabla\chi^h(t,z)|\tau \max_{z\in\overline{\Omega}} |\xi(z)| \\
&\quad \leqslant C\tau
\end{aligned}$$

for some constant $C > 0$ (independent of t). Hence,

$$\frac{1}{\tau}\int_\Omega |\nabla\left(w^h_\tau(t,z) - w^h(t,z)\right)|^2 dz \leqslant C.$$

Furthermore, for any $q \in (2, 2^*]$ with $2^* = \frac{2n}{n-2}$ if $n \geqslant 3$ or any $q \in (2,\infty)$ if $n = 2$, we

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obtain

$$
\begin{aligned}
&\frac{h}{\tau}\int_\Omega |\nabla\big(w^h_\tau(t,z)-w^h(t,z)\big)|^2 dz\\
&\quad\leqslant \int_\Omega \Big|\frac{\chi^h(t,\Phi^{-1}(z;\tau))-\chi^h(t,z)}{\sqrt{\tau}}\Big|\Big|\frac{w^h_\tau(t,z)-w^h(t,z)}{\sqrt{\tau}}\Big| dz\\
&\quad\leqslant \Big\|\frac{\chi^h(t,\Phi^{-1}(z;\tau))-\chi^h(t,z)}{\sqrt{\tau}}\Big\|_{L^{\frac{q}{q-1}}(\Omega)}\Big\|\frac{w^h_\tau(t,z)-w^h(t,z)}{\sqrt{\tau}}\Big\|_{L^q(\Omega)}\\
&\quad\leqslant C\frac{1}{\sqrt{\tau}}|\tau|^{\frac{q-1}{q}}\Big\|\nabla\Big(\frac{w^h_\tau(t,z)-w^h(t,z)}{\sqrt{\tau}}\Big)\Big\|_{L^2(\Omega)}\\
&\quad\to 0 \qquad \text{for } \tau\to 0.
\end{aligned}
$$

In consequence,

$$
\frac{d}{d\tau}h\int_\Omega \big|\nabla\big(w^h_\tau(t,z)-w^h(t,z)\big)\big|^2 dz\Big|_{\tau=0} = \lim_{\tau\to 0}\frac{1}{\tau}h\int_\Omega \big|\nabla\big(w^h_\tau(t,z)-w^h(t,z)\big)\big|^2 dz = 0.
$$

In addition,

$$
\begin{aligned}
\frac{d}{d\tau}\int_\Omega \chi^h_\tau(t)u^h(t)dz\Big|_{\tau=0} &= \int_\Omega \chi^h(t,x)u^h(t,x)\nabla\cdot\xi(x)dx + \int_\Omega \chi^h(t,x)\nabla u^h(t,x)\cdot\xi(x)\,dx\\
&= \int_\Omega u^h(t)\,\xi(x)\cdot\nu^h(t)|\nabla\chi^h(t)|\,. \qquad (4.9)
\end{aligned}
$$

This shows the claim for $\mathscr{F}^h_t$ since the remaining terms of (4.7) do not depend on τ. To verify the claim for $\mathscr{E}^h_t$, we observe

$$
\begin{aligned}
&\frac{h}{2}\int_\Omega \nabla u^h_\tau(t)\nabla\big(u^h_\tau(t)-u^h_D(t)\big) + \frac{1}{2}\int_\Omega \big(u^h_\tau(t)\big)^2 - \int_\Omega \big(u^h_\tau(t)+\chi^h_\tau(t)\big)u^h_D(t)\\
&= \frac{h}{2}\int_\Omega |\nabla w^h_\tau(t)|^2 + \frac{1}{2}\int_\Omega \big(w^h_\tau(t)\big)^2 - \frac{1}{2}\int_\Omega \big(u^h_D(t)\big)^2 - \int_\Omega \chi^h_\tau(t)u^h_D(t)\\
&= \frac{h}{2}\int_\Omega |\nabla\big(w^h_\tau(t)-w^h(t)\big)|^2 + h\int_\Omega \nabla\big(w^h_\tau(t)-w^h(t)\big)\nabla w^h(t) + \frac{h}{2}\int_\Omega |\nabla w^h(t)|^2 + \frac{1}{2}\int_\Omega \big(w^h_\tau(t)\big)^2\\
&\quad - \frac{1}{2}\int_\Omega \big(u^h_D(t)\big)^2 - \int_\Omega \chi^h_\tau(t)u^h_D(t)\\
&= \frac{h}{2}\int_\Omega |\nabla\big(w^h_\tau(t)-w^h(t)\big)|^2 - \int_\Omega \big(w^h_\tau(t)-w^h(t)\big)w^h(t) - \int_\Omega \big(\chi^h_\tau(t)-\chi^h(t)\big)w^h(t)\\
&\quad + \frac{1}{2}\int_\Omega \big(w^h_\tau(t)\big)^2 - \frac{1}{2}\int_\Omega \big(u^h_D(t)\big)^2 + \frac{h}{2}\int_\Omega |\nabla w^h(t)|^2 - \int_\Omega \chi^h_\tau(t)u^h_D(t)
\end{aligned}
$$

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$$= \frac{h}{2}\int_\Omega \left|\nabla\left(w_\tau^h(t) - w^h(t)\right)\right|^2 + \frac{1}{2}\int_\Omega \left(w_\tau^h(t) - w^h(t)\right)^2 + \frac{1}{2}\int_\Omega (w^h(t))^2 - \int_\Omega \chi_\tau^h(t)u^h(t)$$
$$+ \int_\Omega \chi^h(t)w^h(t) - \frac{1}{2}\int_\Omega \left(u_D^h(t)\right)^2 + \frac{h}{2}\int_\Omega |\nabla w^h(t)|^2. \tag{4.10}$$

Since

$$h\int_\Omega \left|\nabla\left(w_\tau^h(t,z) - w^h(t,z)\right)\right|^2 dz + \int_\Omega \left(w_\tau^h(t,z) - w^h(t,z)\right)^2 dz$$
$$= -\int_\Omega \left(\chi^h(t,\Phi^{-1}(z;\tau)) - \chi^h(t,z)\right)\left(w_\tau^h(t,z) - w^h(t,z)\right)dz,$$

we may use the same argumentation as before to derive

$$\frac{d}{d\tau}\left(h\int_\Omega \left|\nabla\left(w_\tau^h(t,z) - w^h(t,z)\right)\right|^2 dz + \int_\Omega \left|\left(w_\tau^h(t,z) - w^h(t,z)\right)\right|^2 dz\right)\Bigg|_{\tau=0} = 0.$$

Due to (4.9), the assertion also follows for $\mathscr{E}_t^h$ since the remaining terms of (4.10) do not depend on τ.

If Ω is a bounded domain with C^1-boundary, we may choose a family of diffeomorphisms $\Phi(\tau,\cdot)$, $\tau \in [-\tau_0, \tau_0]$, of $\overline{\Omega}$ onto itself given by the initial value problem

$$\Phi(0,x) = x \qquad \text{and} \qquad \Phi_{,\tau}(\tau,x) = \xi(\Phi(\tau,x)), \qquad x \in \overline{\Omega},$$

with $\xi \in C^1(\overline{\Omega};\mathbb{R}^n)$ and $\xi \cdot \nu_\Omega = 0$ on $\partial\Omega$. Then, Φ also fulfils the above properties (i)–(iii) and $|\Phi(x;\tau) - \Phi(x;0)| \leqslant \tau \max_{x\in\overline{\Omega}} |\xi(x)|$. Thus,

$$\int_\Omega (\sigma(\cdot,\nu^h(t,\cdot))\nabla\cdot\xi(\cdot) + \sigma_{,x}(\cdot,\nu^h(t,\cdot))\cdot\xi(\cdot) - \nu^h(t,\cdot)\cdot\nabla\xi(\cdot)\,\sigma_{,p}(\cdot,\nu^h(t,\cdot)))|\nabla\chi^h(t,\cdot)|$$
$$- \int_\Omega u^h(t,\cdot)\,\xi(\cdot)\cdot\nu^h(t,\cdot)|\nabla\chi^h(t,\cdot)| = 0$$

for all $\xi \in C^1(\overline{\Omega};\mathbb{R}^n)$ with $\xi\cdot\nu_\Omega = 0$ on $\partial\Omega$, as required. □

5 Convergence to solutions

5.1 The degenerate case

We are going to establish compactness of the discrete solutions χ^h, $h > 0$, in $L^1(\Omega_T)$ similarly to [24].

Lemma 5.1 (Uniform bound) *There exists a constant $C > 0$ (depending only on $\int_\Omega |\nabla\chi(0)|_\sigma$, $||u_D||_{W^{1,1}(0,T;H^1(\Omega))}$, $||f||_{L^2(\Omega_T)}$) such that*

$$\operatorname{ess\,sup}_{t\in(0,T)} \int_\Omega |\nabla\chi^h(t)|_\sigma \;+\; \int_{\Omega_T} |\nabla u^h(t)|^2 \leqslant C. \tag{5.1}$$

Proof We first like to mention that for weak solutions $\tilde{u}^h(t)$, $h > 0$, of $-\triangle v = f^h(t)$ with $v = u_D^h(t)|_{\partial\Omega}$ it holds

$$\int_0^T ||\tilde{u}^h(t)||_{H^1(\Omega)}^2\,dt \leqslant D_1,$$

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where $D_1 > 0$ is some constant depending on $||u_D||_{W^{1,1}(0,T;H^1(\Omega))}$ and $||f||_{L^2(\Omega_T)}$. In view of $\mathscr{F}_t^h(\chi^h(t)) \leqslant \mathscr{F}_t^h(\chi^h(t-h))$, we obtain

$$\int_\Omega |\nabla\chi^h(t)|_\sigma + \frac{h}{2}\int_\Omega \nabla u^h(t)\nabla\big(u^h(t) - u_D^h(t)\big)$$
$$\leqslant \int_\Omega |\nabla\chi^h(t-h)|_\sigma + \frac{h}{2}\int_\Omega f^h(t)\big(\tilde{u}^h(t) - u_D^h(t)\big) + \int_\Omega (\chi^h(t) - \chi^h(t-h))u_D^h(t).$$

By Young's and Poincaré's inequality, we estimate

$$\int_\Omega |\nabla\chi^h(t)|_\sigma + hD_2\int_\Omega |\nabla u^h(t)|^2 \leqslant \int_\Omega |\nabla\chi^h(t-h)|_\sigma + hD_3||f^h(t)||^2_{L^2(\Omega)} + hD_3\,||u_D^h(t)||^2_{H^1(\Omega)}$$
$$+ h||\tilde{u}^h(t)||^2_{L^2(\Omega)} + \int_\Omega (\chi^h(t) - \chi^h(t-h))u_D^h(t) \tag{5.2}$$

with some constants $D_2, D_3 > 0$. Since

$$\int_0^{jh}\int_\Omega |\partial_t^{-h} u_D^h(t)| \leqslant \int_0^{jh}\int_\Omega |\partial_t u_D(t)|,$$

we obtain for $k = 1, 2, \ldots, j$, $j \leqslant M$,

$$\sum_{k=1}^{j}\int_\Omega (\chi^h(kh) - \chi^h((k-1)h))u_D^h(kh)$$
$$= -\int_h^{jh}\int_\Omega \partial_t^{-h} u_D^h(t)\chi^h(t-h) + \int_\Omega \chi^h(jh)\,u_D^h(jh) - \int_\Omega \chi^h(0)\,u_D^h(h)$$
$$\leqslant \int_h^{jh}\int_\Omega |\partial_t^{-h} u_D^h(t)| + 2\,||u_D||_{L^\infty(0,T;L^1(\Omega))}$$
$$\leqslant D_4||u_D||_{W^{1,1}(0,T;L^1(\Omega))},$$

where $D_4 > 0$ is some constant.

Now, we take inequality (5.2) iteratively for $t = kh$, $k \in \mathbb{N}$, and sum over $k = 1, 2, \ldots, j$, $j \leqslant M$, which leads to

$$\int_\Omega |\nabla\chi^h(jh)|_\sigma + D_2\int_{\Omega_{jh}} |\nabla u^h(t)|^2 \leqslant \int_\Omega |\nabla\chi(0)|_\sigma + D_3||f||^2_{L^2(\Omega_T)} + D_5\,||u_D||_{W^{1,1}(0,T;H^1(\Omega))} + D_6$$

for some constants $D_5 > 0$ and $D_6 > 0$. Hence, the assertion is obvious. □

The following lemma is used to control time differences of χ^h (see [24]).

Lemma 5.2 ([24]) *Let $\varphi \in BV(\Omega)$ with $||\varphi||_{L^\infty(\Omega)} \leqslant M$ for some constant $M > 0$. Then, there exist constants $C > 0$ and $\rho_0 > 0$ (depending only on Ω and M) such that for all $\rho \leqslant \rho_0$*

$$\int_\Omega |\varphi| \leqslant \rho\Big(\int_\Omega |\nabla\varphi| + C\,\mathscr{H}^{n-1}(\partial\Omega)\Big) + \frac{C}{\rho}||\varphi||_{H^{-1}(\Omega)}.$$

Lemma 5.3 (Compactness in $L^1(\Omega_T)$)

(i) (Compactness in space) The discrete solutions χ^h, $h > 0$, are bounded in $L^1(0, T; BV(\Omega))$.

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(ii) (Compactness in time, cf. [24])
The discrete solutions χ^h, $h > 0$, fulfil

$$\int_0^{T-\tau}\int_\Omega |\chi^h(\cdot+\tau)-\chi^h(\cdot)| \leqslant C\tau^{1/4}.$$

for some $C > 0$.

In consequence,

$$\chi^h \to \chi \qquad in\ L^1(\Omega_T) \tag{5.3}$$

for a subsequence as $h \to 0$.

Proof To (i): This property immediately follows from Lemma 5.1.
To (ii): Without loss of generality, we may assume $\tau = kh$ and $t = lh$. From (4.2) and Lemma 5.1, we infer

$$\begin{aligned}
||\chi^h(t+\tau)-\chi^h(t)||_{H^{-1}(\Omega)} &= \sup_{||g||_{H_0^1(\Omega)}=1}\left|\int_\Omega(\chi^h(t+\tau)-\chi^h(t))g\right| \\
&= \sup_{||g||_{H_0^1(\Omega)}=1}\left|\int_t^{t+\tau}\int_\Omega \frac{\chi^h(s)-\chi^h(s-h)}{h} g\, ds\right| \\
&\leqslant \int_t^{t+\tau}\left|\left|\frac{\chi^h(s)-\chi^h(s-h)}{h}\right|\right|_{H^{-1}(\Omega)} ds \\
&\leqslant \tau^{\frac{1}{2}}\left(\int_t^{t+\tau}\left(||u^h(s)||^2_{H^1(\Omega)}+||f^h(s)||^2_{L^2(\Omega)}\right)\right)^{\frac{1}{2}} \leqslant C\tau^{\frac{1}{2}}.
\end{aligned} \tag{5.4}$$

Choosing $\rho = \tau^{1/4}$ in Lemma 5.2 shows (ii).

We infer from (i) and (ii) that $\{\chi^h\}$ is relatively compact in $L^1(\Omega_T)$ (cf. [31, 32]), i.e. there exists a subsequence $\{\chi^{h_k}\}_{\{k\in\mathbb{N}\}}$ such that

$$\chi^{h_k} \to \chi \qquad \text{in} \quad L^1(\Omega_T).$$

□

5.2 The non-degenerate case

To pass to the continuous problem, we first establish *a priori* estimates for u^h and χ^h.

Lemma 5.4 (Uniform bound) *There exists a constant $C > 0$ (depending only on $\int_\Omega |u(0)|^2$, $\int_\Omega |\nabla\chi(0)|_\sigma$, $||u_D||_{H^1(0,T;H^1(\Omega))}$, $||f||_{L^2(\Omega_T)}$) such that*

$$\operatorname{ess\,sup}_{t\in(0,T)}\left(\int_\Omega((u^h(t))^2+|\nabla\chi^h(t)|)\right)+\int_{\Omega_T}|\nabla u^h(t)|^2 \leqslant C \tag{5.5}$$

and

$$\int_0^T ||\partial_t^{-h}(u^h(t)+\chi^h(t))||^2_{H^{-1}(\Omega)} \leqslant C. \tag{5.6}$$

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Proof Equation (4.4) yields

$$\frac{h}{2}\int_\Omega \left|\nabla\left(v-u_D^h(t)\right)\right|^2 = -\frac{1}{2}\int_\Omega (v+\chi-u^h(t-h)-\chi^h(t-h))\left(v-u_D^h(t)\right)+\frac{h}{2}\int_\Omega f^h(t)\left(v-u_D^h(t)\right). \tag{5.7}$$

Utilising (5.7), $\mathscr{E}_t^h$ can be re-written in the following form:

$$\begin{aligned}
\mathscr{E}_t^h(\chi) &= \int_\Omega |\nabla\chi|_\sigma + \frac{1}{2}\int_\Omega (u^h(t-h)+\chi^h(t-h)+hf^h(t))\left(v-u_D^h(t)\right)\\
&\quad -\frac{1}{2}\int_\Omega (v+\chi)\left(v-u_D^h(t)\right)+\frac{1}{2}\int_\Omega v^2 - \int_\Omega (v+\chi)\,u_D^h(t)\\
&= \int_\Omega |\nabla\chi|_\sigma + \frac{1}{2}\int_\Omega (u^h(t-h)+\chi^h(t-h)+hf^h(t))\left(v-u_D^h(t)\right)\\
&\quad -\frac{1}{2}\int_\Omega v u_D^h(t) - \frac{1}{2}\int_\Omega \chi\left(v+u_D^h(t)\right)
\end{aligned}$$

Note that

$$\begin{aligned}
\mathscr{E}_t^h(\chi^h(t-h)) &= \int_\Omega |\nabla\chi^h(t-h)|_\sigma - \frac{1}{2}(\hat{u}^h(t)-u^h(t-h))(\hat{u}^h(t)-u_D^h(t))\\
&\quad +\frac{h}{2}\int_\Omega f^h(t)\left(\hat{u}^h(t)-u_D^h(t)\right)+\frac{1}{2}\int_\Omega (\hat{u}^h(t))^2 - \int_\Omega (\hat{u}^h(t)+\chi^h(t-h))u_D^h(t)\\
&= \int_\Omega |\nabla\chi^h(t-h)|_\sigma + \frac{1}{2}\int_\Omega (u^h(t-h)+hf^h(t))\left(\hat{u}^h(t)-u_D^h(t)\right)\\
&\quad -\frac{1}{2}\int_\Omega (\hat{u}^h(t)+\chi^h(t-h))u_D^h(t) - \frac{1}{2}\int_\Omega \chi^h(t-h)u_D^h(t),
\end{aligned} \tag{5.8}$$

where $\hat{u}^h(t)$ is the weak solution of

$$v-u^h(t-h) = h\,(\triangle v + f^h(t)), \qquad v = u_D^h(t)|_{\partial\Omega}. \tag{5.9}$$

Due to $\mathscr{E}_t^h(\chi^h(t)) \leqslant \mathscr{E}_t^h(\chi^h(t-h))$, we conclude

$$\begin{aligned}
&\frac{2}{h}\left(\mathscr{E}_t^h(\chi^h(t)) - \mathscr{E}_t^h(\chi^h(t-h))\right)\\
&\quad = \frac{2}{h}\int_\Omega \left(|\nabla\chi^h(t)|_\sigma - |\nabla\chi^h(t-h)|_\sigma\right) - \int_\Omega \frac{\chi^h(t)-\chi^h(t-h)}{h}u^h(t)\\
&\quad\quad + \int_\Omega (u^h(t-h)+hf^h(t))\frac{u^h(t)-\hat{u}^h(t)}{h}\\
&\quad\quad - \int_\Omega \left(\frac{u^h(t)-\hat{u}^h(t)}{h}+\frac{\chi^h(t)-\chi^h(t-h)}{h}\right)u_D^h(t) \leqslant 0.
\end{aligned} \tag{5.10}$$

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Multiplying (4.4) by $(u^h(t) - u_D^h(t))$ gives

$$\frac{u^h(t) - u^h(t-h)}{h} u^h(t) - \frac{u^h(t) - u^h(t-h)}{h} u_D^h(t) + \frac{\chi^h(t) - \chi^h(t-h)}{h} \big(u^h(t) - u_D^h(t)\big)$$
$$= -\int_\Omega |\nabla\big(u^h(t) - u_D^h(t)\big)|^2 + \int_\Omega f^h(t)\big(u^h(t) - u_D^h(t)\big). \tag{5.11}$$

In addition, testing (5.9) with $(\hat{u}^h(t) - u_D^h(t))$ yields

$$\frac{\hat{u}^h(t) - u^h(t-h)}{h} \hat{u}^h(t) - \frac{\hat{u}^h(t) - u^h(t-h)}{h} u_D^h(t)$$
$$= -\int_\Omega |\nabla\big(\hat{u}^h(t) - u_D^h(t)\big)|^2 + \int_\Omega f^h(t)\big(\hat{u}^h(t) - u_D^h(t)\big). \tag{5.12}$$

Adding (5.11) and (5.12) shows

$$\begin{aligned}
-\int_\Omega \big|\nabla\big(u^h(t) - u_D^h(t)\big)\big|^2 - \int_\Omega \big|\nabla\big(\hat{u}^h(t) - u_D^h(t)\big)\big|^2 + \int_\Omega f^h(t)\big(u^h(t) - 2u_D^h(t) + \hat{u}^h(t)\big) \\
= \frac{1}{h}\Big(\big(u^h(t)\big)^2 - u^h(t-h)u^h(t) + \big(\hat{u}^h(t)\big)^2 - u^h(t-h)\hat{u}^h(t) \\
-\big(u^h(t) - 2u^h(t-h) + \hat{u}^h(t)\big)u_D^h(t) + h\,\partial_t^{-h}\chi\big(u^h(t) - u_D^h(t)\big)\Big) \\
\geqslant \frac{1}{h}\Big(\big(u^h(t)\big)^2 - \big(u^h(t-h)\big)^2 - u^h(t-h)\big(u^h(t) - \hat{u}^h(t)\big) \\
-\big(u^h(t) - 2u^h(t-h) + \hat{u}^h(t)\big)u_D^h(t) + h\,\partial_t^{-h}\chi^h(t)\big(u^h(t) - u_D^h(t)\big)\Big).
\end{aligned} \tag{5.13}$$

Moreover, adding (5.10) and (5.13) leads to

$$\begin{aligned}
\frac{2}{h}\int_\Omega \big(|\nabla\chi^h(t)|_\sigma - |\nabla\chi^h(t-h)|_\sigma\big) - 2\int_\Omega \partial_t^{-h}\big(u_D^h(t)(u^h(t) + \chi^h(t))\big) \\
+ 2\int_\Omega \partial_t^{-h}u_D^h(t)\,\big(u^h(t-h) + \chi^h(t-h)\big) + \int_\Omega \frac{(u^h(t))^2 - (u^h(t-h))^2}{h} \\
\leqslant -\int_\Omega \big(|\nabla(u^h(t) - u_D^h(t))|^2 + |\nabla(\hat{u}^h(t) - u_D^h(t))|^2\big) + 2\int_\Omega f^h(t)\big(\hat{u}^h(t) - u_D^h(t)\big).
\end{aligned}$$

From (4.4), we deduce

$$||\hat{u}^h(t) - u^h(t)||^2_{L^2(\Omega)} \leqslant ||\chi^h(t) - \chi^h(t-h)||_{L^2(\Omega)}\, ||\hat{u}^h(t) - u^h(t)||_{L^2(\Omega)} - h||\nabla\big(\hat{u}^h(t) - u^h(t)\big)||^2_{L^2(\Omega)},$$

and therefore,

$$||\hat{u}^h(t) - u^h(t)||_{L^2(\Omega)} \leqslant ||\chi^h(t) - \chi^h(t-h)||_{L^2(\Omega)}.$$

Hence, we obtain

$$\begin{aligned}
\int_\Omega |f^h(t)\big(\hat{u}^h(t) - u_D^h(t)\big)| \leqslant\ & ||f^h(t)||_{L^2(\Omega)}||\chi^h(t) - \chi^h(t-h)||_{L^2(\Omega)} \\
& + C_\delta||f^h(t)||^2_{L^2(\Omega)} + \delta||u^h(t) - u_D^h(t)||^2_{L^2(\Omega)}
\end{aligned}$$

for any $\delta > 0$ and some $C_\delta > 0$. Note that

$$\int_0^t \int_\Omega |\partial_t^{-h} u_D^h(s)|^2 \leqslant ||\partial_t u_D||^2_{L^2(\Omega_t)}.$$

By means of Poincaré's and Young's inequality, we finally establish

$$\begin{aligned} &\operatorname{ess\,sup}_{t\in(0,T)}\Big(\int_\Omega \big((u^h(t))^2 + |\nabla \chi^h(t)|\big)\Big) + \int_0^T \int_\Omega |\nabla u^h(t)|^2 dx\,dt \\ &\leqslant C_1\Big(\int_\Omega |\nabla \chi(0)|_\sigma + \int_\Omega |u(0)|^2 + ||u_D||^2_{H^1(0,T;H^1(\Omega))} + ||f||^2_{L^2(\Omega_T)}\Big) + C_2, \end{aligned}$$

where $C_1, C_2 > 0$ are some constants and (5.5) is established.

Due to (4.4), we obtain for $\eta \in H_0^1(\Omega)$ with $||\eta||_{H_0^1(\Omega)} \leqslant 1$

$$\int_\Omega \partial_t^{-h}\big(u^h(t) + \chi^h(t)\big)\eta \leqslant \Big(\int_\Omega \big(|\nabla u^h(t)|^2 + |f^h(t)|^2\big)\Big)^{1/2}.$$

From (5.5), we infer

$$\int_0^T ||\partial_t^{-h}\big(u^h(t) + \chi^h(t)\big)||^2_{H^{-1}(\Omega)} \leqslant C_3$$

for some constant $C_3 > 0$. □

Next, we take advantage from an L^1-bound for fractional time derivatives of χ^h and u^h (see [25, 26]), which ensures compactness of χ^h and u^h in $L^1(\Omega_T)$.

Lemma 5.5 (Compactness in time, cf. [25, 26]) *Let $\Omega \subset \mathbb{R}^n$ be a bounded domain with Lipschitz boundary. Furthermore, let*

$$\begin{aligned} &u_D \in H^1(\Omega_T), \quad u \in L^\infty(0,T;L^2(\Omega)), \quad u - u_D \in L^2(0,T,H_0^1(\Omega)), \\ &\chi \in L^\infty(0,T;BV(\Omega;\{0,1\})) \end{aligned}$$

and

$$\partial_t(u+\chi) \in L^2(0,T;H^{-1}(\Omega)).$$

Then, there exists a constant $C > 0$ (depending on the above norms) such that

$$\int_0^{T-\tau} \int_\Omega |\chi(\cdot+\tau) - \chi(\cdot)| + |u(\cdot+\tau) - u(\cdot)| \leqslant C\tau^{\delta_n}$$

with $1/\delta_n = 13 - \frac{8}{n}$.

Due to the *a priori* estimates and Lemma 5.5, we can select (weakly) convergent subsequences as following.

Corollary 5.6 *There exist*

$$u \in \big(u_D + L^2(0,T;H_0^1(\Omega))\big) \cap L^\infty(0,T;L^2(\Omega)), \quad u_D \in H^1(\Omega_T),$$

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and

$$\chi \in L^\infty(0,T;BV(\Omega;\{0,1\}))$$

such that

(i) $u^h \rightharpoonup u$ *in* $L^2(0,T;H^1(\Omega))$,
(ii) $u^h \to u$ *in* $L^1(0,T;L^1(\Omega))$,
(iii) $\chi^h \to \chi$ *in* $L^2(0,T;L^2(\Omega))$,
(iv) $u^h(t) \to u(t)$ *in* $L^1(\Omega)$ *for a.e.* $t \in (0,T)$,
(v) $\chi^h(t) \to \chi(t)$ *in* $L^2(\Omega)$ *for a.e.* $t \in (0,T)$,

for some subsequence as $h \to \infty$.

In the following lemma, we show that for the non-degenerate problem loss of surface area is excluded in the limit.

Lemma 5.7 *The functions* $\chi^h(t)$, $h>0$, *fulfil for a.e.* $t \in (0,T)$:

$$\int_\Omega |\nabla \chi^h(t)|_\sigma \to \int_\Omega |\nabla \chi(t)|_\sigma \qquad \text{as } h \to 0\,.$$

Proof Since $\chi^h(t) \to \chi(t)$ in $L^2(\Omega)$ for a.e. $t \in (0,T)$, we immediately obtain

$$\int_\Omega |\nabla \chi(t)|_\sigma \leqslant \liminf_{h\to 0} \int_\Omega |\nabla \chi^h(t)|_\sigma \quad \text{for a.e. } t \in (0,T)$$

by the lower semi-continuity property of $\int_\Omega |\nabla \chi^h(t)|_\sigma$.

Now, we prove the opposite inequality. Since

$$\mathscr{E}^h_t\big(\chi^h(t)\big) \leqslant \mathscr{E}^h_t\big(\chi(t)\big),$$

we derive

$$\int_\Omega \left(\left|\nabla \chi^h(t)\right|_\sigma + \frac{1}{2}(u^h(t))^2 + \frac{h}{2}\left|\nabla\left(u^h(t) - u^h_D(t)\right)\right|^2 - \left(u^h(t) + \chi^h(t)\right)u^h_D(t) \right)$$
$$\leqslant \int_\Omega \left(|\nabla \chi(t)|_\sigma + \frac{1}{2}(\hat{v}^h(t))^2 + \frac{h}{2}\left|\nabla(\hat{v}^h(t) - u^h_D(t))\right|^2 - \left(\hat{v}^h(t) + \chi(t)\right)u^h_D(t) \right), \qquad (5.14)$$

where $\hat{v}^h(t)$ is the weak solution of

$$\frac{v - u^h(t-h)}{h} + \frac{\chi(t) - \chi^h(t-h)}{h} = \triangle v + f^h(t), \qquad v = u^h_D(t)|_{\partial\Omega}.$$

Note that from (4.4), we conclude

$$\int_\Omega \left(u^h(t) - \hat{v}^h(t)\right)^2 = -\int_\Omega \left(\chi^h(t) - \chi(t)\right)\left(u^h(t) - \hat{v}^h(t)\right) - h\int_\Omega |\nabla\left(u^h(t) - \hat{v}^h(t)\right)|^2.$$

In consequence,

$$||u^h(t) - \hat{v}^h(t)||_{L^2(\Omega)} \leqslant ||\chi^h(t) - \chi(t)||_{L^2(\Omega)} \to 0 \qquad \text{as } h \to 0$$

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for a.e. $t \in (0,T)$. We estimate

$$\left| \int_\Omega \Big(\frac{1}{2}u^h(t) - u_D^h(t)\Big) u^h(t) - \int_\Omega \Big(\frac{1}{2}\hat{v}^h(t) - u_D^h(t)\Big)\, \hat{v}^h(t) \right| \leqslant ||u_D^h(t)||_{L^2(\Omega)} ||u^h(t) - \hat{v}^h(t)||_{L^2(\Omega)}$$
$$+ \frac{1}{2}\int_\Omega \big(|u^h(t)| + |\hat{v}^h(t)|\big)\, |u^h(t) - \hat{v}^h(t)| \to 0 \qquad \text{as } h \to 0,$$

and

$$\left| \int_\Omega \big(\chi^h(t) - \chi(t)\big) u_D^h(t) \right| \leqslant ||\chi^h(t) - \chi(t)||_{L^2(\Omega)}\, ||u_D^h(t)||_{L^2(\Omega)} \to 0 \qquad \text{as } h \to 0$$

for a.e. $t \in (0,T)$ since $u^h(t) - \hat{v}^h(t) \to 0$, $\chi^h(t) \to \chi(t)$ and $u_D^h(t) \to u_D(t)$ in $L^2(\Omega)$ for a.e. $t \in (0,T)$. In addition,

$$\left| h\int_\Omega |\nabla(\hat{v}^h(t) - u_D^h(t))|^2 - h\int_\Omega |\nabla(u^h(t) - u_D^h(t))|^2 \right|$$
$$= \left| \int_\Omega \big((\hat{v}^h(t))^2 - (u^h(t))^2 - \big(u^h(t-h) + u_D^h(t)\big)\big(\hat{v}^h(t) - u^h(t)\big) - hf^h(t)\big(\hat{v}^h(t) - u^h(t)\big) \right.$$
$$\left. - \big(\chi(t) - \chi^h(t)\big)u_D^h(t) + \chi(t)\,\hat{v}^h(t) - \chi^h(t)\, u^h(t) - \chi^h(t-h)\big(\hat{v}^h(t) - u^h(t)\big)\big) \right|$$
$$\to 0 \qquad \text{as} \quad h \to 0$$

for a.e. $t \in (0,T)$. From (5.14), we conclude

$$\int_\Omega |\nabla\chi(t)|_\sigma \geqslant \limsup_{h\to 0} \int_\Omega |\nabla\chi^h(t)|_\sigma$$

for a.e. $t \in (0,T)$. □

5.3 The spatially inhomogeneous and anisotropic Gibbs–Thomson law

Before we pass to the limit in the weak formulation of the discrete spatially inhomogeneous and anisotropic Gibbs–Thomson law, we show some approximation properties.

Lemma 5.8 *Suppose*

$$\int_\Omega \sigma(\cdot, v^h(t,\cdot))|\nabla\chi^h(t,\cdot)| \to \int_\Omega \sigma(\cdot, v(t,\cdot))|\nabla\chi(t,\cdot)|, \qquad h \to 0, \tag{5.15}$$

for a.e. $t \in (0,T)$, where $v^h = -\nabla\chi^h/|\nabla\chi^h|$ and $v = -\nabla\chi/|\nabla\chi|$.
Then, using the same notation as in Proposition 2.5:

(i) $\int_{\Omega\times\mathbb{S}^{n-1}} \sigma(\cdot,\cdot)d\Theta_\infty(t,\cdot,\cdot) \leqslant \int_\Omega \sigma(\cdot, v(t,\cdot))|\nabla\chi(t,\cdot)|$ for a.e. $t \in (0,T)$.
(ii) There exists a sequence $\{g_t^l\}_{l\in\mathbb{N}}$ of functions $g_t^l \in C_c^1(\Omega)$, $t \in (0,T)$ such that

$$g_t^l \to \sigma_{,p}(\cdot, v(t,\cdot)) \qquad \text{in} \;\; L^1(|\nabla\chi(t,\cdot)|)$$

for a.e. $t \in (0,T)$.

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(iii) $\lambda_x^\infty(t) = \delta_{y=v(t,x)}$ *for* $|\nabla\chi(t)|$*-a.e.* $x \in \Omega$ *and a.e.* $t \in (0,T)$.

Proof To (i): Due to Proposition 2.5, we infer

$$\begin{aligned}\int_{\Omega\times\mathbb{S}^{n-1}} \sigma(\cdot,\cdot)\, d\Theta_\infty(t,\cdot,\cdot) &\leqslant \liminf_{j\to\infty} \int_{\Omega\times\mathbb{S}^{n-1}} \sigma(\cdot,\cdot)\, d\Theta_{h_j}(t,\cdot,\cdot)\\ &= \liminf_{j\to\infty} \int_\Omega \sigma(\cdot, v^{h_j}(t,\cdot))\,|\nabla\chi^{h_j}(t,\cdot)|\\ &= \int_\Omega \sigma(\cdot, v(t,\cdot))\,|\nabla\chi(t,\cdot)|\end{aligned}$$

for a.e. $t \in (0,T)$.

To (ii): Smooth approximations g_t^l for the Cahn–Hoffman vector $\sigma_{,p}$ can be constructed as follows: Due to (2.2), there exists for every $\delta > 0$ and a.e. $t \in (0,T)$ approximative functions $g_t^\delta \in K_\sigma$ such that

$$\int_\Omega \left(\sigma(\cdot, v(t,\cdot)) - g_t^\delta(\cdot)\cdot v(t,\cdot)\right)|\nabla\chi(t,\cdot)| \leqslant \delta^2.$$

Thus, by Lemma 2.3,

$$\int_\Omega |\sigma_{,p}(\cdot, v(t,\cdot)) - g_t^\delta(\cdot)|\,|\nabla\chi(t,\cdot)| \leqslant C_1\,\delta$$

for some constant $C_1 > 0$ and a.e. $t \in (0,T)$. This implies the existence of a sequence $\{g_t^l\}_{l\in\mathbb{N}}$, $g_t^l \in C_c^1(\Omega;\mathbb{R}^n)$, with $g_t^l \to \sigma_{,p}(\cdot, v(t,\cdot))$ in $L^1(|\nabla\chi(t,\cdot)|)$ for a.e. $t \in (0,T)$ since $\delta > 0$ may be chosen arbitrarily small.

To (iii): Since $\chi^h(t) \to \chi(t)$ in $L^1(\Omega)$ for a.e. $t \in (0,T)$ and $\limsup_{h\to 0}\int_\Omega |\nabla\chi^h(t)|$ is bounded for a.e. $t \in (0,T)$, we obtain

$$\nabla\chi^h(t) \to \nabla\chi(t) \qquad \text{weakly}^*$$

for a.e. $t \in (0,T)$. Hence, we can choose a set $S \subset (0,T)$ of Lebesgue measure zero such that $\chi^h(t) \to \chi(t)$ in $L^1(\Omega)$ and $\nabla\chi^h(t) \to \nabla\chi(t)$ weakly* for $t \in (0,T)\backslash S$.

From Proposition 2.5, we conclude that there exist a sequence $\{h_j\}_{j\in\mathbb{N}}$ and a non-negative Radon measure $\Theta_\infty(t) \equiv \pi_\infty(t)\otimes\lambda_x^\infty(t)$ on $\Omega\times\mathbb{S}^{n-1}$, $t \in (0,T)\backslash S$ such that

(a) $\Theta_{h_j}(t) \equiv |\nabla\chi^{h_j}(t)| \otimes \delta_{v^{h_j}(t)} \to \Theta_\infty(t) \equiv \pi_\infty(t)\otimes\lambda_x^\infty(t)$ weakly*, δ_y Dirac mass,

(b) $|\nabla\chi^{h_j}(t)| \to \pi_\infty(t)$ weakly*,

(c) $\pi_\infty(t) \geqslant |\nabla\chi(t)|$,

(d)

$$\begin{aligned}\lim_{j\to\infty}\int_\Omega F(x, v^{h_j}(t,x))|\nabla\chi^{h_j}(t,x)| &= \int_{\Omega\times\mathbb{S}^{n-1}} F(x,y)d\Theta_\infty(t,x,y)\\ &= \int_\Omega \left(\int_{\mathbb{S}^{n-1}} F(x,y)d\lambda_x^\infty(t,y)\right)d\pi_\infty(t,x)\end{aligned}$$

for any $F \in C_c(\Omega\times\mathbb{R}^n)$ and all $t \in (0,T)\backslash S$.

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For any $\hat{x} \in \Omega$, we take $r > 0$ such that $B(\hat{x}, r) = \{x \in \mathbb{R}^n : ||x - \hat{x}|| < r\} \Subset \Omega$ and set

$$F_g(x, y; t) = \Phi_1(x)\Phi_2(y)|\sigma_{,p}(x, y) - g_t(x)|^2,$$

where $\Phi_1 \in C_c(\Omega)$ with $0 \leqslant \Phi_1 \leqslant 1$ in Ω and $\Phi_1 \equiv 1$ in $B(\hat{x}, r)$ and $\Phi_2 \in C_c(\mathbb{R}^n)$ with $\Phi_2(y) = 0$ in $\{y \in \mathbb{R}^n : ||y|| < h\}$ for some $h > 0$, $\Phi_2(y) = 1$ on $\mathbb{S}^{n-1}$ and $g_t \in K_\sigma(\Omega)$. Consequently, $F_g(\cdot, \cdot\,; t) \in C_c(\Omega \times \mathbb{R}^n)$. Proposition 2.5 assures (modulo a subsequence)

$$\begin{aligned}
&\int_\Omega \Phi_1(x)\left(\int_{\mathbb{S}^{n-1}} \Phi_2(y)|\sigma_{,p}(x, y) - g_t(x)|^2 d\lambda_x^\infty(t, y)\right)|\nabla\chi(t, x)| \\
&\quad \leqslant \int_\Omega \Phi_1(x)\left(\int_{\mathbb{S}^{n-1}} \Phi_2(y)|\sigma_{,p}(x, y) - g_t(x)|^2 d\lambda_x^\infty(t, y)\right) d\pi_\infty(t, x) \\
&\quad = \lim_{j\to\infty} \int_\Omega \Phi_1(x)\Phi_2(v^{h_j}(t, x))|\sigma_{,p}(x, v^{h_j}(t, x)) - g_t(x)|^2 |\nabla\chi^{h_j}(t, x)| \\
&\quad \leqslant \lim_{j\to\infty} \int_\Omega |\sigma_{,p}(x, v^{h_j}(t, x)) - g_t(x)|^2 |\nabla\chi^{h_j}(t, x)| \qquad (5.16)
\end{aligned}$$

for every $t \in (0, T)\backslash S$. Taking advantage from Lemma 2.3, we estimate

$$\begin{aligned}
&\lim_{j\to\infty} \int_\Omega C\,|\sigma_{,p}(x, v^{h_j}(t, x)) - g_t(x)|^2 |\nabla\chi^{h_j}(t, x)| \\
&\quad \leqslant \lim_{j\to\infty} \int_\Omega \left(\sigma(x, v^{h_j}(t, x)) - g_t(x) \cdot v^{h_j}(t, x)\right)|\nabla\chi^{h_j}(t, x)| \\
&\quad = \int_\Omega \left(\sigma(x, v(t, x)) - g_t(x) \cdot v(t, x)\right)|\nabla\chi(t, x)| \\
&\quad \leqslant \int_\Omega |\sigma_{,p}(x, v(t, x)) - g_t(x)||\nabla\chi(t, x)| \qquad (5.17)
\end{aligned}$$

for every $t \in (0, T)\backslash S$, where $C > 0$ is some constant. Hence, (ii) combined with (5.16) and (5.17) shows

$$\int_\Omega \Phi_1(x)\left(\int_{\mathbb{S}^{n-1}} |\sigma_{,p}(x, y) - \sigma_{,p}(x, v(t, x))|^2 d\lambda_x^\infty(t, y)\right)|\nabla\chi(t, x)| = 0$$

for $t \in (0, T)\backslash S$. In particular

$$\int_\Omega \Phi_1(x)\left(\int_{\mathbb{S}^{n-1}} |\sigma_{,p}(x, y) \cdot y - \sigma_{,p}(x, v(t, x)) \cdot y|^2 d\lambda_x^\infty(t, y)\right)|\nabla\chi(t, x)| = 0$$

for $t \in (0, T)\backslash S$. This implies, according to Lemma 2.2 (ii),

$$\int_{\mathbb{S}^{n-1}} |v(t, x) - y|^4 d\lambda_x^\infty(t, y) = 0 \quad \text{for } |\nabla\chi(t)|\text{-a.e. } x \in B(\hat{x}, r) \text{ and } t \in (0, T)\backslash S.$$

Hence, we obtain that λ_x^∞ is a Dirac mass, i.e. $\lambda_x^\infty(t) = \delta_{y=v(t,x)}$, for $|\nabla\chi(t)|$-a.e. $x \in B(\hat{x}, r)$ and $t \in (0, T)\backslash S$ and the claim follows as $\hat{x} \in \Omega$ was arbitrary. □

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Lemma 5.9 *Let Ω be a bounded domain with Lipschitz boundary and suppose Assumption A 2.1 is satisfied. If $\chi^h(t) \in BV(\Omega;\{0,1\})$ is a minimiser of $\mathscr{F}_t^h$ and condition (5.15) is satisfied, or if $\chi^h(t) \in BV(\Omega;\{0,1\})$ is a minimiser of $\mathscr{E}_t^h$, then*

$$\lim_{h\to 0}\int_{\Omega_T}(\sigma(\cdot, v^h(t,\cdot))\nabla\cdot\xi(t,\cdot)+\sigma_{,x}(\cdot,v^h(t,\cdot))\cdot\xi(t,\cdot)-v^h(t,\cdot)\cdot\nabla\xi(t,\cdot)\,\sigma_{,p}(\cdot,v^h(t,\cdot)))|\nabla\chi^h(t,\cdot)|$$
$$=\int_{\Omega_T}(\sigma(\cdot, v(t,\cdot))\nabla\cdot\xi(t,\cdot)+\sigma_{,x}(\cdot,v(t,\cdot))\cdot\xi(t,\cdot)-v(t,\cdot)\cdot\nabla\xi(t,\cdot)\,\sigma_{,p}(\cdot,v(t,\cdot)))|\nabla\chi(t,\cdot)| \tag{5.18}$$

for all $\xi \in C_c^1(\Omega_T;\mathbb{R}^n)$, where $v^h = -\frac{\nabla\chi^h}{|\nabla\chi^h|}$ and $v = -\frac{\nabla\chi}{|\nabla\chi|}$.

If, in addition, Ω is a bounded domain with C^1-boundary then (5.18) is satisfied for all $\xi \in C^1(\overline{\Omega}_T;\mathbb{R}^n)$ with $\xi\cdot v_\Omega = 0$ on $\partial\Omega$, where v_Ω is the outer unit normal of $\partial\Omega$.

Proof In view of Lemma 5.8 (i), we have

$$\int_{\Omega\times\mathbb{S}^{n-1}}\sigma(x,y)\,d\Theta_\infty(t,x,y)\leqslant\int_\Omega\sigma(x,v(t,x))|\nabla\chi(t,x)|$$

for a.e. $t\in(0,T)$. Since, by Lemma 5.8, $\lambda_x^\infty(t)=\delta_{y=v(t,x)}$ for $|\nabla\chi_-(t)|$-a.e. $x\in\Omega$ and a.e. $t\in(0,T)$, we infer from Lemma 2.5

$$\begin{aligned}\int_\Omega\sigma(x,v(t,x))|\nabla\chi_-(t,x)| &= \int_\Omega\left(\int_{\mathbb{S}^{n-1}}\sigma(x,y)\,d\lambda_x^\infty(t,y)\right)|\nabla\chi_-(t,x)|\\ &=\int_\Omega\left(\int_{\mathbb{S}^{n-1}}\sigma(x,y)\,d\lambda_x^\infty(t,y)\right)g(t,x)\,d\pi_\infty(t,x)\\ &\leqslant\int_{\Omega\times\mathbb{S}^{n-1}}\sigma(x,y)\,d\Theta_\infty(t,x,y),\end{aligned}$$

where g is the density of $|\nabla\chi_-|$ with respect to π_∞ and $0\leqslant g(t,x)\leqslant 1$ for π_∞-a.e. $x\in\Omega$ and a.e. $t\in(0,T)$. Consequently, as $\int_{\mathbb{S}^{n-1}}\sigma(x,y)\,d\lambda_x^\infty(t,y)>0$ for π_∞-a.e. $x\in\Omega$ and a.e. $t\in(0,T)$, we deduce

$$g\equiv 1\quad\text{and}\quad|\nabla\chi_-|=\pi_\infty\quad\text{for }\pi_\infty\text{-a.e. }x\in\Omega\text{ and a.e. }t\in(0,T).$$

Moreover, $\Theta_{h_j}(t,\Omega\times\mathbb{S}^{n-1})=|\nabla\chi^{h_j}(t)|(\Omega)$ converges to $|\nabla\chi(t)|(\Omega)=\Theta_\infty(t,\Omega\times\mathbb{S}^{n-1})$ for a.e. $t\in(0,T)$.

Next, we utilise the property that $\lim_{j\to\infty}\Theta_{h_j}(t,\Omega\times\mathbb{S}^{n-1})=\Theta_\infty(t,\Omega\times\mathbb{S}^{n-1})$ and $\Theta_{h_j}(t)\to\Theta_\infty(t)$ weakly*, $t\in(0,T)$, implies

$$\lim_{j\to\infty}\int_{\Omega\times\mathbb{S}^{n-1}}u(x,y)\,d\Theta_{h_j}(t,x,y)=\int_{\Omega\times\mathbb{S}^{n-1}}u(x,y)\,\Theta_\infty(t,x,y)$$

for every continuous and bounded function $u : \Omega \times \mathbb{S}^{n-1} \to \mathbb{R}$. We conclude

$$\lim_{j\to\infty} \int_\Omega f(x, v^{h_j}(t,x))|\nabla\chi^{h_j}(t,x)| = \lim_{j\to\infty} \int_{\Omega\times\mathbb{S}^{n-1}} f(x,y)\, d\Theta_{h_j}(t,x,y)$$
$$= \int_{\Omega\times\mathbb{S}^{n-1}} f(x,y)\, \Theta_\infty(t,x,y) = \int_\Omega f(x, v(t,x))|\nabla\chi(t,x)|$$

for every continuous and bounded function $f : \Omega \times \mathbb{S}^{n-1} \to \mathbb{R}$ and a.e. $t \in (0,T)$. Thus, we infer

$$\lim_{h\to 0} \int_\Omega \sigma\big(x, v^h(t,x)\big)\nabla\cdot\xi(t,x)|\nabla\chi^h(t,x)| = \int_\Omega \sigma\big(x, v(t,x)\big)\nabla\cdot\xi(t,x)|\nabla\chi(t,x)|$$
$$\lim_{h\to 0} \int_\Omega \sigma_{,x}\big(x, v^h(t,x)\big)\cdot\xi(t,x)|\nabla\chi^h(t,x)| = \int_\Omega \sigma_{,x}\big(x, v(t,x)\big)\cdot\xi(t,x)|\nabla\chi(t,x)|$$
$$\lim_{h\to 0} \int_\Omega v^h(t)\cdot\nabla\xi(t,x)\,\sigma_{,p}\big(x, v^h(t)\big)|\nabla\chi^h(t,x)| = \int_\Omega v(t,x)\cdot\nabla\xi(t,x)\,\sigma_{,p}\big(x, v(t,x)\big)|\nabla\chi(t,x)|$$

for $h \to 0$ and the claim is established by Lebesgue's convergence theorem. □

5.4 Proofs of Theorems 1.1 and 1.2

Now, we are well prepared to prove Theorems 1.1 and 1.2.

Proof of Theorems 1.1 and 1.2 From Lemma 5.1 and Lemma 5.4, respectively, we conclude

$$u^h \rightharpoonup u \quad \text{in } L^2(0,T;H^1(\Omega)) \quad \text{and} \quad \chi^h \to \chi \quad \text{in } L^2(0,T;L^2(\Omega)).$$

The weak compactness of $L^2(0,T;H^1_0(\Omega))$, in turn, implies

$$u \in u_D + L^2(0,T;H^1_0(\Omega)).$$

To establish (1.12) and (1.9), respectively, we consider the time discretisation of the diffusion equations, see (4.2) and (4.4), for $\chi = \chi^h(t)$ and $v = u^h(t)$. Discrete integration of the terms $\int_{\Omega_T} \partial_t^{-h}(\chi^h)\xi$ and $\int_{\Omega_T} \partial_t^{-h}(u^h + \chi^h)\xi$ by parts and passing to the limit $h \to 0$ in (4.2) and (4.4) shows (1.12) and (1.9), respectively.

Now, we show (1.10). From (5.18) of Lemma 5.9, we derive the convergence of the discrete curvature term to the corresponding expression in (1.10). In addition,

$$\lim_{h\to 0} \int_{\Omega_T} u^h(t,\cdot)\,\xi(t,\cdot)\cdot v^h(t,\cdot)|\nabla\chi^h(t,\cdot)| = \lim_{h\to 0} \int_{\Omega_T} \mathrm{div}\big(u^h(t,\cdot)\,\xi(t,\cdot)\big)\,\chi^h(t,\cdot)$$
$$= \int_{\Omega_T} \mathrm{div}\big(u(t,\cdot)\,\xi(t,\cdot)\big)\,\chi(t,\cdot) = \int_{\Omega_T} u(t,\cdot)\,\xi(t,\cdot)\cdot v(t,\cdot)|\nabla\chi(t,\cdot)|.$$

Hence, the assertion follows. □

5.5 Conclusion

The Stefan problem with Gibbs–Thomson law has many applications in material sciences, i.e. describing melting and solidification processes in materials. It has been addressed

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mathematically by several authors. For a realistic modeling, such as solidification of alloys, it is quite important to take surface tension effects into account, which are spatially inhomogeneous and anisotropic. In this work, we have presented existence results for Stefan problems with spatially inhomogeneous and anisotropic Gibbs–Thomson law. Previous results to this topic [19a, 24–26]) have been generalised. We like to mention that in contrast to the isotropic case we cannot apply the Reshetnyak convergence theorem [3] since we do not directly obtain the property $\int_\Omega |\nabla\chi^h(t)| \to \int_\Omega |\nabla\chi(t)|$ as $h \to 0$. To tackle both inhomogeneity and anisotropy, we have used slicing and indicator measures and methods of geometric measure theory.

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