

Asymptotic Behavior for Nonlinear Systems of Phase Transitions

千葉大自然科学 佐藤 直紀 (Naoki Sato)
千葉大自然科学 白水 淳 (Jun Shirohzu)
千葉大教育 剣持 信幸 (Nobuyuki Kenmochi)

1. Introduction

We consider the following nonlinear system:

$$\frac{\partial \rho(u)}{\partial t} + \frac{\partial w}{\partial t} - \Delta u = f(t, x) \quad \text{in } Q := (0, +\infty) \times \Omega, \quad (1.1)$$

$$\nu \frac{\partial w}{\partial t} + \beta(w) + g(w) \ni u \quad \text{in } Q \quad (1.2)$$

with lateral boundary condition:

$$\frac{\partial u}{\partial n} + \alpha_N(x)u = h_N(t, x) \quad \text{on } \Sigma := (0, +\infty) \times \Gamma, \quad (1.3)$$

and initial conditions:

$$u(0, \cdot) = u_0, \quad w(0, \cdot) = w_0 \quad \text{in } \Omega. \quad (1.4)$$

Here Ω is a bounded domain in R^N ($N \geq 1$) with smooth boundary $\Gamma := \partial\Omega$; ρ is a monotone increasing and bi-Lipschitz continuous function on R ; ν is a positive constant; β is a maximal monotone graph in $R \times R$; g is a smooth function defined on R ; α_N is a non-negative, bounded and measurable function on Γ such that $\alpha_N > 0$ on a subset of Γ with positive measure; f, h_N, u_0 and w_0 are given data.

For simplicity problem (1.1)-(1.4) is denoted by (CP). This is a simplified model for a class of solid-liquid phase change problems, and in this context u represents a function related to temperature and w a non-conserved order parameter (the state variable characterizing phase). For instance, we have the following examples:

- (1) Stefan problem with phase relaxation, in which β is the subdifferential of the indicator function of the interval $[0, 1]$ and $g \equiv 0$. This case was discussed as a melting problem with supercooling and superheating effect in [12, 5].
- (2) Phase-field model with constraint, in which β is the same as in (1), $\rho(u) = u$, $g(w) = w^3 - cw$ with a positive constant c , and a diffusion term $-\kappa \Delta w$ is added to the left

side of (1.2). This is a phase-field model with constraint $0 \leq w \leq 1$ and was discussed in [6,9,11]. We may consider system (1.1)-(1.4) as an approximation of this problem with small $\kappa > 0$.

Furthermore we refer to [2,1] for papers dealing with similar problems.

In this paper, we discuss the large-time behavior of the solution $\{u, w\}$. In fact, under the condition that $f(t, x) \rightarrow f^\infty(x)$ and $h_N(t, x) \rightarrow h_N^\infty(x)$ in an appropriate sense as $t \rightarrow +\infty$, it will be shown that as $t \rightarrow +\infty$, $u(t, \cdot)$ and $w(t, \cdot)$ converge to a solution $\{u^\infty, w^\infty\}$ of the corresponding steady-state problem

$$\begin{cases} -\Delta u^\infty = f^\infty(x) & \text{in } \Omega, \\ \frac{\partial u^\infty}{\partial n} + \alpha_N(x)u^\infty = h_N^\infty(x) & \text{on } \Gamma, \\ \beta(w^\infty) + g(w^\infty) \ni u^\infty & \text{in } \Omega. \end{cases}$$

2. Existence and uniqueness result for (CP)

Problem (CP) is discussed under the following assumptions (A1)-(A6):

(A1) $\rho : R \rightarrow R$ is an increasing and bi-Lipschitz continuous function.

(A2) β is a maximal monotone graph in $R \times R$ such that for some numbers σ_*, σ^* with $-\infty < \sigma_* < \sigma^* < +\infty$

$$\overline{D(\beta)} = [\sigma_*, \sigma^*];$$

note in this case that $R(\beta) = R$, so that there is a non-negative proper l.s.c. convex function $\hat{\beta}$ on R whose subdifferential $\partial\hat{\beta}$ coincides with β in R , and in the context of solid-liquid system we can consider that $w = \sigma_*$ (resp. σ^*) indicates the pure solid (resp. liquid) phase and any intermediate value w indicates a state of mixture.

(A3) $g : R \rightarrow R$ is a Lipschitz continuous function with compact support in R ; in this case note that there is a non-negative primitive $\hat{g}$ of g .

(A4) $f \in L^2_{loc}(R_+; L^2(\Omega))$.

(A5) $h_N \in W^{1,2}_{loc}(R_+; L^2(\Gamma))$ with $\sup_{t \geq 0} |h_N|_{W^{1,2}(t, t+1; L^2(\Gamma))} < +\infty$.

(A6) $u_0 \in L^2(\Omega)$ and $w_0 \in L^2(\Omega)$ with $\hat{\beta}(w_0) \in L^1(\Omega)$.

We introduce some function spaces and a convex function in order to discuss (CP) in the framework of abstract evolution equations of the form

$$U'(t) + \partial\varphi^t(U(t)) + G(U(t)) \ni \tilde{f}(t).$$

Let $V := H^1(\Omega)$ with norm

$$|z|_V := \{|\nabla z|_{L^2(\Omega)}^2 + \int_{\Gamma} \alpha_N |z|^2 d\Gamma\}^{\frac{1}{2}},$$

and denote by V^* the dual space of V and by $\langle \cdot, \cdot \rangle$ the duality pairing between V^* and V . Then, identifying $L^2(\Omega)$ with its dual space by means of the usual inner product

$$(v, z) := \int_{\Omega} v z dx,$$

we see that

$$V \subset L^2(\Omega) \subset V^*$$

with compact injections.

Let F be the duality mapping from V onto V^* which is given by the formula

$$\langle Fv, z \rangle = \int_{\Omega} \nabla v \cdot \nabla z dx + \int_{\Gamma} \alpha_N v z d\Gamma \quad \text{for any } v, z \in V.$$

It is easy to see that V^* becomes a Hilbert space with inner product $(\cdot, \cdot)_*$ given by

$$(v, z)_* := \langle v, F^{-1}z \rangle (= \langle z, F^{-1}v \rangle) \quad \text{for any } v, z \in V^*.$$

Now, consider the product space

$$X := V^* \times L^2(\Omega),$$

which becomes a Hilbert space with inner product $(\cdot, \cdot)_X$ given by

$$([e_1, w_1], [e_2, w_2])_X := (e_1, e_2)_* + \nu(w_1, w_2) \quad \text{for any } [e_i, w_i] \in X \ (i = 1, 2).$$

Next, given the boundary data h_N , choose $h : R_+ \rightarrow H^1(\Omega)$ such that for each $t \geq 0$

$$\int_{\Omega} \nabla h(t) \cdot \nabla z dx + \int_{\Gamma} \alpha_N h(t) z d\Gamma = \int_{\Gamma} h_N(t) z d\Gamma \quad \text{for all } z \in V;$$

note from (A5) that $\sup_{t \geq 0} |h|_{W^{1,2}(t, t+1; H^1(\Omega))} < +\infty$.

Also, using h and $\hat{\beta}$, for each $t \geq 0$, define a proper l.s.c. convex function φ^t on X by

$$\varphi^t(U) = \begin{cases} \int_{\Omega} \rho^*(e - w) dx + \int_{\Omega} \hat{\beta}(w) dx - (h(t), e) \\ \quad \text{if } U = [e, w] \in L^2(\Omega) \times L^2(\Omega) \text{ with } \hat{\beta}(w) \in L^1(\Omega), \\ +\infty \quad \text{otherwise,} \end{cases}$$

where ρ^* is a non-negative primitive of ρ^{-1} . We denote by $\partial\varphi^t$ the subdifferential of φ^t in X and its characterization is given by the following theorem.

Theorem 2.1. (cf. [5, 9]) *Let $t \geq 0$, $[e^*, w^*] \in X$ and $[e, w] \in D(\partial\varphi^t)$. Then $[e^*, w^*] \in \partial\varphi^t([e, w])$ if and only if conditions (a) and (b) below are satisfied:*

(a) $e^* = F(\rho^{-1}(e - w) - h(t))$, that is, $\rho^{-1}(e - w) - h(t) \in V$ and

$$\langle e^*, z \rangle = \int_{\Omega} \nabla(\rho^{-1}(e - w) - h(t)) \cdot \nabla z dx + \int_{\Gamma} \alpha_N(\rho^{-1}(e - w) - h(t)) z d\Gamma$$

for all $z \in V$;

(b) there exists a function $\xi \in L^2(\Omega)$ such that $\xi \in \beta(w)$ a.e. on Ω and

$$\nu w^* = \xi - \rho^{-1}(e - w) \quad \text{in } L^2(\Omega).$$

Moreover, for $U_i^* = [e_i^*, w_i^*] \in \partial\varphi^t(U_i)$ with $U_i = [e_i, w_i] \in D(\partial\varphi^t)$ ($i = 1, 2$),

$$(U_1^* - U_2^*, U_1 - U_2)_X = |(e_1 - w_1) - (e_2 - w_2)|_{L^2(\Omega)} + (\xi_1 - \xi_2, w_1 - w_2),$$

where $\xi_i \in L^2(\Omega)$ is as any function ξ in (b) for each $i = 1, 2$.

A weak formulation for (CP) is given as follows.

Definition 2.1. A couple $\{u, w\}$ of functions $u : R_+ \longrightarrow V^*$ and $w : R_+ \longrightarrow L^2(\Omega)$ is called a (weak) solution of (CP) on R_+ , if the following conditions (w1)-(w3) are fulfilled for any finite $T > 0$:

(w1) $\rho(u) \in C([0, T]; V^*) \cap W_{loc}^{1,2}((0, T]; V^*) \cap L^2(0, T; L^2(\Omega))$, $u \in L_{loc}^2((0, T]; H^1(\Omega))$, $w \in C([0, T]; L^2(\Omega)) \cap W_{loc}^{1,2}((0, T]; L^2(\Omega))$, and $\hat{\beta}(w) \in L^1(0, T; L^1(\Omega))$.

(w2) $\rho(u)(0) = \rho(u_0)$ and

$$\langle u'(t) + w'(t), z \rangle + \int_{\Omega} \nabla(u(t) - h(t)) \cdot \nabla z dx + \int_{\Gamma} \alpha_N(u(t) - h(t)) z d\Gamma = (f(t), z)$$

for all $z \in V$ and a.e. $t \in [0, T]$, where the prime ' denotes the derivative in time.

(w3) there exists $\xi \in L_{loc}^2((0, T]; L^2(\Omega))$ such that $\xi \in \beta(w)$ a.e. on $Q_T := (0, T) \times \Omega$ and

$$\nu(w'(t), z) + (\xi(t) + g(w(t)), z) = (u(t), z)$$

for all $z \in L^2(\Omega)$ and a.e. $t \in [0, T]$.

According to Theorem 2.1, (CP) can be reformulated as an evolution equation in X in the following form:

$$\begin{cases} U'(t) + \partial\varphi^t(U(t)) + G(U(t)) \ni \tilde{f}(t), & \text{in } X, t \geq 0, \\ U(0) = [\rho(u_0) + w_0, w_0], \end{cases}$$

where $U(t) = [\rho(u(t)) + w(t), w(t)]$, $G(U(t)) = [0, \frac{1}{\nu}g(w(t))]$ and $\tilde{f}(t) = [f(t), 0]$.

As to the solvability of (CP) we have:

Theorem 2.2. (cf. [6,9]) Assume that (A1)-(A6) hold. Then, for any $T > 0$, (CP) admits one and only one solution $\{u, w\}$ on $[0, T]$ such that

$$\begin{cases} t^{\frac{1}{2}}\rho(u)' \in L^2(0, T; V^*), & t^{\frac{1}{2}}u \in L^2(0, T; H^1(\Omega)), \\ t\rho(u)' \in L^2(0, T; L^2(\Omega)), & tu \in L^\infty(0, T; H^1(\Omega)), \\ t^{\frac{1}{2}}w' \in L^2(0, T; L^2(\Omega)), & t\hat{\beta}(w) \in L^\infty(0, T; L^1(\Omega)), \\ t^{\frac{1}{2}}\xi \in L^2(0, T; L^2(\Omega)) \end{cases}$$

where ξ is the function in condition (w3).

3. Large-time behavior of the solution

Further suppose that there are $h_N^\infty \in L^2(\Gamma)$ and $f^\infty \in L^2(\Omega)$ such that

$$h_N - h_N^\infty \in L^2(R_+; L^2(\Gamma)), \quad f - f^\infty \in L^2(R_+; L^2(\Omega)), \quad (3.1)$$

and consider the steady-state problem (3.2)-(3.3):

$$-\Delta u^\infty = f^\infty(x) \text{ in } \Omega, \quad \frac{\partial u^\infty}{\partial n} + \alpha_N(x)u^\infty = h_N^\infty(x) \quad \text{on } \Gamma, \quad (3.2)$$

$$\beta(w^\infty) + g(w^\infty) \ni u^\infty \quad \text{in } \Omega. \quad (3.3)$$

We should note that problem (3.2) does not include w^∞ , and it has a unique solution $u^\infty \in H^1(\Omega)$ in the variational sense, i.e.,

$$\int_{\Omega} \nabla(u^\infty - h^\infty) \cdot \nabla z dx + \int_{\Gamma} \alpha_N(u^\infty - h^\infty)z d\Gamma = (f^\infty, z) \quad \text{for all } z \in V, \quad (3.4)$$

where $h^\infty \in H^1(\Omega)$ such that

$$\int_{\Omega} \nabla h^\infty \cdot \nabla z dx + \int_{\Gamma} \alpha_N h^\infty z d\Gamma = \int_{\Gamma} h_N^\infty z d\Gamma \quad \text{for all } z \in V.$$

We see from (3.1) that $h - h^\infty \in L^2(R_+; H^1(\Omega))$.

In the sequel we mean by (P^∞) the algebraic relation (3.3) with the solution $u^\infty \in H^1(\Omega)$ of (3.4), and $w^\infty = w^\infty(x)$ is called a solution of (P^∞) .

As the following example shows, the steady-state problem (P^∞) has in general infinitely many solutions.

Example 3.1. Consider the case when

$$f^\infty(x) \equiv 0, \quad h_N^\infty(x) \equiv l_0, \quad \alpha_N(x) \equiv 1, \quad \beta = \partial I_{[-1,1]} \text{ and } g(w) = w^3 - w$$

where l_0 is a constant. Then, clearly $u^\infty \equiv l_0$ and we have the following three possibilities:

- (i) when $l_0 > \frac{2}{3\sqrt{3}}$ (resp. $l_0 < -\frac{2}{3\sqrt{3}}$), the algebraic relation

$$\beta(r) + g(r) \ni u^\infty (= l_0) \quad (3.5)$$

has exactly one solution $r = 1$ (resp. -1).

- (ii) when $l_0 = \frac{2}{3\sqrt{3}}$ (resp. $-\frac{2}{3\sqrt{3}}$), (3.5) has exactly two solutions $r = -\frac{1}{\sqrt{3}}$ (resp. $\frac{1}{\sqrt{3}}$), 1 (resp. -1).
- (iii) when $|l_0| < \frac{2}{3\sqrt{3}}$, (3.5) has exactly three solutions $r = \xi_-, \xi_0, \xi_+$ with $-1 \leq \xi_- < \xi_0 < \xi_+ \leq 1$.

Physically (i) means that if the temperature is kept high (resp. low) enough, then the limit state (as $t \rightarrow +\infty$) will be of pure liquid (resp. solid). On the other hand, (ii) and (iii) mean that if the temperature is kept near the phase transition temperature, then the limit state possibly includes a mushy region. In particular, in the case of (iii), all step functions w^∞ with range in $\{\xi_-, \xi_0, \xi_+\}$ are solutions of (P^∞) and hence (P^∞) has in general infinitely many solutions.

Our main result is stated in the following theorem.

Theorem 3.1. *Suppose that conditions (A1)-(A6) and (3.1) hold, and let $\{u, w\}$ be the solution to (CP) on R_+ . Further, suppose that for each $p \in R$ the (algebraic) inclusion*

$$\beta(r) + g(r) \ni p$$

has a finite number of solutions r in $\overline{D(\beta)}$. Then,

$$u(t) \longrightarrow u^\infty \text{ weakly in } H^1(\Omega) \text{ as } t \longrightarrow +\infty, \quad (3.6)$$

where u^∞ is the unique solution of (3.4), and there exists a function $w^\infty \in L^\infty(\Omega)$ such that

$$\beta(w^\infty(x)) + g(w^\infty(x)) \ni u^\infty(x) \quad \text{for a.e. } x \in \Omega$$

and

$$w(t, x) \longrightarrow w^\infty(x) \text{ for a.e. } x \in \Omega \text{ as } t \longrightarrow +\infty.$$

We prove the theorem by the following four lemmas.

Lemma 3.1. *Under the same assumptions of Theorem 3.1, for the solution $\{u, w\}$ to (CP) on R_+ , we have*

$$u - u_\infty \in L^2(R_+; H^1(\Omega)), \quad w' \in L^2(R_+; L^2(\Omega)) \text{ and } \hat{\beta}(w) \in L^\infty(R_+; L^1(\Omega)), \quad (3.7)$$

$$u \in L^\infty([1, +\infty); H^1(\Omega)). \quad (3.8)$$

Proof. Multiplying the difference of (1.1) and (3.2) by $u(t) - u^\infty$ and (1.2) by $w'(t)$, we get

$$\begin{aligned} & \frac{d}{dt} \left\{ \int_{\Omega} \rho^*(\rho(u(t))) dx - (\rho(u(t)) + w(t), u^\infty) \right\} + (w'(t), u(t)) + \\ & + |\nabla(u(t) - u^\infty)|_{L^2(\Omega)}^2 + \int_{\Gamma} \alpha_N |u(t) - u^\infty|^2 d\Gamma \\ & = (f(t) - f^\infty, u(t) - u^\infty) + \int_{\Gamma} (h(t) - h^\infty)(u(t) - u^\infty) d\Gamma \end{aligned}$$

and

$$\nu |w'(t)|_{L^2(\Omega)}^2 + \frac{d}{dt} \left\{ \int_{\Omega} \hat{\beta}(w(t)) dx + \int_{\Omega} \hat{g}(w(t)) dx \right\} = (u(t), w'(t))$$

for a.e. $t \geq 0$. Adding these two equalities we have

$$\begin{aligned} & \frac{d}{dt} \left\{ \int_{\Omega} \rho^*(\rho(u(t))) dx - (\rho(u(t)) + w(t), u^\infty) + \int_{\Omega} \hat{\beta}(w(t)) dx + \int_{\Omega} \hat{g}(w(t)) dx \right\} + \\ & + \nu |w'(t)|_{L^2(\Omega)}^2 + |\nabla(u(t) - u^\infty)|_{L^2(\Omega)}^2 + \int_{\Gamma} \alpha_N |u(t) - u^\infty|^2 d\Gamma \\ & = (f(t) - f^\infty, u(t) - u^\infty) + \int_{\Gamma} (h(t) - h^\infty)(u(t) - u^\infty) d\Gamma \end{aligned}$$

for a.e. $t \geq 0$, so that there are positive constants C_1 and C_2 such that

$$\begin{aligned} & \frac{d}{dt} \left\{ \int_{\Omega} \rho^*(\rho(u(t))) dx - (\rho(u(t)) + w(t), u^\infty) + \int_{\Omega} \hat{\beta}(w(t)) dx + \int_{\Omega} \hat{g}(w(t)) dx \right\} + \\ & + \nu |w'(t)|_{L^2(\Omega)}^2 + C_1 |u(t) - u^\infty|_{H^1(\Omega)}^2 \\ & \leq C_2 \{ |f(t) - f^\infty|_{L^2(\Omega)}^2 + |h(t) - h^\infty|_{L^2(\Gamma)}^2 \} \\ & \text{for a.e. } t \geq 0. \end{aligned}$$

Therefore, for all $T > 0$, we have

$$\begin{aligned} & \int_{\Omega} \rho^*(\rho(u(T))) dx - (\rho(u(T)) + w(T), u^\infty) + \int_{\Omega} \hat{\beta}(w(T)) dx + \int_{\Omega} \hat{g}(w(T)) dx + \\ & + \nu \int_0^T |w'(t)|_{L^2(\Omega)}^2 dt + C_1 \int_0^T |u(t) - u^\infty|_{H^1(\Omega)}^2 dt \\ & \leq C_2 \left\{ \int_0^T |f(t) - f^\infty|_{L^2(\Omega)}^2 dt + \int_0^T |h(t) - h^\infty|_{L^2(\Gamma)}^2 dt \right\} + \\ & + \int_{\Omega} \rho^*(\rho(u_0)) dx - (\rho(u_0) + w_0, u^\infty) + \int_{\Omega} \hat{\beta}(w_0) dx + \int_{\Omega} \hat{g}(w_0) dx. \end{aligned}$$

Hence (3.7) is obtained. Also, (3.8) is a direct consequence of (3.7) and a standard regularity result for parabolic equations. $\square$

Lemma 3.2. *Under the same assumptions of Theorem 3.1, put*

$$U^t(x) := \int_t^{t+1} |w'(\tau, x)|^2 d\tau \quad \text{for } x \in \Omega.$$

Then, $U^t(x) \rightarrow 0$ as $t \rightarrow +\infty$ for a.e. $x \in \Omega$.

Proof. By Lemma 3.1, we have

$$\lim_{T \nearrow +\infty} \int_T^{+\infty} dt \int_{\Omega} |w'(t, x)|^2 dx = 0,$$

so that

$$\lim_{T \nearrow +\infty} \int_{\Omega} dx \int_T^{+\infty} |w'(t, x)|^2 dt = 0.$$

Hence,

$$\int_T^{+\infty} |w'(t, x)|^2 dt \rightarrow 0 \text{ as } T \rightarrow +\infty \text{ for a.e. } x \in \Omega.$$

This implies the lemma. $\square$

Lemma 3.3. *Under the same assumptions of Theorem 3.1, (3.6) holds.*

Proof. Let $\{u, w\}$ be a solution to (CP) and u^∞ be the solution to (3.4).

Let $\{t_n\}$ be any sequence with $t_n \rightarrow +\infty$ as $n \rightarrow +\infty$, and put

$$u_n(t) := u(t_n + t), \quad w_n(t) := w(t_n + t), \quad f_n(t) := f(t_n + t), \quad h_n(t) := h(t_n + t)$$

$$\text{for } 0 \leq t \leq 1.$$

Since by Lemma 3.1, $u - u^\infty$ and w' are in $L^2(R_+; H^1(\Omega))$ and $L^2(R_+; L^2(\Omega))$, respectively, we see that

$$u_n \rightarrow u^\infty \text{ in } L^2(0, 1; H^1(\Omega)), \quad (3.9)$$

and

$$w'_n \rightarrow 0 \text{ in } L^2(0, 1; L^2(\Omega)), \quad (3.10)$$

as $n \rightarrow +\infty$. Moreover since by Lemma 3.1, u is bounded in $H^1(\Omega)$ on $[1, +\infty)$, we may assume that for a function $\tilde{u}^\infty$ in $H^1(\Omega)$

$$u_n(0) = u(t_n) \rightarrow \tilde{u}^\infty \text{ weakly in } H^1(\Omega) \quad (3.11)$$

as $n \rightarrow +\infty$. Now, consider the Cauchy problem for each n

$$\begin{cases} \rho(u_n)'(t) + \partial \Phi_n^t(u_n(t)) = f_n(t) - w'_n(t) & \text{in } L^2(\Omega), \quad 0 \leq t \leq 1, \\ u_n(0) = u(t_n) \end{cases}$$

where Φ_n^t is a proper l.s.c. and convex function on $L^2(\Omega)$ such that for each n and $t \in [0, 1]$

$$\Phi_n^t(z) := \begin{cases} \frac{1}{2} |z - h_n(t)|_V^2 & \text{if } z \in V, \\ +\infty & \text{otherwise,} \end{cases}$$

and $\partial \Phi_n^t$ is the subdifferential of Φ_n^t in $L^2(\Omega)$. From (3.9), (3.10) and (3.11), we see that

$$\Phi_n^t \rightarrow \Phi_\infty \quad \text{on } L^2(\Omega) \text{ in the sense of Mosco for every } t \in [0, 1],$$

$$f_n - w'_n \longrightarrow f^\infty \quad \text{in } L^2(0, 1; L^2(\Omega))$$

and

$$u_n(0) \longrightarrow \tilde{u}^\infty \quad \text{in } L^2(\Omega)$$

as $n \longrightarrow +\infty$, where Φ_∞ is a proper l.s.c. and convex function on $L^2(\Omega)$ such that

$$\Phi_\infty(z) := \begin{cases} \frac{1}{2}|z - h^\infty|_V^2 & \text{if } z \in V, \\ +\infty & \text{otherwise.} \end{cases}$$

Therefore, by a general theory in [8],

$$u_n \longrightarrow \tilde{u} \quad \text{in } C([0, 1]; L^2(\Omega)) \text{ as } t \longrightarrow +\infty, \quad (3.12)$$

where $\tilde{u}$ is the solution of

$$\begin{cases} \rho(\tilde{u})'(t) + \partial\Phi_\infty(\tilde{u}(t)) = f^\infty & \text{in } L^2(\Omega), 0 \leq t \leq 1, \\ \tilde{u}(0) = \tilde{u}^\infty. \end{cases}$$

From (3.9) and (3.12) it follows that $\tilde{u} = u^\infty$ on $[0, 1]$. Consequently (3.6) holds. $\square$

Lemma 3.4. *Under the same assumptions of Theorem 3.1, put*

$$V(x) := \{r \in \overline{D(\beta)}; w(t_n, x) \rightarrow r \text{ for some } t_n \text{ with } t_n \rightarrow +\infty\} \quad \text{for } x \in \Omega.$$

Then,

- (1) $V(x) \neq \emptyset$ for a.e. $x \in \Omega$;
- (2) $\beta(r) + g(r) \ni u^\infty(x)$ for all $r \in V(x)$ and a.e. $x \in \Omega$;
- (3) $V(x)$ is a singleton for a.e. $x \in \Omega$.

Proof. (1) is clear by the boundedness of $w(t, x)$ on R .

Let $x \in \Omega$ with $\lim_{t \rightarrow +\infty} \int_t^{t+1} |w'(\tau, x)|^2 d\tau = 0$ (cf. Lemma 3.2) and $r \in V(x)$. Then, there exists a sequence $\{t_n\}$ such that

$$t_n \longrightarrow +\infty \text{ and } w(t_n, x) \longrightarrow r \quad \text{as } n \longrightarrow +\infty.$$

Fixing x , put

$$w_n(t) := w(t_n + t, x), \quad u_n(t) := u(t_n + t, x) \quad \text{for } 0 \leq t \leq 1.$$

By Lemma 3.3 and (A2), we may assume that

$$u_n - g(w_n) \longrightarrow u^\infty(x) - g(r) \quad \text{in } L^2(0, 1) \text{ as } t \longrightarrow +\infty$$

Now consider a sequence of ODEs:

$$\begin{cases} w'_n(t) + \beta(w_n(t)) + g(w_n(t)) \ni u_n(t) & \text{for } 0 \leq t \leq 1, \\ w_n(0) = w(t_n, x). \end{cases}$$

By a general theory in [8] again, w_n converges in $C([0, 1])$ to the solution $\tilde{w}$ of

$$\begin{cases} \tilde{w}'(t) + \beta(\tilde{w}(t)) + g(\tilde{w}(t)) \ni u^\infty(x) & \text{for } 0 \leq t \leq 1, \\ \tilde{w}(0) = r. \end{cases} \quad (3.13)$$

But, since $\tilde{w}' \equiv 0$ i.e. $\tilde{w} \equiv r$ by assumption, we see from (3.13) that

$$\beta(r) + g(r) \ni u^\infty(x).$$

Thus, (2) is proved. At last, we show (3). Suppose that $V(x)$ has more than two elements for some $x \in \Omega$, say $r_1, r_2 \in V(x)$, $r_1 < r_2$. By definition, there exists two sequence $\{s_n\}$ and $\{t_n\}$ such that

$$\begin{aligned} s_n &\longrightarrow +\infty, \quad w(s_n, x) \longrightarrow r_1, \\ t_n &\longrightarrow +\infty, \quad w(t_n, x) \longrightarrow r_2 \end{aligned}$$

as $n \longrightarrow +\infty$, and

$$s_n < t_n < s_{n+1} < t_{n+1} \quad \text{for } n = 1, 2, 3, \dots$$

From the continuity of w with respect to t , for any $r \in (r_1, r_2)$, there exists a sequence $\{\tau_n\}$ with $\tau_n \longrightarrow +\infty$ ($n \longrightarrow +\infty$) such that

$$s_n < \tau_n < t_n \quad \text{for } n = 1, 2, 3, \dots \text{ and } w(\tau_n, x) = r \text{ for large } n.$$

This implies that $r \in V(x)$ and hence $[r_1, r_2] \subset V(x)$. This contradicts the assumption that $\beta(r) + g(r) \ni u^\infty(x)$ has a finite number of solutions r in $\overline{D(\beta)}$. Thus, $V(x)$ must be a singleton for a.e. $x \in \Omega$. $\square$

In particular, (2) and (3) of Lemma 3.4 imply that $w(t, x)$ converges to a solution $w^\infty(x)$ for a.e. $x \in \Omega$ as $t \longrightarrow +\infty$ and the limit w^∞ is a solution of (P^∞) . Thus we complete the proof of Theorem 3.1.

References

1. D. Blanchard, A. Damlamian and H. Ghidouche, A nonlinear system for phase change with dissipation, *Diff. Int. Eq.* **2**(3)(1989), 344-362.
2. D. Blanchard and H. Ghidouche, A nonlinear system for irreversible phase change, *Euro. J. Appl. Math.* **1**(1990), 91-100.

3. G. Caginalp, An analysis of a phase field model of a free boundary, *Arch. Rat. Mech. Anal.*, **92**(1986), 205-245.
4. A. Damlamian and N. Kenmochi, Asymptotic behavior of solutions to a multi-phase Stefan problem, *Japan J. Appl. Math.*, **3**(1986), 15-35.
5. A. Damlamian, N. Kenmochi and N. Sato, Subdifferential operator approach to a class of nonlinear systems for Stefan problems with phase relaxation, to appear in *Nonlinear Anal. TMA*.
6. A. Damlamian, N. Kenmochi and N. Sato, Phase field equations with constraints, "*Non-linear Mathematical Problems in Industry*", pp. 391-404, Gakuto. Inter. Ser. Math. Sci. Appl. Vol.2, Gakkōtoshō, Tokyo, 1993.
7. G. J. Fix, Phase field models for free boundary problems, *Free Boundary Problems: Theory and Applications*, pp.580-589, Pitman Reserch Notes in Math. Ser. Vol. 79, 1983.
8. N. Kenmochi, Solvability of nonlinear evolution equations with time-dependent constraints and applications, *Bull. Fac. Education, Chiba Univ.*, **30**(1981), 1-87.
9. N. Kenmochi, Systems of nonlinear PDEs arising from dynamical phase transitions, to appear in *Lecture Notes Math.*, Springer.
10. N. Kenmochi and M. Niezgódka, Systems of nonlinear parabolic equations for phase change problems, *Adv. Math. Sci. Appl.*, **3**(1994), 89-117.
11. Ph. Laurençot, A double obstacle problem, to appear in *J. Math. Anal. Appl.*
12. A. Visintin, Stefan problems with phase relaxation, *IMA J. Math.*, **34**(1985), 225-245.

Naoki SATO, Jun SHIROHIZU
 Department of Mathematics
 Graduate School of Science and Technology
 Chiba University
 263 Chiba, Japan

Nobuyuki KENMOCHI
 Department of Mathematics, Faculty of Education
 Chiba University
 263 Chiba, Japan