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Nonlinear Fokker-Planck equation with reflecting boundary conditions

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Abstract

We study the existence and uniqueness of a mild solution to a nonlinear Fokker-Planck equation with reflecting boundary conditions, by using a monotonicity approach. Then we prove that the mild solution is also a distributional one.

Keywords: Fokker-Planck equation, m-accretive operator, mild solution, McKean-Vlasov stochastic differential equation

AMS [2020] Primary 60H30, 60H10, 60G46; secondary 35Q84, 35D99

1 Introduction

In the present work we are interested in the study of a nonlinear Fokker-Planck equation with Neumann boundary conditions of the following type

$$\begin{cases} \frac{\partial y}{\partial t} - \frac{1}{2} \Delta \beta(y) - \operatorname{div}(b(\xi)y) = 0, & [0, T] \times \mathcal{O}, \\ \frac{1}{2} \frac{\partial}{\partial n} \beta(y) + (b(\xi) \cdot n(\xi))y = 0, & [0, T] \times \partial \mathcal{O}, \\ y(0, \xi) = y_0(\xi), & \xi \in \mathcal{O}. \end{cases} \quad (1)$$

Here $\mathcal{O} \subset \mathbb{R}^d$, $d \geq 1$, is assumed to be an open bounded and convex domain with smooth boundary $\partial \mathcal{O}$. We denoted by n the outward normal to $\partial \mathcal{O}$ and by $\frac{\partial}{\partial n}$ the outward normal derivative. The closer of \mathcal{O} is denoted by $\overline{\mathcal{O}} = K$.

Assumptions

We shall assume the following hypotheses on the functions $\beta : \mathbb{R} \rightarrow \mathbb{R}$ and $b : \overline{\mathcal{O}} \rightarrow \mathbb{R}^d$:

- i) $\beta \in C(\mathbb{R})$, $\beta(0) = 0$, and β is increasing maximal monotone such that, for $m \geq 1$ we have

$$|\beta(r)| \leq \alpha_1 |r|^m + \alpha_2, \text{ for all } r \in \mathbb{R},$$

for some constants $\alpha_1 > 0$ and $\alpha_2 \geq 0$.

- ii) j is the potential of β , i.e. $\partial j = \beta$, and we assume that for the same $m \geq 1$ we have

$$j(r) \geq \alpha_3 r^{m+1}, \text{ for all } r \in \mathbb{R},$$

for some positive constant α_3 .

- iii) $b \in C^1(\overline{\mathcal{O}})$ is a given function such that $\operatorname{div} b \leq 0$ in $\overline{\mathcal{O}}$, $b \cdot n \geq 0$ on $\partial\mathcal{O}$ and $|b|_\infty < 1$.

Equation (1), where y is a probability density, is known in the literature as the nonlinear Fokker-Planck equation with reflection. For reader's convenience we shall give some details concerning the connection with a stochastic differential equation.

If we choose the solution $y : [0, T] \times \mathcal{O} \rightarrow \mathbb{R}$ in the class of probability density functions on \mathcal{O} , i.e. such that $y \in L^1(\mathcal{O})$, $y \geq 0$ a.e. on \mathcal{O} and $\int_{\mathcal{O}} y(\xi) d\xi = 1$, then y can be seen as the probability density of the law \mathcal{L}_X , where X is the weak solution (in the stochastic sense) to the following stochastic differential equation with reflection

$$\begin{cases} dX(t) + b(X(t)) dt + N_K(X(t)) dt \ni \sqrt{\frac{\beta(y(t, X(t)))}{y(t, X(t))}} dW_t \\ X(0) = X_0 \end{cases} \quad (2)$$

in a probability space $(\Omega, \mathcal{F}, (\mathcal{F}_t)_t, \mathbb{P})$ where $(\mathcal{F}_t)_t$ is the normal filtration and W_t , $t \geq 0$, is a Wiener process.

Keeping in mind that $K = \overline{\mathcal{O}}$, we recall that $N_K : K \rightarrow 2^{\mathbb{R}^d}$ is the normal cone to K , i.e.

$$N_K(x) = \{z \in \mathbb{R}^d; (z, x - y)_{\mathbb{R}^d} \geq 0, \quad \forall y \in K\}.$$

Actually, the reflecting boundary condition from equation (1) gives the second drift term $N_K(X)$ from the stochastic equation (2).

Concerning the stochastic differential equation, we recall the definition of the solution.

Definition 1 *We call a strong solution to the stochastic differential equation (2) a pair of continuous \mathbb{R}^d -valued and \mathcal{F}_t -adapted processes $(X(t), \eta(t))$, $t \in [0, T]$ such that*

- 1) $X(t) \in K$, \mathbb{P} -a.s., for all $t \in [0, T]$.

2) $\exists \eta \in BV([0, T]; \mathbb{R}^d)$, \mathbb{P} -a.s., such that

$$X(t) + \int_0^t b(X(s)) ds + \eta(t) = X_0 + \int_0^t \sqrt{\frac{\beta(y(s, X(s)))}{y(s, X(s))}} dW_s$$

$$\int_0^T (X(s) - Z(s)) \cdot d\eta(s) \geq 0, \quad \forall Z \in C([0, T]; K).$$

As usual, $BV([0, T]; \mathbb{R}^d)$ is the space of functions with bounded variation and $\int_0^T (X(s) - Z(s)) \cdot d\eta(s)$ is the Riemann-Stieltjes integral.

Equations as (2) are usually referred as McKean-Vlasov SDEs. For classical results concerning this equation see [12], [16], [17], [19], [21]. Recently there was a large interest concerning this subject in different situations (see e.g. [5], [13], [14], [18]).

One can prove that, if y is a solution to (1), then there is a martingale solution X to (2) which has y as probability density, by using the superposition principle by Trevisan [22] (which is a generalization of the work of Figalli [11]) and by a classical result of Stroock-Varadhan (see [20]). For the general McKean-Vlasov equation see e.g. [6], [7]. For an immediate extension to a stochastic reflection problem as in the present case see [3].

In the present work we are interested to treat the well-posedness of the nonlinear Fokker-Planck equation (1) in $L^1(\mathcal{O})$. This work follows the direction opened by Barbu and Röckner in [5], [6], [7], [8] for the Fokker-Planck equation with Dirichlet boundary conditions under different sets of assumptions. This approach is based on the Crandall and Liggett existence theorem for a nonlinear Cauchy problem in a Banach space.

Concerning the Fokker-Planck equation with Neumann boundary condition we refer to [3] for a controllability problem treating an equation with a particular form of the function β which is Lipschitz.

In the present work we study a general Fokker-Planck equation with Neumann boundary conditions, under general growth conditions on β . The main objective of this paper is to prove existence and uniqueness of the mild solution to equation (1) and then to show that it is also a variational solution.

For reader's convenience we shall first recall the following definitions.

Definition 2 Let $y_0 \in L^2(\mathcal{O})$. The function y is called a mild solution to equation (1) if $y \in C([0, T]; L^1(\mathcal{O}))$ and

$$y(t) = \lim_{\delta \rightarrow \infty} y_\delta(t) \text{ in } L^1(\mathcal{O}), \text{ uniformly on } [0, T],$$

where $y_\delta : [0, T] \rightarrow \mathbb{R}$ is a step function such that

$$y_\delta(t) = y_\delta^i, \quad \forall t \in [i\delta, (i+1)\delta), \quad i = 0, 1, \dots, N_\delta - 1,$$

for $N_\delta = \lceil \frac{T}{\delta} \rceil$ which satisfies

$$\frac{1}{\delta} \int_{\mathcal{O}} (y_\delta^{i+1}(\xi) - y_\delta^i(\xi)) \psi(\xi) d\xi + \int_{\mathcal{O}} \left(\frac{1}{2} \nabla \beta(y_\delta^{i+1}) + b(\xi) y_\delta^{i+1} \right) \nabla \psi(\xi) d\xi = 0,$$

for $\forall \psi \in H^1(\mathcal{O})$ such that $y_\delta^0 = y_0$ and $\beta(y_\delta^{i+1}) \in H^1(\mathcal{O})$.

Definition 3 Let $y_0 \in L^2(\mathcal{O})$. We say that y is a distributional solution to (1) if

$$y \in C([0, 1]; L^1(\mathcal{O})), \quad \beta(y) \in L^2(0, T; H_0^1(\mathcal{O}))$$

such that

$$\begin{aligned} \int_0^T \int_{\mathcal{O}} \left(y \frac{\partial \varphi}{\partial t} - \frac{1}{2} \nabla \beta(y) \cdot \nabla \varphi - (b \cdot \nabla \varphi) y \right) d\xi dt \\ + \int_{\mathcal{O}} y_0(\xi) \varphi(0, \xi) d\xi = 0 \end{aligned} \quad (3)$$

for all $\varphi \in C^1([0, T] \times \overline{\mathcal{O}})$, $\varphi(T, \cdot) = 0$.

Notations

For an open subset $\mathcal{O} \subset \mathbb{R}^d$ we denote by $L^p(\mathcal{O})$, $1 \leq p \leq \infty$, the space of standard Lebesgue p -integrable functions on \mathcal{O} , and by $W^{1,p}(\mathcal{O})$ the Sobolev space $\{u \in L^p(\mathcal{O}), D_i u \in L^p(\mathcal{O}) \text{ for } i = 1, 2, \dots, d\}$ where $D_i = \frac{\partial}{\partial x_i}$ is taken in the sense of Schwartz distributions. In particular, we denote by $H^1(\mathcal{O}) = W^{1,2}(\mathcal{O})$.

2 The main results

We can formulate now the main result of this work.

Theorem 4 Assuming the hypotheses above, for each $y \in L^1(\mathcal{O})$, there is a unique mild solution y to equation (1).

Moreover, if $y_0 \geq 0$ a.e. on \mathcal{O} and $\int_{\mathbb{R}} y_0(\xi) d\xi = 1$, then $y(t)$ is a probability density function on \mathcal{O} for $\forall t \in [0, T]$.

Furthermore, y is also a distributional solution to (1).

The main idea is to rewrite equation (1) as a Cauchy problem of the form

$$\begin{cases} dy + A(y) = 0, & (0, T), \\ y(0) = y_0, \end{cases}$$

in the space $L^1(\mathcal{O})$, where $A : D(A) \subset L^1(\mathcal{O}) \rightarrow L^1(\mathcal{O})$ is an appropriate m -accretive operator and to apply the Crandall-Liggett theorem. To this purpose we shall first study this operator in the $L^2(\mathcal{O})$ space framework.

The $L^2(\mathcal{O})$ approach

We define the operator

$$\begin{aligned} A_0 & : D(A_0) \subset L^2(\mathcal{O}) \rightarrow L^2(\mathcal{O}) \\ D(A_0) & = \left\{ u \in L^2(\mathcal{O}); \Delta\beta(u) + \operatorname{div}(bu) \in L^2(\mathcal{O}), \right. \\ & \quad \left. \frac{\partial}{\partial n}\beta(u) + (b \cdot n)u = 0 \text{ a.e. on } \partial\mathcal{O} \right\} \\ A_0(u) & = -\Delta\beta(u) - \operatorname{div}(bu). \end{aligned}$$

For some $f \in L^2(\mathcal{O})$ arbitrarily fixed and $u \in H^1(\mathcal{O})$, if we consider the equation

$$A_0 u = f$$

i.e.

$$\begin{cases} -\frac{1}{2}\Delta\beta(u) - \operatorname{div}(bu) = f, & \text{in } \mathcal{O} \\ \frac{1}{2}\frac{\partial}{\partial n}\beta(u) + (b \cdot n)u = 0, & \text{on } \partial\mathcal{O} \end{cases}$$

we can write its variational formulation as follows

$$\int_{\mathcal{O}} \left(\frac{1}{2}\nabla\beta(u(\xi)) + b(\xi)u(\xi) \right) \nabla\psi(\xi) d\xi = \int_{\mathcal{O}} f(\xi)\psi(\xi) d\xi, \quad \forall \psi \in H^1(\mathcal{O}).$$

Proposition 5 *Assuming the hypotheses above, there is $\lambda_0 > 0$ such that, for all $f \in L^2(\mathcal{O})$ and $\lambda \in (0, \lambda_0)$ arbitrarily fixed, the equation*

$$u + \lambda A_0 u = f \tag{4}$$

has a unique variational solution u .

Furthermore, if we denote by $(I + \lambda A_0)^{-1}(f)$ the solution to equation (4) for each λ and f , we have the following propertie

$$\left| (I + \lambda A_0)^{-1}(f_1) - (I + \lambda A_0)^{-1}(f_2) \right|_{L^1(\mathcal{O})} \leq |f_1 - f_2|_{L^1(\mathcal{O})}, \quad \forall f_1, f_2 \in L^2(\mathcal{O}). \tag{5}$$

In addition, we have that $(I + \lambda A_0)^{-1}(f)$ is a probability density function on \mathcal{O} for all $f \in L^2(\mathcal{O})$ which is also a probability density function.

Proof. We shall first rewrite (4) as

$$\begin{cases} u - \frac{1}{2}\lambda\Delta\beta(u) - \lambda\operatorname{div}(bu) = f, & \text{in } \mathcal{O}, \\ \frac{1}{2}\frac{\partial}{\partial n}\beta(u) + (b \cdot n)u = 0, & \text{on } \partial\mathcal{O}, \end{cases} \tag{6}$$

with the variational formulation

$$\begin{aligned} & \int_{\mathcal{O}} u\psi d\xi + \frac{\lambda}{2} \int_{\mathcal{O}} \nabla\beta(u(\xi)) \nabla\psi d\xi + \lambda \int_{\mathcal{O}} (b(\xi) \cdot \nabla\psi(\xi)) u(\xi) d\xi \quad (7) \\ &= \int_{\mathcal{O}} f(\xi) \psi(\xi) d\xi, \quad \psi \in H^1(\mathcal{O}). \end{aligned}$$

We approximate the operator β by $\tilde{\beta}_\varepsilon(r) = \beta_\varepsilon(r) + \varepsilon r$ where β_ε is the Yosida approximation of β , i.e.,

$$\beta_\varepsilon(r) = \frac{1}{\varepsilon} (r - J_\varepsilon(r)) = \beta(J_\varepsilon(r))$$

for

$$J_\varepsilon(r) = (Id + \varepsilon\beta)^{-1}(r), \quad \forall r \in \mathbb{R}.$$

Since β_ε is Lipschitz and increasing, we can easily see that $\tilde{\beta}_\varepsilon$ is also Lipschitz and strongly monotone, that is

$$\left(\tilde{\beta}_\varepsilon(r) - \tilde{\beta}_\varepsilon(\bar{r})\right) (r - \bar{r}) \geq \varepsilon |r - \bar{r}|^2, \quad \forall r, \bar{r} \in \mathbb{R}.$$

Note that this property implies that $\left(\tilde{\beta}_\varepsilon\right)^{-1}$ is also Lipschitz, where $\left(\tilde{\beta}_\varepsilon\right)^{-1}$ is the inverse of $\tilde{\beta}_\varepsilon$.

We approximate equation (6) by

$$\begin{cases} u^\varepsilon - \frac{1}{2} \lambda \Delta \tilde{\beta}_\varepsilon(u^\varepsilon) - \lambda \operatorname{div}(bu^\varepsilon) = f, & \text{in } \mathcal{O}, \\ \frac{1}{2} \frac{\partial}{\partial n} \tilde{\beta}_\varepsilon(u^\varepsilon) + (b \cdot n) u^\varepsilon = 0, & \text{on } \partial\mathcal{O}, \end{cases} \quad (8)$$

with the variational formulation

$$\begin{aligned} & \int_{\mathcal{O}} u^\varepsilon \psi d\xi + \frac{\lambda}{2} \int_{\mathcal{O}} \nabla \tilde{\beta}_\varepsilon(u^\varepsilon(\xi)) \nabla \psi d\xi + \lambda \int_{\mathcal{O}} (b(\xi) \cdot \nabla \psi(\xi)) u^\varepsilon(\xi) d\xi \quad (9) \\ &= \int_{\mathcal{O}} f(\xi) \psi(\xi) d\xi, \quad \psi \in H^1(\mathcal{O}). \end{aligned}$$

If we denote by $\left(\tilde{\beta}_\varepsilon\right)^{-1}$ the inverse of $\tilde{\beta}_\varepsilon$, we can rewrite (8) as follows

$$\begin{cases} \left(\tilde{\beta}_\varepsilon\right)^{-1}(v^\varepsilon) - \frac{1}{2} \lambda \Delta v^\varepsilon - \lambda \operatorname{div}\left(b \left(\tilde{\beta}_\varepsilon\right)^{-1}(v^\varepsilon)\right) = f, & \text{in } \mathcal{O}, \\ \frac{1}{2} \frac{\partial}{\partial n} v^\varepsilon + (b \cdot n) \left(\tilde{\beta}_\varepsilon\right)^{-1}(v^\varepsilon) = 0, & \text{on } \partial\mathcal{O}. \end{cases} \quad (10)$$

Note that since $\tilde{\beta}_\varepsilon$ is strictly monotone, we can easily see that $\left(\tilde{\beta}_\varepsilon\right)^{-1}$ is Lipschitz on \mathbb{R} .

Let us define the operator

$$B^\varepsilon : H^1(\mathcal{O}) \rightarrow (H^1)^*(\mathcal{O})$$

such that, for each $v \in H^1(\mathcal{O})$ we have

$$\begin{aligned} (H^1)^* \langle B^\varepsilon(v), \varphi \rangle_{H^1} &= \int_{\mathcal{O}} \left(\tilde{\beta}_\varepsilon \right)^{-1}(v) \varphi d\xi \\ &+ \frac{\lambda}{2} \int_{\mathcal{O}} \nabla v \nabla \varphi d\xi \\ &+ \lambda \int_{\mathcal{O}} b(\xi) \cdot \nabla \varphi \left(\tilde{\beta}_\varepsilon \right)^{-1}(v) d\xi, \text{ for } \forall \varphi \in H^1(\mathcal{O}). \end{aligned}$$

We can now rewrite equation (10) as

$$B^\varepsilon(v^\varepsilon) = f. \quad (11)$$

We shall first show that the operator B^ε is strictly monotone. We have

$$\begin{aligned} (H^1)^* \langle B^\varepsilon(v) - B^\varepsilon(\bar{v}), v - \bar{v} \rangle_{H^1} &= \int_{\mathcal{O}} \left(\left(\tilde{\beta}_\varepsilon \right)^{-1}(v) - \left(\tilde{\beta}_\varepsilon \right)^{-1}(\bar{v}) \right) (v - \bar{v}) d\xi \\ &+ \frac{\lambda}{2} \int_{\mathcal{O}} \nabla(v - \bar{v}) d\xi \\ &+ \lambda \int_{\mathcal{O}} b(\xi) \cdot \nabla(v - \bar{v}) \left(\left(\tilde{\beta}_\varepsilon \right)^{-1}(v) - \left(\tilde{\beta}_\varepsilon \right)^{-1}(\bar{v}) \right) d\xi. \end{aligned}$$

Since by assumption *i*) we have that

$$\left(\left(\tilde{\beta}_\varepsilon \right)^{-1}(v) - \left(\tilde{\beta}_\varepsilon \right)^{-1}(\bar{v}) \right) (v - \bar{v}) \geq \varepsilon \left| \left(\tilde{\beta}_\varepsilon \right)^{-1}(v) - \left(\tilde{\beta}_\varepsilon \right)^{-1}(\bar{v}) \right|^2$$

we obtain

$$\begin{aligned} (H^1)^* \langle B^\varepsilon(v) - B^\varepsilon(\bar{v}), v - \bar{v} \rangle_{H^1} &\geq \frac{\lambda}{4} \int_{\mathcal{O}} |\nabla(v - \bar{v})|^2 d\xi \\ &+ (\varepsilon - |b|_\infty \lambda) \int_{\mathcal{O}} \left| \left(\tilde{\beta}_\varepsilon \right)^{-1}(v) - \left(\tilde{\beta}_\varepsilon \right)^{-1}(\bar{v}) \right|^2 \\ &\geq 0, \text{ for } \lambda < \frac{\varepsilon}{2|b|_\infty} = \lambda_0. \end{aligned}$$

Keeping in mind that $\beta(0) = 0$ we have also that

$$(H^1)^* \langle B^\varepsilon(v), v \rangle_{H^1} \geq \frac{\lambda}{4} \int_{\mathcal{O}} |\nabla(v)|^2 d\xi + (\varepsilon - |b|_\infty \lambda) \int_{\mathcal{O}} \left| \left(\tilde{\beta}_\varepsilon \right)^{-1}(v) \right|^2,$$

for $\lambda < \frac{\varepsilon}{2|b|_\infty} = \lambda_0$. Since $\tilde{\beta}_\varepsilon$ is Lipschitz we have that $\left| \left(\tilde{\beta}_\varepsilon \right)^{-1}(v) \right| \geq C|v|$, for some positive constant $C(\varepsilon)$ and for each ε fixed, and therefore B^ε is coercive from H^1 to $(H^1)^*$.

Keeping in mind that B^ε is also continuous and monotone, we can now use the Minty-Browder theorem and get that B^ε is surjective. Therefore equation (11) has a unique solution $v^\varepsilon \in H^1(\mathcal{O})$ for each ε fixed.

We obtain that $u^\varepsilon = \tilde{\beta}_\varepsilon(v^\varepsilon) \in L^2(\mathcal{O})$ is a solution to (6).

We shall now prove that

$$|u^\varepsilon(\lambda, f_1) - u^\varepsilon(\lambda, f_2)|_{L^1(\mathcal{O})} \leq |f_1 - f_2|_{L^1(\mathcal{O})}, \quad \forall f_1, f_2 \in L^2(\mathcal{O}),$$

by using a similar approach with the one suggested in [4] [5] and [6]. To this purpose we define the function

$$\chi_\alpha(r) = \begin{cases} 1, & r > \alpha, \\ \frac{r}{\alpha}, & |r| \leq \alpha, \\ -1, & r < -\alpha, \end{cases}$$

for $\alpha > 0$.

On the other hand, from the variational form of the solution, we have for $u_i^\varepsilon = u^\varepsilon(\lambda, f_i)$ where $f_i \in L^2(\mathcal{O})$, $i = \overline{1, 2}$, that

$$\begin{aligned} & \int_{\mathcal{O}} (u_1^\varepsilon - u_2^\varepsilon) \psi d\xi + \frac{\lambda}{2} \int_{\mathcal{O}} \left(\nabla \tilde{\beta}_\varepsilon(u_1^\varepsilon) - \nabla \tilde{\beta}_\varepsilon(u_2^\varepsilon) \right) \nabla \psi d\xi \\ & + \lambda \int_{\mathcal{O}} b(\xi) \cdot \nabla \psi (u_1^\varepsilon - u_2^\varepsilon) d\xi \\ & = \int_{\mathcal{O}} (f_1 - f_2) \psi d\xi, \quad \psi \in H^1(\mathcal{O}). \end{aligned}$$

If we take $\psi = \chi_\alpha \left(\tilde{\beta}_\varepsilon(u_1^\varepsilon) - \tilde{\beta}_\varepsilon(u_2^\varepsilon) \right)$, in the previous relation, we get

$$\begin{aligned} & \int_{\mathcal{O}} (u_1^\varepsilon - u_2^\varepsilon) \chi_\alpha \left(\tilde{\beta}_\varepsilon(u_1^\varepsilon) - \tilde{\beta}_\varepsilon(u_2^\varepsilon) \right) d\xi \\ & + \frac{\lambda}{2} \int_{\mathcal{O}} \left| \nabla \tilde{\beta}_\varepsilon(u_1^\varepsilon) - \nabla \tilde{\beta}_\varepsilon(u_2^\varepsilon) \right|^2 \chi'_\alpha d\xi \\ & + \lambda \int_{\mathcal{O}} b(\xi) \cdot \nabla \left(\tilde{\beta}_\varepsilon(u_1^\varepsilon) - \tilde{\beta}_\varepsilon(u_2^\varepsilon) \right) \chi'_\alpha (u_1^\varepsilon - u_2^\varepsilon) d\xi \\ & \leq \int_{\mathcal{O}} |f_1 - f_2| d\xi, \end{aligned}$$

where we denoted by $\chi'_\alpha = \chi'_\alpha \left(\tilde{\beta}_\varepsilon(u_1^\varepsilon) - \tilde{\beta}_\varepsilon(u_2^\varepsilon) \right)$.

Since $\chi_\alpha < 1$, $\chi'_\alpha > 0$ and keeping in mind the explicit form of χ_α we have

$$\begin{aligned} & \int_{\mathcal{O}} (u_1^\varepsilon - u_2^\varepsilon) \chi_\alpha \left(\tilde{\beta}_\varepsilon(u_1^\varepsilon) - \tilde{\beta}_\varepsilon(u_2^\varepsilon) \right) d\xi \\ & \leq \frac{\lambda}{\alpha} |b|_\infty \int_{[\tilde{\beta}_\varepsilon(u_1) - \tilde{\beta}_\varepsilon(u_2) < \alpha]} \left| \nabla \left(\tilde{\beta}_\varepsilon(u_1^\varepsilon) - \tilde{\beta}_\varepsilon(u_2^\varepsilon) \right) \right| |u_1^\varepsilon - u_2^\varepsilon| d\xi \\ & \quad + \int_{\mathcal{O}} |f_1 - f_2| d\xi. \end{aligned} \tag{12}$$

We calculate the first term from the right hand side of the previous relation.

Since $\tilde{\beta}_\varepsilon$ is strongly increasing and therefore $\left(\tilde{\beta}_\varepsilon \right)^{-1}$ is Lipschitz, we have that

$$|u_1^\varepsilon - u_2^\varepsilon| \leq \frac{1}{\varepsilon} \left| \tilde{\beta}_\varepsilon(u_1^\varepsilon) - \tilde{\beta}_\varepsilon(u_2^\varepsilon) \right|,$$

and therefore

$$\begin{aligned} & \lim_{\alpha \rightarrow 0} \frac{\lambda}{\alpha} |b|_\infty \int_{[\tilde{\beta}_\varepsilon(u_1) - \tilde{\beta}_\varepsilon(u_2) < \alpha]} \left| \nabla \left(\tilde{\beta}_\varepsilon(u_1^\varepsilon) - \tilde{\beta}_\varepsilon(u_2^\varepsilon) \right) \right| |u_1^\varepsilon - u_2^\varepsilon| d\xi \\ & \leq \lim_{\alpha \rightarrow 0} \frac{\lambda}{\varepsilon} |b|_\infty \int_{[\tilde{\beta}_\varepsilon(u_1) - \tilde{\beta}_\varepsilon(u_2) < \alpha]} \left| \nabla \left(\tilde{\beta}_\varepsilon(u_1^\varepsilon) - \tilde{\beta}_\varepsilon(u_2^\varepsilon) \right) \right| d\xi = 0. \end{aligned}$$

Going back to (12) and considering that $\lim_{\alpha \rightarrow 0} \chi_\alpha = \text{sgn}$ and

$$\text{sgn} \left(\tilde{\beta}_\varepsilon(u_1^\varepsilon) - \tilde{\beta}_\varepsilon(u_2^\varepsilon) \right) = \text{sgn}(u_1^\varepsilon - u_2^\varepsilon)$$

we obtain that

$$\lim_{\alpha \rightarrow 0} \int_{\mathcal{O}} (u_1^\varepsilon - u_2^\varepsilon) \chi_\alpha \left(\tilde{\beta}_\varepsilon(u_1^\varepsilon) - \tilde{\beta}_\varepsilon(u_2^\varepsilon) \right) d\xi = |u_1^\varepsilon - u_2^\varepsilon|_{L^1(\mathcal{O})}.$$

This leads to

$$|u_1^\varepsilon - u_2^\varepsilon|_{L^1(\mathcal{O})} \leq |f_1 - f_2|_{L^1(\mathcal{O})}, \quad \forall f_1, f_2 \in L^2(\mathcal{O}). \tag{13}$$

We shall now pass to the limit for $\varepsilon \rightarrow 0$ in the approximating equation (8) with the variational formulation (9). To this purpose we need the following estimates.

First we take $\psi = u^\varepsilon$ and we get

$$\int_{\mathcal{O}} |u^\varepsilon|^2 d\xi + \frac{1}{2} \lambda \int_{\mathcal{O}} \nabla \tilde{\beta}_\varepsilon(u^\varepsilon) \nabla u^\varepsilon d\xi + \lambda \int_{\mathcal{O}} (b \cdot \nabla u^\varepsilon) u^\varepsilon d\xi = \int_{\mathcal{O}} f u^\varepsilon d\xi.$$

Since, by assumption *iii*) we have that

$$\frac{1}{2} \int_{\mathcal{O}} b \cdot \nabla (u^\varepsilon)^2 d\xi = -\frac{1}{2} \int_{\mathcal{O}} \text{div} b (u^\varepsilon)^2 d\xi + \frac{1}{2} \int_{\partial \mathcal{O}} (b \cdot n) (u^\varepsilon)^2 d\xi \geq 0$$

we get $\{u^\varepsilon\}$ is bounded in $L^2(\mathcal{O})$.

Then we take $\psi = \tilde{\beta}_\varepsilon(u^\varepsilon)$ and we get

$$\begin{aligned} & \int_{\mathcal{O}} u^\varepsilon \tilde{\beta}_\varepsilon(u^\varepsilon) d\xi + \frac{1}{2} \lambda \int_{\mathcal{O}} \left| \nabla \tilde{\beta}_\varepsilon(u^\varepsilon) \right|^2 d\xi + \lambda \int_{\mathcal{O}} \left(b \cdot \nabla \tilde{\beta}_\varepsilon(u^\varepsilon) \right) u^\varepsilon d\xi \quad (14) \\ &= \int_{\mathcal{O}} f \tilde{\beta}_\varepsilon(u^\varepsilon) d\xi. \end{aligned}$$

We calculate

$$\begin{aligned} \int_{\mathcal{O}} u^\varepsilon \tilde{\beta}_\varepsilon(u^\varepsilon) d\xi &= \int_{\mathcal{O}} u^\varepsilon \beta_\varepsilon(u^\varepsilon) d\xi + \int_{\mathcal{O}} |u^\varepsilon|^2 d\xi \\ &\geq \int_{\mathcal{O}} (u^\varepsilon - J_\varepsilon(u^\varepsilon)) \beta(J_\varepsilon(u^\varepsilon)) d\xi + \int_{\mathcal{O}} J_\varepsilon(u^\varepsilon) \beta(J_\varepsilon(u^\varepsilon)) d\xi \\ &\geq \alpha_3 \int_{\mathcal{O}} |J_\varepsilon(u^\varepsilon)|^{m+1} d\xi \end{aligned}$$

and

$$\lambda \int_{\mathcal{O}} \left(b \cdot \nabla \tilde{\beta}_\varepsilon(u^\varepsilon) \right) u^\varepsilon d\xi \leq \frac{1}{4} \lambda \int_{\mathcal{O}} \left| \nabla \tilde{\beta}_\varepsilon(u^\varepsilon) \right|^2 d\xi + C \int_{\mathcal{O}} |u^\varepsilon|^2 d\xi.$$

By going back to (14) we get

$$\begin{aligned} & \alpha_3 \int_{\mathcal{O}} |J_\varepsilon(u^\varepsilon)|^{m+1} d\xi + \frac{1}{4} \lambda \int_{\mathcal{O}} \left| \nabla \tilde{\beta}_\varepsilon(u^\varepsilon) \right|^2 d\xi \quad (15) \\ & \leq C + \frac{\rho}{2} \int_{\mathcal{O}} |f|^{m+1} d\xi + \frac{1}{2\rho} \int_{\mathcal{O}} \left| \tilde{\beta}_\varepsilon(u^\varepsilon) \right|^{\frac{m+1}{m}} d\xi. \end{aligned}$$

Since

$$\tilde{\beta}_\varepsilon(u^\varepsilon) = \beta_\varepsilon(u^\varepsilon) + \varepsilon u^\varepsilon$$

we have

$$\int_{\mathcal{O}} \left| \tilde{\beta}_\varepsilon(u^\varepsilon) \right|^{\frac{m+1}{m}} d\xi \leq 2^{\frac{1}{m}} |\beta(J_\varepsilon(u^\varepsilon))|^{\frac{m+1}{m}} + 2^{\frac{1}{m}} \varepsilon^{\frac{m+1}{m}} |u^\varepsilon|^{\frac{m+1}{m}}.$$

On the other hand, since $|\beta(r)| \leq \alpha_1 |r|^m + \alpha_2, \forall r \in \mathbb{R}$, we have that

$$|\beta(J_\varepsilon(u^\varepsilon))|^{\frac{m+1}{m}} = \int_{\mathcal{O}} |\beta(J_\varepsilon(u^\varepsilon))|^{\frac{m+1}{m}} d\xi \leq C \left(\int_{\mathcal{O}} |J_\varepsilon(u^\varepsilon)|^{m+1} d\xi + 1 \right).$$

By replacing in (15) we get that, for a constant ρ sufficiently large, that

$$\frac{\alpha_3}{2} \int_{\mathcal{O}} |J_\varepsilon(u^\varepsilon)|^{m+1} d\xi + \frac{1}{4} \lambda \int_{\mathcal{O}} \left| \nabla \tilde{\beta}_\varepsilon(u^\varepsilon) \right|^2 d\xi \leq C.$$

From the previous estimates, it follows that

$$\{u_\varepsilon\} \text{ bounded in } L^2(\mathcal{O})$$

$$\begin{aligned} \{J_\varepsilon(u^\varepsilon)\} &\text{ bounded in } L^{m+1}(\mathcal{O}) \\ \{\beta_\varepsilon(u^\varepsilon)\} &\text{ bounded in } L^{\frac{m+1}{m}}(\mathcal{O}) \\ \{\nabla\beta_\varepsilon(u^\varepsilon)\} &\text{ bounded in } L^2(\mathcal{O}) \subset L^{\frac{m+1}{m}}(\mathcal{O}). \end{aligned}$$

Since the Sobolev space $W^{1, \frac{m+1}{m}}(\mathcal{O})$ is compactly embedded in $L^{\frac{m+1}{m}}(\mathcal{O})$ we have that

$$\beta_\varepsilon(u^\varepsilon) \rightarrow \eta \text{ strongly in } L^{\frac{m+1}{m}}(\mathcal{O})$$

and therefore $\beta(u) = \eta$.

We can get (5) by passing to the limit in (13).

In order to conclude the proof of the proposition, it only remain to show that u is a probability density function on \mathcal{O} for each $f \in L^2(\mathcal{O})$ which is a probability density function.

We assume that f is a probability density, i.e. $f \geq 0$ a.e. in \mathcal{O} and $\int_{\mathcal{O}} f(\xi) d\xi = 1$.

Let us first take $\psi = u^-$ in (7). We obtain

$$\begin{aligned} & - \int_{[u<0]} |u|^2 d\xi - \frac{\lambda}{2} \int_{[u<0]} \nabla\beta(u) \nabla u d\xi + \lambda \int_{\mathcal{O}} b \cdot \nabla u^- u d\xi \quad (16) \\ & = - \int_{[u<0]} f u d\xi. \end{aligned}$$

We calculate

$$\begin{aligned} & \lambda \int_{\mathcal{O}} b \cdot \nabla u^- u d\xi \\ & = -\lambda \int_{\mathcal{O}} b \cdot \nabla u^- u^- d\xi \\ & = -\frac{\lambda}{2} \int_{\mathcal{O}} b \cdot \nabla (u^-)^2 d\xi \\ & = \frac{\lambda}{2} \int_{\mathcal{O}} \operatorname{div} b (u^-)^2 d\xi - \frac{\lambda}{2} \int_{\partial\mathcal{O}} b \cdot n (u^-)^2 d\xi \\ & = \frac{\lambda}{2} \int_{[u<0]} \operatorname{div} b (u^-)^2 d\xi - \frac{\lambda}{2} \int_{\partial\mathcal{O}} (b \cdot n) (u^-)^2 d\xi < 0. \end{aligned}$$

Keeping in mind the assumptions on b , we obtain that $u^- = 0$ a.e. on \mathcal{O} since the left hand side of (16) is negative and $-\int_{[u<0]} f u d\xi > 0$. It is then immediate that

$$\int_{\mathcal{O}} u(\xi) d\xi = \int_{\mathcal{O}} f(\xi) d\xi = 1$$

and we can conclude that u is a probability density function. The proof of the proposition is now complete. ■

The $L^1(\mathcal{O})$ approach

Let us first consider the operator $\bar{A}: D(\bar{A}) \subset L^1(\mathcal{O}) \rightarrow L^1(\mathcal{O})$ defined by

$$\bar{A}(u) = -\Delta\beta(u) + \operatorname{div}(bu)$$

where

$$D(\bar{A}) = \left\{ u \in L^1(\mathcal{O}); \Delta\beta(u) + \operatorname{div}(bu) \in L^1(\mathcal{O}), \right. \\ \left. \frac{\partial}{\partial n}\beta(u) + (b \cdot n)u = 0 \text{ a.e. on } \partial\mathcal{O} \right\},$$

where Δ is taken in the sense of distributions on \mathcal{O} .

We can prove now the following result.

Proposition 6 *For all $f \in L^1(\mathcal{O})$ and $\forall \lambda \in (0, \lambda_0)$, the equation*

$$u + \lambda\bar{A}u = f$$

has a solution $u = (I + \lambda\bar{A})^{-1}f$.

Moreover

$$\left| (I + \lambda\bar{A})^{-1}f_1 - (I + \lambda\bar{A})^{-1}f_2 \right|_{L^1(\mathcal{O})} \leq |f_1 - f_2|_{L^1(\mathcal{O})}, \quad (17)$$

$\forall f_1, f_2 \in L^1(\mathcal{O})$.

Proof. For $f \in L^1(\mathcal{O})$ arbitrarily fixed we have a sequence $\{f_n\} \subset L^2(\mathcal{O})$ such that $f_n \rightarrow f$ strongly in $L^1(\mathcal{O})$ for $n \rightarrow \infty$. Since we have existence of a solution for the following equation

$$u_n + \lambda\bar{A}u_n = f_n,$$

we can rewrite it as

$$u_n = (I + \lambda\bar{A})^{-1}f_n.$$

Using Proposition 5 we have that

$$\left| (I + \lambda A_0)^{-1}f_1 - (I + \lambda A_0)^{-1}f_2 \right|_{L^1(\mathcal{O})} \leq |f_1 - f_2|_{L^1(\mathcal{O})},$$

for all $f_1, f_2 \in L^2(\mathcal{O})$ which implies directly that

$$|u_n - u_m|_{L^1(\mathcal{O})} \leq |f_n - f_m|_{L^1(\mathcal{O})}, \quad \forall n, m \in \mathbb{N},$$

and then $(u_n)_n$ converges strongly in $L^1(\mathcal{O})$ to some $u \in L^1(\mathcal{O})$. Since $(I + \lambda A_0)^{-1}(f) = (I + \lambda\bar{A})^{-1}(f)$, for $f \in L^2(\mathcal{O})$ we get that $\bar{A}u_n \rightarrow \bar{A}u$ in $L^1(\mathcal{O})$ and

$$u + \lambda\bar{A}u = f.$$

Hence the operator \bar{A} is closed in $L^1 \times L^1$. The estimate follows by the previous result. ■

We can finally define the operator

$$A : D(A) \subset L^1(\mathcal{O}) \rightarrow L^1(\mathcal{O})$$

$$Ay = \bar{A}y, \quad \forall y \in D(A) = (I + \lambda \bar{A})^{-1}(L^1(\mathcal{O}))$$

for same $\lambda > 0$ (equivalently, for each $\lambda > 0$).

Concerning the operator above we have the following result.

Proposition 7 *The operator A is m -accretive in $L^1(\mathcal{O})$, that is, $R(I + \lambda A) = L^1(\mathcal{O})$, for $\forall \lambda > 0$ and*

$$\left| (I + \lambda A)^{-1} f_1 - (I + \lambda A)^{-1} f_2 \right|_{L^1(\mathcal{O})} \leq |f_1 - f_2|_{L^1(\mathcal{O})},$$

for $\forall f_1, f_2 \in L^1(\mathcal{O})$, $\lambda > 0$.

The proof of this result follows directly from the previous one by the definition of the operator A .

Proof of the Theorem 4. In order to use the Crandall-Liggett theorem for the Cauchy problem

$$\begin{cases} \frac{dy}{dt} + A(y) = 0, & t \in (0, T), \\ y(0) = y_0, \end{cases}$$

where $y_0 \in L^1(\mathcal{O})$, we need to have $\overline{D(A)} = L^1(\mathcal{O})$, but this follows by a similar argument as the one used in Theorem 2 from [4].

For reader's convenience we shall sketch it here. We first consider for each $\varepsilon > 0$ the approximating operator

$$A_\varepsilon : D(A_\varepsilon) \subset L^2(\mathcal{O}) \rightarrow L^2(\mathcal{O})$$

defined by

$$A_\varepsilon(u) = -\Delta \tilde{\beta}_\varepsilon(u) - \operatorname{div}(b \cdot u), \quad \text{for } \forall u \in D(A_\varepsilon)$$

where

$$D(A_\varepsilon) = \left\{ u \in H^1(\mathcal{O}); \tilde{\beta}_\varepsilon(u) \in H^2(\mathcal{O}), \right. \\ \left. \frac{\partial}{\partial n} \tilde{\beta}_\varepsilon(u) + (b \cdot n)u = 0, \text{ a.e. on } \partial\mathcal{O} \right\}.$$

By Proposition 5 we have that

$$|u_\varepsilon^1 - u_\varepsilon^2|_{L^1(\mathcal{O})} \leq |f_1 - f_2|_{L^1(\mathcal{O})}, \quad \text{for } \forall f_1, f_2 \in L^2(\mathcal{O}),$$

where u_ε^i is the solution of $u_\varepsilon^i + \lambda A_\varepsilon (u_\varepsilon^i) = f_i$, $i = \overline{1, 2}$ and also that

$$\lim_{\varepsilon \rightarrow 0} u_\varepsilon = u = J_\lambda (f) \text{ in } L^1(\mathcal{O}), \quad \forall f \in L^2(\mathcal{O}), \quad \lambda \in (0, \lambda_0).$$

Since $C_0^\infty(\mathbb{R}^d) \subset D(A_\varepsilon)$ it follows that $D(A_\varepsilon)$ is dense in $L^1(\mathcal{O})$ and therefore so is $D(A)$.

We get that, for each $y_0 \in L^1(\mathcal{O}) = \overline{D(A)}$, the problem above has a unique mild solution $y \in C([0, T]; L^1(\mathcal{O}))$. Moreover,

$$y(t) = \lim_{n \rightarrow \infty} \left(I + \frac{t}{n} A \right)^{-n} y_0, \quad \text{in } L^1(\mathcal{O}),$$

uniformly in t on compact intervals (see e.g. [1]).

Keeping in mind the definition of a mild solution, this means that

$$y(t) = \lim_{\delta \rightarrow 0} y_\delta(t), \quad \text{in } L^1(\mathcal{O})$$

uniformly on $[0, T]$, where

$$y_\delta(t) = y_\delta^{i+1}, \quad \forall t \in [i\delta, (i+1)\delta),$$

where $i = 0, 1, \dots, N_\delta - 1$ for $N_\delta = \lceil \frac{T}{\delta} \rceil$, and

$$\begin{cases} y_\delta^{i+1} + \delta A(y_\delta^{i+1}) = y_\delta^i, & i = 0, 1, \dots, N_\delta - 1 \\ y_\delta^0 = y_0. \end{cases} \quad (18)$$

Moreover $y = y(t, y_0)$ generates a semigroup of contraction in $L^1(\mathcal{O})$, i.e.

$$|y(t, y_0^1) - y(t, y_0^2)|_{L^1(\mathcal{O})} \leq |y_0^1 - y_0^2|_{L^1(\mathcal{O})}, \quad \forall y_0^1, y_0^2 \in L^1(\mathcal{O}).$$

If we take $y_0 \in L^2(\mathcal{O})$ and keep in mind that by Proposition 6 we have

$$(I + \lambda \bar{A})^{-1} f = (I + \lambda A)^{-1} f, \quad \forall f \in L^2(\mathcal{O}),$$

it follows that $y_\delta^{i+1} \in D(A)$ and

$$\frac{1}{\delta} (y_\delta^{i+1} - y_\delta^i) = -A y_\delta^{i+1}, \quad \forall i = 0, 1, \dots, N_\delta - 1.$$

This means that y is the mild solution to equation (1) in the sense of Definition 2. By the accretivity of the operator A in $L^1(\mathcal{O})$ it is easily seen that we have also uniqueness of the solution.

In order to conclude the proof of the theorem we only need to show that y is also a distributional solution to equation (1).

From the definition of the mild solution we have that

$$\frac{1}{\delta} \int_{\mathcal{O}} (y_\delta^{i+1} - y_\delta^i) \beta(y_\delta^{i+1}) d\xi + \frac{1}{2} \int_{\mathcal{O}} |\nabla \beta(y_\delta^{i+1})|^2 d\xi$$

$$+ \int_{\mathcal{O}} b(\xi) \cdot \nabla \beta(y_\delta^{i+1}) y_\delta^{i+1} d\xi = 0,$$

and keeping in mind that $\partial j = \beta$ we can compute

$$\begin{aligned} & \int_{\mathcal{O}} j(y_\delta^{i+1}) d\xi - \int_{\mathcal{O}} j(y_\delta^i) d\xi + \frac{\delta}{2} \int_{\mathcal{O}} |\nabla \beta(y_\delta^{i+1})|_2^2 d\xi \\ & + \delta \int_{\mathcal{O}} b(\xi) \cdot \nabla \beta(y_\delta^{i+1}) y_\delta^{i+1} d\xi = 0. \end{aligned}$$

If we take the sum for $i = \overline{1, k}$ we get

$$\begin{aligned} & \int_{\mathcal{O}} j(y_\delta^{k+1}) d\xi - \int_{\mathcal{O}} j(y_\delta^0) d\xi + \frac{\delta}{2} \sum_{i=0}^k |\nabla \beta(y_\delta^{i+1})|_2^2 \\ & + \delta \sum_{i=0}^k \int_{\mathcal{O}} b(\xi) \cdot \nabla \beta(y_\delta^{i+1}) y_\delta^{i+1} d\xi = 0, \end{aligned}$$

which leads to

$$\begin{aligned} & \int_{\mathcal{O}} j(y_\delta^{k+1}) d\xi + \frac{\delta}{2} \sum_{i=0}^k |\nabla \beta(y_\delta^{i+1})|_2^2 \\ & \leq \int_{\mathcal{O}} j(y_\delta^0) d\xi + \delta \sum_{i=0}^k |b|_\infty |y_\delta^{i+1}|_2 |\nabla \beta(y_\delta^{i+1})|_2, \end{aligned}$$

for $\forall k = 0, 1, \dots, N_\delta - 1$.

We obtain that

$$\int_{\mathcal{O}} j(y_\delta^{k+1}) d\xi + \frac{\delta}{4} \sum_{i=0}^k |\nabla \beta(y_\delta^{i+1})|_2^2 \leq \int_{\mathcal{O}} j(y_\delta^0) d\xi + \delta |b|_\infty \sum_{i=0}^k |y_\delta^{i+1}|_2^2.$$

Since $y_\delta(t) = y_\delta^i$ for $t \in [i\delta, (i+1)\delta)$ we get by the previous estimate that

$$\begin{aligned} & \int_{\mathcal{O}} j(y_\delta(t)) d\xi + \frac{1}{4} \int_0^t |\nabla \beta(y_\delta(s))|_2^2 ds \\ & \leq \int_{\mathcal{O}} j(y_0) d\xi + |b|_\infty \int_0^t |y_\delta(s)|_2^2 ds, \quad \forall t \in [0, T]. \end{aligned}$$

From the assumptions we have on j we get that

$$\begin{aligned} & \sup_{t \in [0, T]} |y_\delta(t)|_2^2 + \frac{1}{4} \int_0^T |\nabla \beta(y_\delta(s))|_2^2 ds \\ & \leq \int_{\mathcal{O}} j(y_0) d\xi + |b|_\infty^2 T \sup_{t \in [0, T]} |y_\delta(s)|_2^2 ds, \end{aligned}$$

and therefore

$$\left(1 - |b|_\infty^2\right) \sup_{t \in [0, T]} \|y_\delta(t)\|_2^2 + \frac{1}{4} \int_0^T \|\nabla \beta(y_\delta(s))\|_2^2 ds \leq \int_{\mathcal{O}} j(y_0) d\xi$$

We know that

$$\begin{aligned} y_\delta &\rightarrow y \text{ in } C([0, T]; L^1(\mathcal{O})) \\ y_\delta &\rightharpoonup y \text{ weakly in } L^\infty(0, T; L^2(\mathcal{O})) \\ \beta(y_\delta) &\rightharpoonup \eta \text{ weakly in } L^2(0, T; H^1(\mathcal{O})) \\ \beta &\text{ maximal monotone in } L^2(\mathcal{O}) \times L^2(\mathcal{O}). \end{aligned}$$

Since β is continuous and

$$y_\delta(t, \xi) \rightarrow y(t, \xi) \text{ a.e. on } (0, T) \times \mathcal{O}$$

it follows that

$$\eta(t, \xi) = \lim_{\delta \rightarrow 0} \beta(y_\delta(t, \xi)) \text{ a.e. on } (0, T) \times \mathcal{O}.$$

We can now conclude the proof that y is also a distributional solution. We shall use the previous estimate to pass to the limit in the mild solution in order to obtain that it is also a distributional solution. More precisely, if we take

$$\frac{1}{\delta} \int_{\mathcal{O}} (y_\delta^{i+1} - y_\delta^i) \psi d\xi + \int_{\mathcal{O}} \left(\frac{1}{2} \nabla \beta(y_\delta^{i+1}) + b(\xi) y_\delta^{i+1} \right) \cdot \nabla \psi d\xi = 0$$

and keep in mind that

$$y_\delta(t) = y_\delta^i, \quad t \in [i\delta, (i+1)\delta)$$

we obtain, for all $\psi \in C^1([0, T] \times \overline{\mathcal{O}})$ such that $\psi(T, \cdot) \equiv 0$, that

$$\begin{aligned} &\frac{1}{\delta} \int_{\mathcal{O}} \int_0^{T-\delta} (y_\delta(t+\delta) - y_\delta(t)) \psi(t, \xi) d\xi \\ &+ \int_{\mathcal{O}} \int_0^{T-\delta} \left(\frac{1}{2} \nabla \beta(y_\delta(t+\delta)) + b(\xi) y_\delta(t+\delta) \right) \cdot \nabla \psi(t, \xi) d\xi = 0. \end{aligned}$$

After some elementary calculus we get for the first term that

$$\begin{aligned} &\frac{1}{\delta} \int_{\mathcal{O}} \int_0^{T-\delta} y_\delta(t+\delta) \psi(t, \xi) d\xi - \frac{1}{\delta} \int_{\mathcal{O}} \int_0^{T-\delta} y_\delta(t) \psi(t, \xi) d\xi \\ &= -\frac{1}{\delta} \int_{\mathcal{O}} \int_0^{T-\delta} y_\delta(t) (\psi(t, \xi) - \psi(t-\delta, \xi)) d\xi \\ &\quad - \frac{1}{\delta} \int_{\mathcal{O}} \int_0^\delta y_\delta(t) \psi(t, \xi) d\xi \\ &\quad + \frac{1}{\delta} \int_{\mathcal{O}} \int_{T-\delta}^T y_\delta(t) \psi(t, \xi) d\xi. \end{aligned}$$

By going back to the previous relation and replacing this expression we get that

$$\begin{aligned} & -\frac{1}{\delta} \int_{\mathcal{O}} \int_0^{T-\delta} y_\delta(t) (\psi(t, \xi) - \psi(t - \delta, \xi)) d\xi \\ & -\frac{1}{\delta} \int_{\mathcal{O}} \int_0^\delta y_\delta(t) \psi(t, \xi) d\xi + \frac{1}{\delta} \int_{\mathcal{O}} \int_{T-\delta}^T y_\delta(t) \psi(t, \xi) d\xi \\ & + \int_{\mathcal{O}} \int_0^{T-\delta} \left(\frac{1}{2} \nabla \beta(y_\delta(t + \delta)) + b(\xi) y_\delta(t + \delta) \right) \cdot \nabla \psi(t, \xi) d\xi = 0 \end{aligned}$$

and finally, by letting $\delta \rightarrow 0$, it follows that y is a variational solution in the sense of Definition 3. ■

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