

## Research article

Yulan Wang, Michael Winkler, and Zhaoyin Xiang\*

# Global solvability in a three-dimensional Keller-Segel-Stokes system involving arbitrary superlinear logistic degradation

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**Abstract:** The Keller-Segel-Stokes system

$$\begin{cases} n_t + u \cdot \nabla n &= \Delta n - \nabla \cdot (n \nabla c) + \rho n - \mu n^\alpha, \\ c_t + u \cdot \nabla c &= \Delta c - c + n, \\ u_t &= \Delta u + \nabla P - n \nabla \Lambda, \quad \nabla \cdot u = 0, \end{cases} \quad (*)$$

is considered in a bounded domain  $\Omega \subset \mathbb{R}^3$  with smooth boundary, with parameters  $\rho \geq 0$ ,  $\mu > 0$  and  $\alpha > 1$ , and with a given gravitational potential  $\Lambda \in W^{2,\infty}(\Omega)$ .

It is shown that in this general setting, when posed under no-flux boundary conditions for  $n$  and  $c$  and homogeneous Dirichlet boundary conditions for  $u$ , and for any suitably regular initial data, an associated initial value problem possesses at least one globally defined solution in an appropriate generalized sense. Since it is well-known that in the absence of absorption, already the corresponding fluid-free subsystem with  $u \equiv 0$  and  $\mu = 0$  admits some solutions blowing up in finite time, this particularly indicates that any power-type superlinear degradation of the form in  $(*)$  goes along with some significant regularizing effect.

**Keywords:** chemotaxis; Stokes; logistic source; generalized solution

**MSC:** 92C17 (primary); 35Q92, 35Q35, 35D99 (secondary)

## 1 Introduction

**The damping role of logistic sources in classical Keller-Segel systems.** Chemotaxis, the biased movement of individuals corresponding to concentration gradients of a chemical signal, is known to be a mechanism of great significance for pattern formation in numerous biological contexts. Concentrating on cross-diffusion and signal production through cells as the main ingredients of a corresponding feedback loop, the apparently most prominent mathematical description of essential aspects within such processes is achieved by the classical Keller-Segel model ([8]) in its minimal version, as given by

$$\begin{cases} n_t &= \Delta n - \nabla \cdot (n \nabla c), \\ c_t &= \Delta c - c + n. \end{cases} \quad (1.1)$$

**Yulan Wang**, School of Science, Xihua University, Chengdu 610039, China, E-mail: wangyulan-math@163.com

**Michael Winkler**, Institut für Mathematik, Universität Paderborn, 33098 Paderborn, Germany, E-mail: michael.winkler@math.uni-paderborn.de

**\*Corresponding Author: Zhaoyin Xiang**, School of Mathematical Sciences, University of Electronic Science and Technology of China, Chengdu 611731, China, E-mail: zxiang@uestc.edu.cn

Indeed, several studies have revealed a distinct ability of this system to describe spontaneous aggregation in two- and higher-dimensional settings; for instance, it is well-known that the homogeneous Neumann problem associated with (1.1) in balls  $\Omega \subset \mathbb{R}^N$  possesses some solutions blowing up in finite time when either  $N \geq 3$ , or when  $N = 2$  and the total mass of cells is large ([5], [27]).

In cases when the respective application contexts involve large time scales, model refinements which appropriately account for proliferation and death of cells seem in order. Yet leaving further coupling unaddressed, Keller-Segel-growth systems of the form

$$\begin{cases} n_t &= \Delta n - \nabla \cdot (n \nabla c) + \rho n - \mu n^\alpha, \\ c_t &= \Delta c - c + n, \end{cases} \quad (1.2)$$

provide modifications of (1.1) which incorporate such mechanisms through the inclusion of standard logistic proliferation terms, and hence in a manner quite common in biomathematical modeling. Mathematically, the introduction of such logistic effects can rule out the possibility of unboundedness phenomena in the style of those known to occur for (1.1); indeed, in the most prototypical framework related to the choice  $\alpha = 2$ , corresponding Neumann-type initial-boundary value problems admit bounded smooth solutions for essentially arbitrary initial data if either the spatial dimension  $N$  satisfies  $N = 2$  and  $\mu$  is any positive number ([13]), or  $N \geq 3$  and  $\mu \geq \mu_0$  with some suitably large  $\mu_0 = \mu_0(\rho, \Omega) > 0$  ([25]; cf. also [7], [34], [35] and the references therein for some more studies concerned with global classical solvability of (1.2)).

Further findings in the literature, however, indicate that also the presence of weaker degradation terms may go along with significant relaxation effects in comparison with (1.1): For instance, in the weakly quadratic absorption case when in (1.2) we have  $\alpha = 2$ ,  $N \geq 3$  and  $\mu \in (0, \mu_0)$ , after all some global solutions can be seen to exist within a natural weak solution concept ([11]). By resorting to some yet weaker notions of solvability, global solutions could more recently also be constructed for systems merely containing certain subquadratic degradation terms, where first steps in this direction required that  $\alpha \geq 2 - \frac{1}{N}$  when  $N \geq 2$  ([20], [21]), and where subsequent approaches successively facilitated extensions to the wider ranges  $\alpha > \frac{2N+4}{N+4}$  ([32]) and  $\alpha > \min\{\frac{2N+4}{N+4}, 2 - \frac{2}{N}\}$  ([36]); very recently, a framework generalized solvability was designed which allows for the construction of global solutions even in quite arbitrary superlinearly dampened logistic-type Keller-Segel systems, including the choice of arbitrary  $\alpha > 1$  in (1.2) whenever  $N \geq 2$  ([33]). It might be noted that in general it seems indeed appropriate to suitably relax requirements on regularity of “solutions” to (1.2), as some caveats assert the occurrence of blow-up, with respect to spatial  $L^\infty$  norms of  $n$ , in parabolic-elliptic variants of (1.2): It is known, for example, that such explosions occur in the variant of (1.2) in which the respective second equation is replaced with  $0 = \Delta c - c + n$  when  $\alpha < \frac{7}{6}$  for  $N \in \{3, 4\}$ , or  $\alpha < 1 + \frac{1}{2(N-1)}$  for  $N \geq 5$  ([30]; see also [3], [17], [26] for several precedents in this direction).

**Keller-Segel-fluid systems involving logistic degradation.** The object of the present study is the Keller-Segel-Stokes system

$$\begin{cases} n_t + u \cdot \nabla n &= \Delta n - \nabla \cdot (n \nabla c) + \rho n - \mu n^\alpha, & x \in \Omega, t > 0, \\ c_t + u \cdot \nabla c &= \Delta c - c + n, & x \in \Omega, t > 0, \\ u_t &= \Delta u + \nabla P - n \nabla \Lambda, \quad \nabla \cdot u = 0, & x \in \Omega, t > 0, \end{cases} \quad (1.3)$$

which quite in general can be viewed as an extension of (1.2) that accounts for interaction of proliferating and chemotactically migrating populations with liquid environments through transport and buoyancy in the style of the modeling approach in [19]. More specifically, this system can, in particular, be used to model effects of chemotaxis on processes of coral fertilization, as addressed in [9] and [10] in the context of a related parabolic-elliptic chemotaxis system involving a given solenoidal fluid field. Indeed, in [9] and [10] the chemotactically directed motion of spermatozooids toward eggs is described in the framework of a two-component model accounting for transport through a prescribed fluid, with a focus on the question how far taxis may affect the reaction mechanism, in that particular context corresponding to the choice  $\rho = 0$  and hence to a merely sink-type reaction term of the form  $-\mu n^\alpha$ , by influencing the total fertilization rate, as measured by the quantity  $\int_\Omega n(x, t) dx$ . The model (1.3) now extends this by considering the fluid field as an additional unknown, the

evolution of which is governed by the incompressible Stokes system forced by the population density variable due to buoyancy in a given external gravitational potential  $\Lambda$ .

Due to an accordingly increased mathematical complexity, systems of the form (1.3) seem much less thoroughly understood than associated chemotaxis-only counterparts; in particular, the literature in this direction seems limited to the case  $\alpha = 2$  of quadratic degradation: A result on global existence of weak solutions to a no-flux/no-flux/Dirichlet initial-boundary value therefor in two-dimensional bounded domains was established in [1] when  $\rho = 0$ , and in [15] it was seen that actually global bounded classical solutions can be found, even in a corresponding variant of (1.3) involving the full Navier-Stokes equations rather than its Stokes simplification, and for arbitrary  $\rho \geq 0$ . The three-dimensional version of (1.3) with  $\alpha = 2$  is known to possess global bounded smooth solutions in convex domains whenever  $\mu > 23$  ([16]), whereas for arbitrary  $\mu > 0$  at least some global generalized solutions exist, again even a corresponding Navier-Stokes framework ([31]). No existence result, however, seems available for any chemotaxis-(Navier-)Stokes systems of the form (1.3) which involves subquadratic degradation in that  $\alpha < 2$ .

**Main results.** In order to address this apparently open solvability question in the context of a prototypically simple initial-boundary value problem for (1.3), we shall subsequently consider

$$\begin{cases} n_t + u \cdot \nabla n &= \Delta n - \nabla \cdot (n \nabla c) + \rho n - \mu n^\alpha, & x \in \Omega, t > 0, \\ c_t + u \cdot \nabla c &= \Delta c - c + n, & x \in \Omega, t > 0, \\ u_t &= \Delta u + \nabla P - n \nabla \Lambda, \quad \nabla \cdot u = 0, & x \in \Omega, t > 0, \\ \frac{\partial n}{\partial \nu} = \frac{\partial c}{\partial \nu} = 0, \quad u = 0, & & x \in \partial \Omega, t > 0, \\ n(x, 0) = n_0(x), \quad c(x, 0) = c_0(x), \quad u(x, 0) = u_0(x), & & x \in \Omega, \end{cases} \quad (1.4)$$

in a bounded domain  $\Omega \subset \mathbb{R}^3$  with smooth boundary, with parameters  $\rho \geq 0$ ,  $\mu > 0$  and  $\alpha > 1$ , and with a given gravitational potential  $\Lambda \in W^{2,\infty}(\Omega)$ .

Throughout our analysis, we shall assume that the initial data therein are such that

$$\begin{cases} n_0 \in C^0(\overline{\Omega}) \text{ is nonnegative, that} \\ c_0 \in W^{1,\infty}(\Omega) \text{ is nonnegative, and that} \\ u_0 \in D(A^\vartheta) \text{ with some } \vartheta \in (\frac{3}{4}, 1), \end{cases} \quad (1.5)$$

where  $A$  denotes the realization of the Stokes operator in the solenoidal subspace  $L^2_\sigma(\Omega) = \{\varphi \in L^2(\Omega) | \nabla \cdot \varphi = 0\}$  of  $L^2(\Omega)$ .

In this framework, we shall see that also in this considerably more complex setting than the fluid-free one in (1.2), actually *any*  $\alpha > 1$  is sufficient to ensure global existence of certain solutions:

**Theorem 1.1.** *Let  $\Omega \subset \mathbb{R}^3$  be a bounded domain with smooth boundary, and suppose that  $\rho \geq 0$ ,  $\mu > 0$  and*

$$\alpha > 1, \quad (1.6)$$

*and that  $\Lambda \in W^{2,\infty}(\Omega)$ . Then for any choice of  $(n_0, c_0, u_0)$  fulfilling (1.5), the problem (1.4) possesses at least one global generalized solution  $(n, c, u)$  in the sense of Definition 2.5 below.*

**Main ideas and key steps.** In view of the circumstance that for small values of  $\alpha > 1$  we apparently can only expect quite poor a priori information on solution regularity, a major challenge, newly arising in the analysis of (1.4) when compared to that of (1.2), will especially be linked to the question how far regularity features of the taxis gradient may be influenced by the considered fluid interaction. Unlike in the associated unperturbed case with  $u \equiv 0$  in which some strong spatio-temporal  $L^q$  precompactness properties of  $\nabla c$  can be derived solely from temporally uniform  $L^1$  bounds for  $n$  on the basis of rather standard regularization features in the corresponding semilinear heat equation solved by  $c$  (see, e.g., [33, Lemma 5.1]), in the present situation a corresponding argument evidently needs to appropriately cope with the additional appearance

of the nonlinear convective term  $-u \cdot \nabla c$  in the second equation from (1.4). The core of our analysis will thus consist in making adequate use of some basic integrability properties of the fluid velocity field, as quite directly resulting from  $L^1$  boundedness of  $n$  thanks to standard smoothing properties of the Stokes semigroup (Lemma 2.3), in order to derive certain compactness features of  $c$  and especially  $\nabla c$ , where by referring to certain strong  $L^p$  topologies inter alia ensure a.e. pointwise convergence along some sequences of solutions to suitably regularized problems (cf. (2.1) and Lemma 5.1). A key step toward this will be accomplished in Lemma 3.7, in which an argument based on maximal Sobolev regularity in inhomogeneous linear heat equations will be applied to a variant of  $(-\Delta + 1)^{-\frac{1}{2}+\delta}c$  for suitably small  $\delta = \delta(\alpha) > 0$ , and where said basic regularity features of  $n$  and  $u$  will be used to estimate correspondingly arising inhomogeneities through an appropriate interpolation inequality, to be prepared in Lemma 3.6. In the context of a suitably weak solution concept quite closely paralleling that pursued in the fluid-free counterpart in [33], this pointwise convergence property will form an essential ingredient in an adequate limit process, to be performed in Lemma 5.2.

## 2 Preliminaries

### 2.1 Appropriate solutions and basic properties thereof

As a conveniently regularized variant of (1.4), for  $\varepsilon \in (0, 1)$  we shall subsequently consider the approximate problem

$$\begin{cases} n_{\varepsilon t} + u_{\varepsilon} \cdot \nabla n_{\varepsilon} &= \Delta n_{\varepsilon} - \nabla \cdot (n_{\varepsilon} \nabla c_{\varepsilon}) + \rho n_{\varepsilon} - \mu n_{\varepsilon}^{\alpha}, & x \in \Omega, \ t > 0, \\ c_{\varepsilon t} + u_{\varepsilon} \cdot \nabla c_{\varepsilon} &= \Delta c_{\varepsilon} - c_{\varepsilon} + \frac{n_{\varepsilon}}{1+\varepsilon n_{\varepsilon}}, & x \in \Omega, \ t > 0, \\ u_{\varepsilon t} &= \Delta u_{\varepsilon} + \nabla P_{\varepsilon} - n_{\varepsilon} \nabla \Lambda, & x \in \Omega, \ t > 0, \\ \frac{\partial n_{\varepsilon}}{\partial \nu} = \frac{\partial c_{\varepsilon}}{\partial \nu} = 0, \quad u_{\varepsilon} = 0, & & x \in \partial \Omega, \ t > 0, \\ n_{\varepsilon}(x, 0) = n_0(x), \quad c_{\varepsilon}(x, 0) = c_0(x), \quad u_{\varepsilon}(x, 0) = u_0(x), & & x \in \Omega, \end{cases} \quad (2.1)$$

that according to a well-established construction on the basis of the contraction mapping principle can be seen to admit local-in-time smooth solutions which, due to boundedness of  $0 \leq n \mapsto \frac{n}{1+\varepsilon n}$  for each  $\varepsilon \in (0, 1)$ , can actually be extended so as to become global classical solutions (cf., e.g., [29] and [23] for details in closely related situations):

**Lemma 2.1.** *Let  $\varepsilon \in (0, 1)$ . Then there exist uniquely determined functions*

$$\begin{cases} n_{\varepsilon} \in C^0(\overline{\Omega} \times [0, \infty)) \cap C^{2,1}(\overline{\Omega} \times (0, \infty)), \\ c_{\varepsilon} \in \bigcap_{q>3} C^0([0, \infty); W^{1,q}(\Omega)) \cap C^{2,1}(\overline{\Omega} \times (0, \infty)) \quad \text{and} \\ u_{\varepsilon} \in C^0([0, \infty); D(A^{\theta})) \cap C^{2,1}(\overline{\Omega} \times (0, \infty)) \end{cases}$$

such that  $n_{\varepsilon} \geq 0$  and  $c_{\varepsilon} \geq 0$  in  $\Omega \times (0, \infty)$ , and that (2.1) is satisfied in the classical sense with some  $P_{\varepsilon} \in C^{1,0}(\Omega \times (0, \infty))$ .

The following basic and essentially well-known properties of these solutions are due to the presence of the degradation term in the first equation of (2.1).

**Lemma 2.2.** *Let  $\alpha > 1$ . Then*

$$\int_{\Omega} n_{\varepsilon}(\cdot, t) \leq m := \max \left\{ \int_{\Omega} n_0, \left( \frac{\rho}{\mu} \right)^{\frac{1}{\alpha-1}} |\Omega| \right\} \quad \text{for all } t > 0 \text{ and } \varepsilon \in (0, 1), \quad (2.2)$$

and moreover

$$\int_0^T \int_{\Omega} n_{\varepsilon}^{\alpha} \leq \frac{(1 + \rho T) \cdot m}{\mu} \quad \text{for all } T > 0 \text{ and } \varepsilon \in (0, 1). \quad (2.3)$$

*Proof.* By integration of the first equation in (2.1) we see that

$$\frac{d}{dt} \int_{\Omega} n_{\varepsilon} = \rho \int_{\Omega} n_{\varepsilon} - \mu \int_{\Omega} n_{\varepsilon}^{\alpha} \quad \text{for all } t > 0, \quad (2.4)$$

so that since  $\int_{\Omega} n_{\varepsilon}^{\alpha} \geq |\Omega|^{1-\alpha} \left\{ \int_{\Omega} n_{\varepsilon} \right\}^{\alpha}$  for all  $t > 0$  by the Hölder inequality, (2.2) readily follows through a straightforward ODE comparison argument. Thereupon, a direct time integration in (2.4) shows that

$$\int_{\Omega} n_{\varepsilon}(\cdot, T) + \mu \int_0^T \int_{\Omega} n_{\varepsilon}^{\alpha} \leq \int_{\Omega} n_0 + \rho \int_0^T \int_{\Omega} n_{\varepsilon} \leq \int_{\Omega} n_0 + \rho T m \quad \text{for all } T > 0$$

and hence establishes (2.3).  $\square$

Through a standard argument based on well-known smoothing properties of the Stokes semigroup, the  $L^1$  boundedness feature expressed in (2.2) can readily be seen to entail the following (cf. also [22, Lemma 2.5] and [29, Corollary 3.4]).

**Lemma 2.3.** *Let  $\alpha > 1$ , and let  $\delta \in (0, \frac{3}{2})$  and  $T > 0$ . Then there exists  $C(\delta, T) > 0$  such that*

$$\|u_{\varepsilon}(\cdot, t)\|_{L^{3-\delta}(\Omega)} \leq C(\delta, T) \quad \text{for all } t \in (0, T) \text{ and any } \varepsilon \in (0, 1) \quad (2.5)$$

and

$$\|\nabla u_{\varepsilon}(\cdot, t)\|_{L^{\frac{3}{2}-\delta}(\Omega)} \leq C(\delta, T) \quad \text{for all } t \in (0, T) \text{ and each } \varepsilon \in (0, 1). \quad (2.6)$$

## 2.2 A generalized notion of solvability

In this section, we quite closely follow the approach in [33] to develop a generalized solution concept suitable for our purposes. This will be based on the following observation on how products of the form  $\phi(n)\psi(c)$  evolve in time, along suitably smooth trajectories either of (2.1) for  $\varepsilon \in (0, 1)$ , or of the original problem (1.4) – the existence of the latter being formally presupposed here only.

**Lemma 2.4.** *Let  $\phi, \psi$  and  $\Phi$  belong to  $C^2([0, \infty))$  with  $\phi \geq 0, \psi > 0, \phi'' > 0$  and  $\Phi' = \sqrt{\phi''}$  on  $[0, \infty)$ , and suppose that  $\varepsilon \in [0, 1)$  and  $T \in (0, \infty]$ , and that  $n \in C^{2,1}(\bar{\Omega} \times (0, T)), c \in C^{2,1}(\bar{\Omega} \times (0, T)), u \in C^{2,1}(\bar{\Omega} \times (0, T); \mathbb{R}^3)$  and  $P \in C^{1,0}(\Omega \times (0, T))$  are such that  $n \geq 0$  and  $c \geq 0$  and that (2.1) holds in  $\Omega \times (0, T)$ . Then for arbitrary  $\varphi \in C^{\infty}(\bar{\Omega} \times (0, T))$ ,*

$$\begin{aligned} & \int_{\Omega} \partial_t \{ \phi(n) \psi(c) \} \cdot \varphi \\ &= - \int_{\Omega} \left| \nabla \left( \Phi(n) \sqrt{\psi(c)} \right) + \left\{ \frac{\phi'(n)}{\sqrt{\phi''(n)}} \cdot \frac{\psi'(c)}{\sqrt{\psi(c)}} - \frac{1}{2} \Phi(n) \frac{\psi'(c)}{\sqrt{\psi(c)}} - \frac{1}{2} n \sqrt{\phi''(n)} \sqrt{\psi(c)} \right\} \cdot \nabla c \right|^2 \cdot \varphi \\ & \quad - \int_{\Omega} \left\{ \phi(n) \psi''(c) - \frac{\phi'^2(n)}{\phi''(n)} \cdot \frac{\psi'^2(c)}{\psi(c)} - \frac{1}{4} n^2 \phi''(n) \psi(c) \right\} \cdot |\nabla c|^2 \varphi \\ & \quad - \int_{\Omega} \frac{\phi'(n)}{\sqrt{\phi''(n)}} \sqrt{\psi(c)} \nabla \left( \Phi(n) \sqrt{\psi(c)} \right) \cdot \nabla \varphi \\ & \quad + \int_{\Omega} \left\{ n \phi'(n) \psi(c) - \phi(n) \psi'(c) + \frac{1}{2} \frac{\Phi(n) \phi'(n)}{\sqrt{\phi''(n)}} \psi'(c) \right\} \nabla c \cdot \nabla \varphi + \int_{\Omega} \phi(n) \psi(c) u \cdot \nabla \varphi \\ & \quad + \int_{\Omega} \left\{ (\rho n - \mu n^{\alpha}) \phi'(n) \psi(c) - c \phi(n) \psi'(c) + \frac{n}{1 + \varepsilon n} \phi(n) \psi'(c) \right\} \cdot \varphi. \end{aligned} \quad (2.7)$$

*Proof.* This result can be proved by quite a trivial modification of that from Lemma 3.1 in [33].  $\square$

On the basis of a formal evaluation of (2.7) for  $\varepsilon = 0$ , we can thereby extend the solution concept specified in [33] to the present case involving fluid interaction in a straightforward manner (cf. also [24] and [12] for related precedents).

**Definition 2.5.** Let

$$\begin{cases} n \in L^1_{loc}(\bar{\Omega} \times [0, \infty)), \\ c \in L^1_{loc}([0, \infty); W^{1,1}(\Omega)) \quad \text{and} \\ u \in L^1_{loc}([0, \infty); W^{1,1}_0(\Omega; \mathbb{R}^3)) \end{cases} \quad (2.8)$$

be such that  $n \geq 0$ ,  $c \geq 0$  and  $\nabla \cdot u = 0$  a.e. in  $\Omega \times (0, \infty)$ . Then we will call  $(n, c, u)$  a global generalized solution of (1.4) if

$$\int_{\Omega} n(\cdot, t) \leq \int_{\Omega} n_0 + \rho \int_0^t \int_{\Omega} n - \mu \int_0^t \int_{\Omega} n^\alpha \quad \text{for a.e. } t > 0 \quad (2.9)$$

and

$$-\int_0^\infty \int_{\Omega} c \varphi_t - \int_{\Omega} c_0 \varphi(\cdot, 0) = -\int_0^\infty \int_{\Omega} \nabla c \cdot \nabla \varphi - \int_0^\infty \int_{\Omega} c \varphi + \int_0^\infty \int_{\Omega} n \varphi + \int_0^\infty \int_{\Omega} cu \cdot \nabla \varphi \quad (2.10)$$

for all  $\varphi \in C_0^\infty(\bar{\Omega} \times [0, \infty))$ , if

$$-\int_0^\infty \int_{\Omega} u \cdot \varphi_t - \int_{\Omega} u_0 \cdot \varphi(\cdot, 0) = -\int_0^\infty \int_{\Omega} \nabla u \cdot \nabla \varphi - \int_0^\infty \int_{\Omega} n \varphi \cdot \nabla \Lambda \quad (2.11)$$

for all  $\varphi \in C_0^\infty(\Omega \times [0, \infty))$  fulfilling  $\nabla \cdot \varphi = 0$  in  $\Omega \times (0, \infty)$ , and if moreover one can find functions  $\phi, \psi$  and  $\Phi$  which belong to  $C^2([0, \infty))$  and satisfy

$$\phi' < 0, \quad \psi > 0 \quad \text{and} \quad \phi'' > 0 \quad \text{on } [0, \infty) \quad (2.12)$$

as well as

$$\Phi' = \sqrt{\phi''} \quad \text{on } [0, \infty), \quad (2.13)$$

such that

$$\begin{aligned} & \left\{ \phi(n) \psi''(c) - \frac{\phi'^2(n)}{\phi''(n)} \cdot \frac{\psi'^2(c)}{\psi(c)} - \frac{1}{4} n^2 \phi''(n) \psi(c) \right\} |\nabla c|^2, \quad n \phi'(n) \psi(c) |\nabla c|, \\ & \phi(n) \psi'(c) |\nabla c|, \quad \frac{\Phi(n) \phi'(n)}{\sqrt{\phi''(n)}} \psi'(c) |\nabla c| \quad \text{and} \quad \phi(n) \psi(c) |u| \quad \text{as well as} \\ & n^\alpha \phi'(n) \psi(c), \quad c \phi(n) \psi'(c) \quad \text{and} \quad n \phi(n) \psi'(c) \quad \text{belong to } L^1_{loc}(\bar{\Omega} \times [0, \infty)), \end{aligned} \quad (2.14)$$

that

$$\Phi(n) \sqrt{\psi(c)} \in L^2_{loc}([0, \infty); W^{1,2}(\Omega)), \quad (2.15)$$

and that

$$\begin{aligned} & -\int_0^\infty \int_{\Omega} \phi(n) \psi(c) \varphi_t - \int_{\Omega} \phi(n_0) \psi(c_0) \varphi(\cdot, 0) \\ & \leq -\int_0^\infty \int_{\Omega} \left| \nabla \left( \Phi(n) \sqrt{\psi(c)} \right) + \left\{ \frac{\phi'(n)}{\sqrt{\phi''(n)}} \cdot \frac{\psi'(c)}{\sqrt{\psi(c)}} - \frac{1}{2} \Phi(n) \frac{\psi'(c)}{\sqrt{\psi(c)}} - \frac{1}{2} n \sqrt{\phi''(n)} \cdot \sqrt{\psi(c)} \right\} \nabla c \right|^2 \varphi \\ & - \int_0^\infty \int_{\Omega} \left\{ \phi(n) \psi''(c) - \frac{\phi'^2(n)}{\phi''(n)} \cdot \frac{\psi'^2(c)}{\psi(c)} - \frac{1}{4} n^2 \phi''(n) \psi(c) \right\} \cdot |\nabla c|^2 \varphi \end{aligned}$$

$$\begin{aligned}
& - \int_0^\infty \int_\Omega \frac{\phi'(n)}{\sqrt{\phi''(n)}} \sqrt{\psi(c)} \nabla (\Phi(n) \sqrt{\psi(c)}) \cdot \nabla \varphi \\
& + \int_0^\infty \int_\Omega \left\{ n \phi'(n) \psi(c) - \phi(n) \psi'(c) + \frac{1}{2} \frac{\Phi(n) \phi'(n)}{\sqrt{\phi''(n)}} \psi'(c) \right\} \nabla c \cdot \nabla \varphi \\
& + \int_0^\infty \int_\Omega \phi(n) \psi(c) u \cdot \nabla \varphi \\
& + \int_0^\infty \int_\Omega \left\{ (\rho n - \mu n^a) \phi'(n) \psi(c) - c \phi(n) \psi'(c) + n \phi(n) \psi'(c) \right\} \cdot \varphi
\end{aligned} \tag{2.16}$$

for each nonnegative  $\varphi \in C_0^\infty(\overline{\Omega} \times [0, \infty))$ .

**Remark.** Similar to a corresponding comment made in [33] for the associated fluid-free counterpart, quite simple adaptation of the arguments detailed in [12, Lemma 2.5] and [28, Lemma 2.1] shows that this concept is indeed consistent with that of classical solvability in the sense that if  $n_0 \in C^0(\overline{\Omega})$ ,  $c_0 \in C^0(\overline{\Omega})$  and  $u_0 \in C^0(\overline{\Omega}; \mathbb{R}^3)$  are such that  $u_0|_{\partial\Omega} = 0$ , and if  $0 \leq n \in C^0(\overline{\Omega} \times [0, \infty)) \cap C^{2,1}(\overline{\Omega} \times (0, \infty))$ ,  $0 \leq c \in C^0(\overline{\Omega} \times [0, \infty)) \cap C^{2,1}(\overline{\Omega} \times (0, \infty))$  and  $u \in C^0(\overline{\Omega} \times [0, \infty); \mathbb{R}^3) \cap C^{2,1}(\overline{\Omega} \times (0, \infty); \mathbb{R}^3)$  are such that  $(n, c, u)$  forms a global generalized solution of (1.4) in the above sense, then there exists  $P \in C^{1,0}(\Omega \times (0, \infty))$  such that  $(n, c, u, p)$  in fact solves (1.4) in the classical sense.

### 3 A strong precompactness feature of $c_\varepsilon$

Next approaching the core of our analysis, in this section we intend to derive a strong precompactness feature of  $c_\varepsilon$  with respect to the norm in  $L^1((0, T); W^{1,1}(\Omega))$  for arbitrary  $T > 0$  (see Lemma 3.9), which will play a key role not only in the course of a suitable limit process in the second equation of (2.1), but also in the final verification of the supersolution property in Lemma 5.2.

Our first step in this direction results from a standard testing procedure applied to the second equation from (2.1), which thanks to the space-time integrability property in (2.3) yields the following.

**Lemma 3.1.** Let  $\alpha > 1$  and

$$p^{(\alpha)} := \begin{cases} \frac{3\alpha}{5-2\alpha} & \text{if } \alpha < \frac{5}{2}, \\ +\infty & \text{if } \alpha \geq \frac{5}{2}. \end{cases} \tag{3.1}$$

Then for each  $T > 0$  and any  $p \in (1, \infty)$  fulfilling  $p \leq p^{(\alpha)}$  there exists  $C(p, T) > 0$  such that

$$\int_\Omega c_\varepsilon^p(\cdot, t) \leq C(p, T) \quad \text{for all } t \in (0, T) \text{ and } \varepsilon \in (0, 1) \tag{3.2}$$

and

$$\int_0^T \int_\Omega c_\varepsilon^{p-2} |\nabla c_\varepsilon|^2 \leq C(p, T) \quad \text{for all } \varepsilon \in (0, 1). \tag{3.3}$$

*Proof.* Since  $\nabla \cdot u_\varepsilon = 0$ , from the second equation in (2.1) we obtain that

$$\frac{1}{p} \frac{d}{dt} \int_\Omega c_\varepsilon^p + (p-1) \int_\Omega c_\varepsilon^{p-2} |\nabla c_\varepsilon|^2 + \int_\Omega c_\varepsilon^p = \int_\Omega n_\varepsilon c_\varepsilon^{p-1} \quad \text{for all } t > 0, \tag{3.4}$$

where by the Hölder inequality, writing  $f_\varepsilon(t) := \int_\Omega n_\varepsilon^\alpha(\cdot, t)$  for  $t > 0$  and  $\varepsilon \in (0, 1)$  we see that

$$\begin{aligned} \int_\Omega n_\varepsilon c_\varepsilon^{p-1} &\leq f_\varepsilon^{\frac{1}{\alpha}}(t) \cdot \left\{ \int_\Omega c_\varepsilon^{\frac{(p-1)\alpha}{\alpha-1}} \right\}^{\frac{\alpha-1}{\alpha}} \\ &= f_\varepsilon^{\frac{1}{\alpha}}(t) \|c_\varepsilon^{\frac{p}{2}}\|_{L^{\frac{2(p-1)\alpha}{p(\alpha-1)}}(\Omega)}^{\frac{2(p-1)}{p}} \quad \text{for all } t > 0. \end{aligned} \quad (3.5)$$

Here since our assumption on  $p$  warrants that if  $\alpha < \frac{5}{2}$  then

$$\frac{2(p-1)\alpha}{p(\alpha-1)} = \frac{2\alpha}{\alpha-1} \cdot \left(1 - \frac{1}{p}\right) \leq \frac{2\alpha}{\alpha-1} \cdot \left(1 - \frac{5-2\alpha}{3\alpha}\right) = \frac{10}{3},$$

and that thus in both cases  $\alpha < \frac{5}{2}$  and  $\alpha \geq \frac{5}{2}$  we have  $\frac{2(p-1)\alpha}{p(\alpha-1)} < 6$ , we may invoke the Gagliardo-Nirenberg inequality to find  $C_1 = C_1(p) > 0$  such that

$$\|c_\varepsilon^{\frac{p}{2}}\|_{L^{\frac{2(p-1)\alpha}{p(\alpha-1)}}(\Omega)}^{\frac{2(p-1)}{p}} \leq C_1 \|\nabla c_\varepsilon^{\frac{p}{2}}\|_{L^2(\Omega)}^{\frac{3(p-\alpha)}{p\alpha}} \|c_\varepsilon^{\frac{p}{2}}\|_{L^2(\Omega)}^{\frac{(2p+1)\alpha-3p}{p\alpha}} + C_1 \|c_\varepsilon^{\frac{p}{2}}\|_{L^2(\Omega)}^{\frac{2(p-1)}{p}} \quad \text{for all } t > 0 \text{ and } \varepsilon \in (0, 1),$$

noting that the latter conclusion is trivially valid when  $\frac{2(p-1)\alpha}{p(\alpha-1)} \leq 2$ , that is, when  $p \leq \alpha$ . Again due to the inequality  $p \leq p^{(\alpha)}$ , we next see that if  $\alpha < \frac{5}{2}$  then herein

$$\frac{3(p-\alpha)}{p\alpha} = \frac{3}{\alpha} \cdot \left(1 - \frac{\alpha}{p}\right) \leq \frac{3}{\alpha} \cdot \left(1 - \frac{\alpha}{\frac{3\alpha}{5-2\alpha}}\right) = \frac{2(\alpha-1)}{\alpha} < 2,$$

so that regardless of the size of  $\alpha$  we have  $\frac{3(p-\alpha)}{p\alpha} < 2$ . Accordingly, Young's inequality applies so as to yield  $C_2 = C_2(p) > 0$  such that

$$\begin{aligned} f_\varepsilon^{\frac{1}{\alpha}}(t) \|c_\varepsilon^{\frac{p}{2}}\|_{L^{\frac{2(p-1)\alpha}{p(\alpha-1)}}(\Omega)}^{\frac{2(p-1)}{p}} &\leq \frac{2(p-1)}{p^2} \|\nabla c_\varepsilon^{\frac{p}{2}}\|_{L^2(\Omega)}^2 + C_2 f_\varepsilon^{\frac{2p}{(2p+3)\alpha-3p}}(t) \|c_\varepsilon^{\frac{p}{2}}\|_{L^2(\Omega)}^{2 \cdot \frac{(2p+1)\alpha-3p}{(2p+3)\alpha-3p}} \\ &\quad + C_1 f_\varepsilon^{\frac{1}{\alpha}}(t) \|c_\varepsilon^{\frac{p}{2}}\|_{L^2(\Omega)}^{\frac{2(p-1)}{p}} \\ &= \frac{p-1}{2} \int_\Omega c_\varepsilon^{p-2} |\nabla c_\varepsilon|^2 + C_2 f_\varepsilon^{\frac{2p}{(2p+3)\alpha-3p}}(t) \cdot \left\{ \int_\Omega c_\varepsilon^p \right\}^{\frac{(2p+1)\alpha-3p}{(2p+3)\alpha-3p}} \\ &\quad + C_1 f_\varepsilon^{\frac{1}{\alpha}}(t) \cdot \left\{ \int_\Omega c_\varepsilon^p \right\}^{\frac{p-1}{p}} \quad \text{for all } t > 0 \text{ and } \varepsilon \in (0, 1), \end{aligned}$$

whence combining (3.5) with (3.4) shows that  $y_\varepsilon(t) := \int_\Omega c_\varepsilon^p(\cdot, t)$ ,  $t \geq 0$ ,  $\varepsilon \in (0, 1)$ , and  $g_\varepsilon(t) := \frac{p-1}{2} \int_\Omega c_\varepsilon^{p-2}(\cdot, t) |\nabla c_\varepsilon(\cdot, t)|^2$ ,  $t > 0$ ,  $\varepsilon \in (0, 1)$ , satisfy

$$\frac{1}{p} y'_\varepsilon(t) + g_\varepsilon(t) \leq C_2 f_\varepsilon^{\frac{2p}{(2p+3)\alpha-3p}}(t) y_\varepsilon^{\frac{(2p+1)\alpha-3p}{(2p+3)\alpha-3p}}(t) + C_1 f_\varepsilon^{\frac{1}{\alpha}}(t) y_\varepsilon^{\frac{p-1}{p}}(t) \quad \text{for all } t > 0 \text{ and } \varepsilon \in (0, 1). \quad (3.6)$$

Only at this point, we now take full advantage of the condition  $p \leq p^{(\alpha)}$ , which namely ensures that

$$1 - \frac{(2p+3)\alpha-3p}{2p} = \frac{(5-2\alpha)p-3\alpha}{2p} \leq 0$$

and thus  $\frac{2p}{(2p+3)\alpha-3p} \leq 1$ . Since furthermore, clearly,

$$\frac{(2p+1)\alpha-3p}{(2p+3)\alpha-3p} < 1 \quad \text{and} \quad \frac{p-1}{p} < 1,$$

several applications of Young's inequality enable us to see that (3.6) actually entails the inequality

$$\frac{1}{p} y'_\varepsilon(t) + g_\varepsilon(t) \leq (C_1 + C_2) \cdot (f_\varepsilon(t) + 1) \cdot (y_\varepsilon(t) + 1) \quad \text{for all } t > 0 \text{ and } \varepsilon \in (0, 1), \quad (3.7)$$



which by nonnegativity of  $g_\varepsilon$  firstly implies that

$$y_\varepsilon(t) + 1 \leq \left(y_\varepsilon(0) + 1\right) \cdot e^{p(C_1+C_2) \int_0^t (f_\varepsilon(s)+1)ds} \quad \text{for all } t > 0 \text{ and } \varepsilon \in (0, 1).$$

As a consequence of Lemma 2.2, this shows that  $\sup_{\varepsilon \in (0,1)} \sup_{t \in (0,T)} (y_\varepsilon(t)+1)$  is finite for all  $T > 0$ , whereupon a direct integration in (3.7) reveals that therefore also  $\sup_{\varepsilon \in (0,1)} \int_0^T g_\varepsilon(s)ds < \infty$  for all  $T > 0$ . By definition of  $(y_\varepsilon)_{\varepsilon \in (0,1)}$  and  $(g_\varepsilon)_{\varepsilon \in (0,1)}$ , both (3.2) and (3.3) have thereby been established.  $\square$

A straightforward interpolation turns (3.2) and (3.3) into the following.

**Lemma 3.2.** *Let  $\alpha \in (1, \frac{5}{2})$  and  $p^{(\alpha)}$  be as in (3.1), and let  $q \in (p^{(\alpha)}, 3p^{(\alpha)}]$ . Then for all  $T > 0$  there exists  $C(q, T) > 0$  such that*

$$\int_0^T \|c_\varepsilon(\cdot, t)\|_{L^q(\Omega)}^{\frac{2p^{(\alpha)}q}{3(q-p^{(\alpha)})}} dt \leq C(q, T) \quad \text{for all } \varepsilon \in (0, 1). \quad (3.8)$$

*Proof.* We abbreviate  $p := p^{(\alpha)}$  and observe that then our assumption on  $q$  guarantees that  $\frac{2q}{p} \leq 6$  and  $\frac{2q}{p} > 2$ , so that an application of the Gagliardo-Nirenberg inequality yields  $C_1 = C_1(q) > 0$  such that

$$\|\varphi\|_{L^{\frac{2q}{p}}(\Omega)}^{\frac{4q}{3(q-p)}} \leq C_1 \|\nabla \varphi\|_{L^2(\Omega)}^2 \|\varphi\|_{L^2(\Omega)}^{\frac{2(3p-q)}{3(q-p)}} + C_1 \|\varphi\|_{L^2(\Omega)}^{\frac{4q}{3(q-p)}} \quad \text{for all } \varphi \in W^{1,2}(\Omega).$$

Therefore,

$$\begin{aligned} \int_0^T \|c_\varepsilon(\cdot, t)\|_{L^q(\Omega)}^{\frac{2pq}{3(q-p)}} dt &= \int_0^T \|c_\varepsilon^{\frac{p}{2}}(\cdot, t)\|_{L^{\frac{2q}{p}}(\Omega)}^{\frac{4q}{3(q-p)}} dt \\ &\leq C_1 \int_0^T \|\nabla c_\varepsilon^{\frac{p}{2}}(\cdot, t)\|_{L^2(\Omega)}^2 \|c_\varepsilon^{\frac{p}{2}}(\cdot, t)\|_{L^2(\Omega)}^{\frac{2(3p-q)}{3(q-p)}} dt + C_1 \int_0^T \|c_\varepsilon^{\frac{p}{2}}(\cdot, t)\|_{L^2(\Omega)}^{\frac{4q}{3(q-p)}} dt \\ &= \frac{p^2 C_1}{4} \int_0^T \left\{ \int_\Omega c_\varepsilon^{p-2}(\cdot, t) |\nabla c_\varepsilon(\cdot, t)|^2 \right\} \cdot \left\{ \int_\Omega c_\varepsilon^p(\cdot, t) \right\}^{\frac{3p-q}{3(q-p)}} dt \\ &\quad + C_1 \int_0^T \left\{ \int_\Omega c_\varepsilon^p(\cdot, t) \right\}^{\frac{2q}{3(q-p)}} dt \\ &\leq \frac{p^2 C_1}{4} \cdot \left\{ \sup_{t \in (0,T)} \int_\Omega c_\varepsilon^p(\cdot, t) \right\}^{\frac{3p-q}{3(q-p)}} \cdot \int_0^T \int_\Omega c_\varepsilon^{p-2} |\nabla c_\varepsilon|^2 \\ &\quad + C_1 T \cdot \left\{ \sup_{t \in (0,T)} \int_\Omega c_\varepsilon^p(\cdot, t) \right\}^{\frac{2q}{3(q-p)}} \quad \text{for all } T > 0 \text{ and } \varepsilon \in (0, 1), \end{aligned}$$

whence the claim immediately results from Lemma 3.1.  $\square$

Again by interpolation, in light of Lemma 3.2 the estimate (3.3) moreover entails some weight-free spatio-temporal  $L^q$ -estimate involving an exponent  $q > 1$ :

**Lemma 3.3.** *Let  $\alpha > 1$ . Then for all  $T > 0$  there exists  $C(T) > 0$  such that*

$$\int_0^T \int_\Omega |\nabla c_\varepsilon|^{\frac{5}{4}} \leq C(T) \quad \text{for all } \varepsilon \in (0, 1). \quad (3.9)$$

*Proof.* If  $\alpha \geq \frac{10}{7}$  and hence in (3.1) we have  $p^{(\alpha)} \geq 2$ , the claim immediately follows upon invoking Lemma 3.1 with  $p := 2$ .

If  $\alpha < \frac{10}{7}$  and hence  $p^{(\alpha)} < 2$ , however, Lemma 3.1 and Lemma 3.2 ensure that given  $T > 0$  we can pick  $C_1(T) > 0$  and  $C_2(T) > 0$  such that

$$\int_0^T \int_{\Omega} c_{\varepsilon}^{p^{(\alpha)}-2} |\nabla c_{\varepsilon}|^2 \leq C_1(T) \quad \text{for all } \varepsilon \in (0, 1) \quad (3.10)$$

and

$$\int_0^T \int_{\Omega} c_{\varepsilon}^{\frac{5p^{(\alpha)}}{3}} \leq C_2(T) \quad \text{for all } \varepsilon \in (0, 1). \quad (3.11)$$

According to Young's inequality, this implies that for any such  $T$ ,

$$\begin{aligned} \int_0^T \int_{\Omega} |\nabla c_{\varepsilon}|^{\frac{5p^{(\alpha)}}{p^{(\alpha)}+3}} &= \int_0^T \int_{\Omega} \left\{ c_{\varepsilon}^{p^{(\alpha)}-2} |\nabla c_{\varepsilon}|^2 \right\}^{\frac{5p^{(\alpha)}}{2(p^{(\alpha)}+3)}} \cdot c_{\varepsilon}^{\frac{5p^{(\alpha)}(2-p^{(\alpha)})}{2(p^{(\alpha)}+3)}} \\ &\leq \int_0^T \int_{\Omega} c_{\varepsilon}^{p^{(\alpha)}-2} |\nabla c_{\varepsilon}|^2 + \int_0^T \int_{\Omega} c_{\varepsilon}^{\frac{5p^{(\alpha)}}{3}} \\ &\leq C_1(T) + C_2(T) \quad \text{for all } \varepsilon \in (0, 1), \end{aligned}$$

so that (3.9) results also in this case, because

$$\frac{5p^{(\alpha)}}{p^{(\alpha)}+3} = \frac{5}{1+\frac{3}{p^{(\alpha)}}} \geq \frac{5}{1+3} = \frac{5}{4}$$

due to the inequality  $p^{(\alpha)} > 1$ . □

In conjunction with the information on fluid integrability from Lemma 2.3, the weighted gradient estimate in (3.3) can be seen to furthermore entail that the nonlinear convection term in the second equation from (2.1) admits the following estimate which, as we underline here, involves some superlinear summability power with respect to spatial integration, but only some possibly small positive integrability exponent in time.

**Lemma 3.4.** *Let  $\alpha > 1$ . Then there exist  $p > 1$  and  $\lambda > 0$  with the property that for all  $T > 0$  one can find  $C(T) > 0$  such that*

$$\int_0^T \|u_{\varepsilon}(\cdot, t) \cdot \nabla c_{\varepsilon}(\cdot, t)\|_{L^p(\Omega)}^{\lambda} dt \leq C(T) \quad \text{for all } \varepsilon \in (0, 1). \quad (3.12)$$

*Proof.* We first consider the case when  $\alpha < \frac{10}{7}$ , in which with  $p^{(\alpha)}$  taken from (3.1) we observe that then  $p^{(\alpha)} > \alpha$  and  $p^{(\alpha)} < 2$ . Moreover, since  $2 - p^{(\alpha)} < p^{(\alpha)}$  due to the fact that  $p^{(\alpha)} > 1$ , it is possible to fix  $\delta > 0$  small enough such that besides

$$\delta < \frac{1}{6}, \quad (3.13)$$

we can achieve that

$$q := \frac{3(1+2\delta)(2-p^{(\alpha)})}{1-6\delta} \quad (3.14)$$

satisfies

$$q \leq 3p^{(\alpha)} \quad (3.15)$$

and

$$\frac{\delta(2-p^{(\alpha)})}{2-\delta} \leq \frac{2p^{(\alpha)}q}{3(q-p^{(\alpha)})_+}. \quad (3.16)$$

A first application of the Hölder inequality thereupon shows that for all  $T > 0$  and  $\varepsilon \in (0, 1)$ ,

$$\int_0^T \|u_{\varepsilon}(\cdot, t) \cdot \nabla c_{\varepsilon}(\cdot, t)\|_{L^{1+\delta}(\Omega)}^{\delta} dt \leq \int_0^T \|u_{\varepsilon}(\cdot, t)\|_{L^{\frac{3(1+\delta)(1+2\delta)}{1+4\delta}}(\Omega)}^{\delta} \|\nabla c_{\varepsilon}(\cdot, t)\|_{L^{\frac{3(1+2\delta)}{2}}(\Omega)}^{\delta} dt$$

$$\leq C_1(T) \int_0^T \|\nabla c_\varepsilon(\cdot, t)\|_{L^{\frac{3(1+2\delta)}{2}}(\Omega)}^\delta dt, \quad (3.17)$$

where

$$C_1(T) := \sup_{\varepsilon \in (0,1)} \sup_{t \in (0,T)} \|u_\varepsilon(\cdot, t)\|_{L^{\frac{3(1+\delta)(1+2\delta)}{1+4\delta}}(\Omega)}^\delta$$

is finite according to Lemma 2.3, because

$$\frac{3(1+\delta)(1+2\delta)}{1+4\delta} = \frac{3(1+3\delta+2\delta^2)}{1+4\delta} < \frac{3(1+3\delta+\delta)}{1+4\delta} = 3$$

due to the inequality  $\delta < \frac{1}{2}$  implied by (3.13).

Next, making full use of (3.13) we employ the Hölder inequality for a second time to see that the integrand on the right of (3.17) can be estimated according to

$$\begin{aligned} \|\nabla c_\varepsilon\|_{L^{\frac{3(1+2\delta)}{2}}(\Omega)}^\delta &= \left\{ \int_\Omega |\nabla c_\varepsilon|^{\frac{3(1+2\delta)}{2}} \right\}^{\frac{2\delta}{3(1+2\delta)}} \\ &= \left\{ \int_\Omega (c_\varepsilon^{p^{(\alpha)}-2} |\nabla c_\varepsilon|^2)^{\frac{3(1+2\delta)}{4}} \cdot c_\varepsilon^{\frac{3(1+2\delta)(2-p^{(\alpha)})}{4}} \right\}^{\frac{2\delta}{3(1+2\delta)}} \\ &\leq \left\{ \int_\Omega c_\varepsilon^{p^{(\alpha)}-2} |\nabla c_\varepsilon|^2 \right\}^{\frac{\delta}{2}} \cdot \left\{ \int_\Omega c_\varepsilon^{\frac{3(1+2\delta)(2-p^{(\alpha)})}{1-6\delta}} \right\}^{\frac{\delta(1-6\delta)}{6(1+2\delta)}} \\ &= \left\{ \int_\Omega c_\varepsilon^{p^{(\alpha)}-2} |\nabla c_\varepsilon|^2 \right\}^{\frac{\delta}{2}} \cdot \|c_\varepsilon\|_{L^q(\Omega)}^{\frac{\delta(2-p^{(\alpha)})}{2}} \quad \text{for all } t > 0 \text{ and } \varepsilon \in (0, 1), \end{aligned}$$

because  $p^{(\alpha)} < 2$ . Thanks to the fact that  $\delta < 2$ , a final application of the Hölder inequality therefore shows that as a consequence of (3.17), for all  $T > 0$  and  $\varepsilon \in (0, 1)$  we have

$$\begin{aligned} \int_0^T \|u_\varepsilon(\cdot, t) \cdot \nabla c_\varepsilon(\cdot, t)\|_{L^{1+\delta}(\Omega)}^\delta dt &\leq C_1(T) \int_0^T \left\{ \int_\Omega c_\varepsilon^{p^{(\alpha)}-2} |\nabla c_\varepsilon|^2 \right\}^{\frac{\delta}{2}} \cdot \|c_\varepsilon(\cdot, t)\|_{L^q(\Omega)}^{\frac{\delta(2-p^{(\alpha)})}{2}} \\ &\leq C_1(T) \cdot \left\{ \int_0^T \int_\Omega c_\varepsilon^{p^{(\alpha)}-2} |\nabla c_\varepsilon|^2 \right\}^{\frac{\delta}{2}} \cdot \left\{ \int_0^T \|c_\varepsilon(\cdot, t)\|_{L^q(\Omega)}^{\frac{\delta(2-p^{(\alpha)})}{2-\delta}} dt \right\}^{\frac{2-\delta}{2}}. \end{aligned}$$

For any such  $\alpha$ , the conclusion thus follows upon observing that

$$\sup_{\varepsilon \in (0,1)} \int_0^T \int_\Omega c_\varepsilon^{p^{(\alpha)}-2} |\nabla c_\varepsilon|^2 < \infty$$

due to Lemma 3.1, and that if  $q > p^{(\alpha)}$  then

$$\sup_{\varepsilon \in (0,1)} \int_0^T \|c_\varepsilon(\cdot, t)\|_{L^q(\Omega)}^{\frac{\delta(2-p^{(\alpha)})}{2-\delta}} dt < \infty$$

thanks to (3.15), (3.16) and Lemma 3.2, whereas if  $q \leq p^{(\alpha)}$  then even

$$\sup_{\varepsilon \in (0,1)} \sup_{t \in (0,T)} \|c_\varepsilon(\cdot, t)\|_{L^q(\Omega)} < \infty \quad \text{for all } T > 0$$

by Lemma 3.1 and, e.g., Young's inequality.

If  $\alpha \geq \frac{10}{7}$ , however, then in (3.1) we have  $p^{(\alpha)} \geq 2$ , so that Lemma 3.1 entails that

$$C_2(T) := \sup_{\varepsilon \in (0,1)} \int_0^T \int_{\Omega} |\nabla c_{\varepsilon}|^2 < \infty \quad \text{for all } T > 0,$$

while from Lemma 2.3 we know that

$$C_3(T) := \sup_{\varepsilon \in (0,1)} \sup_{t \in (0,T)} \|u_{\varepsilon}(\cdot, t)\|_{L^{\frac{5}{2}}(\Omega)} < \infty \quad \text{for all } T > 0.$$

By means of the Hölder inequality we can thus estimate

$$\begin{aligned} \int_0^T \|u_{\varepsilon}(\cdot, t) \cdot \nabla c_{\varepsilon}(\cdot, t)\|_{L^{\frac{10}{9}}(\Omega)}^2 dt &\leq \int_0^T \|u_{\varepsilon}(\cdot, t)\|_{L^{\frac{5}{2}}(\Omega)}^2 \|\nabla c_{\varepsilon}(\cdot, t)\|_{L^2(\Omega)}^2 dt \\ &\leq C_2(T) C_3^2(T) \quad \text{for all } T > 0 \text{ and } \varepsilon \in (0, 1), \end{aligned}$$

from which the claim directly follows in this case.  $\square$

Apart from that, when rewritten in the form  $u_{\varepsilon} \cdot \nabla c_{\varepsilon} = \nabla \cdot (c_{\varepsilon} u_{\varepsilon})$  the convection term addressed above enjoys a further regularity property, now in a reflexive Lebesgue setting with regard to both the space and the time variable.

**Lemma 3.5.** *If  $\alpha > 1$ , then there exists  $p > 1$  such that to each  $T > 0$  there corresponds some  $C(T) > 0$  satisfying*

$$\int_0^T \int_{\Omega} |c_{\varepsilon} u_{\varepsilon}|^p \leq C(T) \quad \text{for all } \varepsilon \in (0, 1). \quad (3.18)$$

*Proof.* We fix  $\delta > 0$  small such that

$$\delta < \frac{1}{2}, \quad (3.19)$$

and that

$$\frac{(1+\delta)(1+6\delta)}{2(1+2\delta)} \leq 1, \quad (3.20)$$

and let  $q := \frac{3(1+2\delta)}{2}$ . Then (3.19) ensures that, as in Lemma 3.4,

$$\frac{3(1+\delta)(1+2\delta)}{1+4\delta} < 3,$$

so that Lemma 2.3 applies so as to warrant that for each  $T > 0$ ,

$$C_1(T) := \sup_{\varepsilon \in (0,1)} \sup_{t \in (0,T)} \|u_{\varepsilon}(\cdot, t)\|_{L^{\frac{3(1+\delta)(1+2\delta)}{1+4\delta}}(\Omega)} < \infty. \quad (3.21)$$

Apart from that, using Lemma 3.1 we see that if  $q \leq p^{(\alpha)}$ , with  $p^{(\alpha)}$  taken from (3.1), then also

$$C_2(T) := \sup_{\varepsilon \in (0,1)} \sup_{t \in (0,T)} \|c_{\varepsilon}(\cdot, t)\|_{L^q(\Omega)} < \infty \quad \text{for all } T > 0, \quad (3.22)$$

whereas if  $q > p^{(\alpha)}$ , and hence necessarily  $\alpha < \frac{5}{2}$ , then Lemma 3.2 asserts that

$$C_3(T) := \sup_{\varepsilon \in (0,1)} \int_0^T \|c_{\varepsilon}(\cdot, t)\|_{L^q(\Omega)}^{1+\delta} dt < \infty \quad \text{for all } T > 0, \quad (3.23)$$

because then due to the fact that  $p^{(\alpha)} > 1$ , (3.19) ensures that

$$q < \frac{3 \cdot (1 + 2 \cdot \frac{1}{2})}{2} = 3 < 3p^{(\alpha)},$$

and because our restriction (3.20) guarantees that

$$(1 + \delta) \cdot \frac{3(q - p^{(\alpha)})}{2p^{(\alpha)}q} = \frac{3(1 + \delta)}{2} \cdot \left( \frac{1}{p^{(\alpha)}} - \frac{1}{q} \right) < \frac{3(1 + \delta)}{2} \cdot \left( 1 - \frac{1}{q} \right) = \frac{(1 + \delta)(1 + 6\delta)}{2(1 + 2\delta)} \leq 1$$

and thus  $1 + \delta \leq \frac{2p^{(\alpha)}q}{3(q - p^{(\alpha)})}$ . Now since the Hölder inequality implies that according to our choice of  $q$  we have

$$\int_0^T \int_{\Omega} |c_{\varepsilon} u_{\varepsilon}|^{1+\delta} \leq \int_0^T \|c_{\varepsilon}(\cdot, t)\|_{L^q(\Omega)}^{1+\delta} \|u_{\varepsilon}(\cdot, t)\|_{L^{\frac{3(1+\delta)(1+2\delta)}{1+4\delta}}(\Omega)}^{1+\delta} dt \quad \text{for all } T > 0 \text{ and } \varepsilon \in (0, 1),$$

in the case  $q \leq p^{(\alpha)}$  we may use the definitions of  $(C_1(T))_{T>0}$  and  $(C_2(T))_{T>0}$  in (3.21) and (3.22) to see that

$$\int_0^T \int_{\Omega} |c_{\varepsilon} u_{\varepsilon}|^{1+\delta} \leq C_1^{1+\delta}(T) C_2^{1+\delta}(T) \cdot T \quad \text{for all } T > 0 \text{ and } \varepsilon \in (0, 1),$$

while if  $q > p^{(\alpha)}$  then on the basis of (3.21) and (3.23) we can estimate

$$\int_0^T \int_{\Omega} |c_{\varepsilon} u_{\varepsilon}|^{1+\delta} \leq C_1^{1+\delta}(T) C_3(T) \quad \text{for all } T > 0 \text{ and } \varepsilon \in (0, 1),$$

and thus conclude on letting  $p := 1 + \delta$ . □

In order to prepare an appropriate exploitation of the latter two lemmata, let us state the following interpolation inequality in which, as throughout the remainder of this section, given  $p > 1$  we let  $B = B_p$  denote the realization of  $-\Delta + 1$  under homogeneous Neumann boundary conditions in  $L^p(\Omega)$ .

**Lemma 3.6.** *Let  $p > 1$  and  $\delta \in (0, \frac{1}{2})$ . Then for all  $\eta \in (0, \frac{1}{2})$  there exists  $C = C(p, \delta, \eta) > 0$  such that*

$$\|B^{-\frac{1}{2}+\delta} \nabla \cdot \varphi\|_{L^p(\Omega)} \leq C \|\nabla \cdot \varphi\|_{L^p(\Omega)}^{\frac{2\delta+2\eta}{1+2\eta}} \|\varphi\|_{L^p(\Omega)}^{\frac{1-2\delta}{1+2\eta}} \quad \text{for all } \varphi \in C^1(\overline{\Omega}; \mathbb{R}^3) \text{ such that } \varphi \cdot \nu|_{\partial\Omega} = 0. \quad (3.24)$$

*Proof.* According to Theorem 14.1 in [2], let us first pick  $C_1 = C_1(p, \delta, \eta) > 0$  such that

$$\|B^{-\frac{1}{2}+\delta} \psi\|_{L^p(\Omega)} \leq C_1 \|\psi\|_{L^p(\Omega)}^{\frac{2\delta+2\eta}{1+2\eta}} \|B^{-\frac{1}{2}-\eta} \psi\|_{L^p(\Omega)}^{\frac{1-2\delta}{1+2\eta}} \quad \text{for all } \psi \in C^0(\overline{\Omega}), \quad (3.25)$$

and observe that due to the topological equivalence of  $D(B^{\frac{1}{2}-\eta})$  to  $W^{1-2\eta,p}(\Omega)$  ([6, Theorem 1.6.1]) and the continuity of the embeddings  $W^{1,p}(\Omega) \hookrightarrow W^{1-2\eta,p}(\Omega)$  and  $D(B^{\frac{1}{2}-\eta}) \hookrightarrow D(B^{-\frac{1}{2}-\eta})$ , by relying on a Poincaré inequality we can choose  $C_2 = C_2(p, \eta) > 0$  and  $C_3 = C_3(p, \eta) > 0$  such that

$$\|B^{\frac{1}{2}-\eta} \psi\|_{L^p(\Omega)} \leq C_2 \|\nabla \psi\|_{L^p(\Omega)} \quad \text{for all } \psi \in W^{1,p}(\Omega) \text{ such that } \int_{\Omega} \psi = 0 \quad (3.26)$$

and

$$\|B^{-\frac{1}{2}-\eta} \psi\|_{L^p(\Omega)} \leq C_3 \|B^{\frac{1}{2}-\eta} \psi\|_{L^p(\Omega)} \quad \text{for all } \psi \in W^{1,p}(\Omega). \quad (3.27)$$

We moreover recall that the Helmholtz projection acts as a bounded operator on  $L^p(\Omega; \mathbb{R}^3)$  ([14]), whence we can fix  $C_4 = C_4(p) > 0$  fulfilling

$$\|\mathcal{P}\psi\|_{L^p(\Omega)} \leq C_4 \|\psi\|_{L^p(\Omega)} \quad \text{for all } \psi \in L^p(\Omega; \mathbb{R}^3). \quad (3.28)$$

Consequently, given  $\varphi \in C^1(\overline{\Omega}; \mathbb{R}^3)$  we can find  $\rho \in W^{1,p}(\Omega)$  such that  $\int_{\Omega} \rho = 0$  and  $\varphi = \mathcal{P}\varphi + \nabla \rho$ , where  $\nabla \cdot (\mathcal{P}\varphi) = 0$  in  $\mathcal{D}'(\Omega)$  ([14]). Therefore, taking any  $\varphi \in C^1(\overline{\Omega}; \mathbb{R}^3)$  with  $\varphi \cdot \nu|_{\partial\Omega} = 0$  and an arbitrary  $\psi \in C_0^\infty(\Omega)$  we see that since  $B$  and all its fractional powers are self-adjoint in  $L^2(\Omega)$ , and since evidently  $\int_{\partial\Omega} (\varphi \cdot \nu) B^{-\frac{1}{2}-\eta} \psi = 0$  and  $\int_{\Omega} \mathcal{P}\varphi \cdot \nabla (B^{-\frac{1}{2}-\eta} \psi) = 0$  as well as  $\int_{\partial\Omega} \rho \frac{\partial}{\partial \nu} (B^{-\frac{1}{2}-\eta} \psi) = 0$ , we see that

$$\int_{\Omega} (B^{-\frac{1}{2}-\eta} \nabla \cdot \varphi) \cdot \psi = \int_{\Omega} (\nabla \cdot \varphi) \cdot B^{-\frac{1}{2}-\eta} \psi$$

$$\begin{aligned}
&= - \int_{\Omega} \varphi \cdot \nabla (B^{-\frac{1}{2}-\eta} \psi) \\
&= - \int_{\Omega} \nabla \rho \cdot \nabla (B^{-\frac{1}{2}-\eta} \psi) \\
&= \int_{\Omega} \rho \Delta (B^{-\frac{1}{2}-\eta} \psi) \\
&= \int_{\Omega} \rho \cdot (-B + 1) (B^{-\frac{1}{2}-\eta} \psi) \\
&= - \int_{\Omega} \rho \cdot B^{\frac{1}{2}-\eta} \psi + \int_{\Omega} \rho \cdot B^{-\frac{1}{2}-\eta} \psi \\
&= - \int_{\Omega} B^{\frac{1}{2}-\eta} \rho \cdot \psi + \int_{\Omega} B^{-\frac{1}{2}-\eta} \rho \cdot \psi \\
&\leq \|B^{\frac{1}{2}-\eta} \rho\|_{L^p(\Omega)} \|\psi\|_{L^{\frac{p}{p-1}}(\Omega)} + \|B^{-\frac{1}{2}-\eta} \rho\|_{L^p(\Omega)} \|\psi\|_{L^{\frac{p}{p-1}}(\Omega)}
\end{aligned}$$

by the Hölder inequality, so that thanks to (3.27), (3.26) and (3.28),

$$\begin{aligned}
\|B^{-\frac{1}{2}-\eta} \nabla \cdot \varphi\|_{L^p(\Omega)} &= \sup_{\substack{\psi \in C_0^\infty(\Omega) \\ \|\psi\|_{L^{\frac{p}{p-1}}(\Omega)} \leq 1}} \int_{\Omega} (B^{-\frac{1}{2}-\eta} \nabla \cdot \varphi) \cdot \psi \\
&\leq \|B^{\frac{1}{2}-\eta} \rho\|_{L^p(\Omega)} + \|B^{-\frac{1}{2}-\eta} \rho\|_{L^p(\Omega)} \\
&\leq (1 + C_3) \|B^{\frac{1}{2}-\eta} \rho\|_{L^p(\Omega)} \\
&\leq C_2(1 + C_3) \|\nabla \rho\|_{L^p(\Omega)} \\
&= C_2(1 + C_3) \|\varphi - \mathcal{P}\varphi\|_{L^p(\Omega)} \\
&\leq C_2(1 + C_3)(1 + C_4) \|\varphi\|_{L^p(\Omega)}.
\end{aligned}$$

In view of (3.25), this shows that for any such  $\varphi$  we have

$$\begin{aligned}
\|B^{-\frac{1}{2}+\delta} \nabla \cdot \varphi\|_{L^p(\Omega)} &\leq C_1 \|\nabla \cdot \varphi\|_{L^p(\Omega)}^{\frac{2\delta+2\eta}{1+2\eta}} \|B^{-\frac{1}{2}-\eta} \nabla \cdot \varphi\|_{L^p(\Omega)}^{\frac{1-2\delta}{1+2\eta}} \\
&\leq C_1 \|\nabla \cdot \varphi\|_{L^p(\Omega)}^{\frac{2\delta+2\eta}{1+2\eta}} \cdot \left\{ C_2(1 + C_3)(1 + C_4) \right\}^{\frac{1-2\delta}{1+2\eta}} \|\varphi\|_{L^p(\Omega)}^{\frac{1-2\delta}{1+2\eta}},
\end{aligned}$$

and that thus (3.24) holds with an obvious choice of  $C(p, \delta, \eta)$ .  $\square$

We can thereby accomplish the main step of our analysis in this section by combining Lemma 3.4 and Lemma 3.5 to achieve the following estimate of  $c_\varepsilon$  in a space which is compactly embedded into  $W^{1,1}(\Omega)$ .

**Lemma 3.7.** *If  $\alpha > 1$ , then there exist  $p > 1$  and  $\delta > 0$  such that for any choice of  $\tau > 0$  and  $T > \tau$  one can fix  $C(\tau, T) > 0$  satisfying*

$$\int_{\tau}^T \int_{\Omega} |B^{\frac{1}{2}+\delta} c_\varepsilon|^p \leq C(\tau, T) \quad \text{for all } \varepsilon \in (0, 1). \quad (3.29)$$

*Proof.* We first invoke Lemma 3.4 and Lemma 3.5 to fix  $p_0 > 1$  and  $\lambda \in (0, 2)$  with the property that for all  $T > 0$  we can find  $C_1(T) > 0$  and  $C_2(T) > 0$  fulfilling

$$\int_0^T \|u_\varepsilon(\cdot, t) \cdot \nabla c_\varepsilon(\cdot, t)\|_{L^{p_0}(\Omega)}^\lambda dt \leq C_1(T) \quad \text{for all } \varepsilon \in (0, 1) \quad (3.30)$$

and

$$\int_0^T \int_{\Omega} |c_{\varepsilon} u_{\varepsilon}|^{p_0} \leq C_2(T) \quad \text{for all } \varepsilon \in (0, 1), \quad (3.31)$$

and we then pick  $p > 1$  such that

$$p < p_0, \quad p \leq p^{(\alpha)} \quad \text{and} \quad p \leq \alpha, \quad (3.32)$$

which is possible since  $p^{(\alpha)} > 1$  and  $\alpha > 1$ . We thereafter use that  $4p - 2\lambda > 4 \cdot 1 - 2 \cdot 2 = 0$  and  $(1 - 2\delta)p\lambda - [\lambda - (4p - 2\lambda)\delta] \cdot p_0 \rightarrow (p - p_0)\lambda < 0$  as  $\delta \searrow 0$  in choosing some suitably small  $\delta > 0$  such that

$$\delta < \frac{1}{2} \quad \text{and} \quad \delta < \frac{\lambda}{4p - 2\lambda}, \quad (3.33)$$

and such that moreover

$$\frac{(1 - 2\delta)p\lambda}{\lambda - (4p - 2\lambda)\delta} \leq p_0, \quad (3.34)$$

where the last inequality in (3.33) warrants that the operator  $B^{-\frac{1}{2}+\delta}$  is bounded in  $L^p(\Omega)$ , whence with some  $C_3 > 0$  we have

$$\|B^{-\frac{1}{2}+\delta} \varphi\|_{L^p(\Omega)}^p \leq C_3 \|\varphi\|_{L^p(\Omega)}^p \quad \text{for all } \varphi \in L^p(\Omega). \quad (3.35)$$

Next, we invoke standard maximal Sobolev regularity theory in  $L^p(\Omega)$  ([4]) to fix  $C_4 > 0$  such that whenever  $T > 0$ ,  $w \in C^{2,1}(\overline{\Omega} \times [0, T])$  and  $f \in C^0(\overline{\Omega} \times [0, T])$  are such that

$$\begin{cases} w_t = \Delta w - w + f(x, t), & x \in \Omega, \quad t \in (0, T), \\ \frac{\partial w}{\partial \nu} = 0, & x \in \partial\Omega, \quad t \in (0, T), \\ w(x, 0) = 0, & x \in \Omega, \end{cases}$$

we have

$$\int_0^T \int_{\Omega} |Bw|^p \leq C_4 \int_0^T \int_{\Omega} |f|^p. \quad (3.36)$$

We now let  $\tau > 0$  and  $T > 0$  be given and take any nondecreasing cut-off function  $\zeta \in C^\infty([0, \infty))$  such that  $\zeta \equiv 0$  in  $[0, \frac{\tau}{2}]$  and  $\zeta \equiv 1$  in  $[\tau, \infty)$ , and observe that then for each  $\varepsilon \in (0, 1)$ ,

$$w_{\varepsilon}(\cdot, t) := \zeta(t) \cdot B^{-\frac{1}{2}+\delta} c_{\varepsilon}(\cdot, t), \quad t \in [0, T],$$

defines a function  $w_{\varepsilon}$  on  $\overline{\Omega} \times [0, T]$  which since  $c_{\varepsilon}(\cdot, t) \in D(B)$  for all  $t > 0$ , and since  $B^{-\frac{1}{2}+\delta}$  maps  $D(B)$  into itself, belongs to  $C^{2,1}(\overline{\Omega} \times [0, T])$  and satisfies  $\frac{\partial w_{\varepsilon}}{\partial \nu} = 0$  on  $\partial\Omega \times (0, T)$  as well as  $w_{\varepsilon}(\cdot, 0) \equiv 0$  in  $\Omega$ . Furthermore, using (2.1) we see that

$$\begin{aligned} w_{\varepsilon t} &= \zeta(t) B^{-\frac{1}{2}+\delta} c_{\varepsilon t} + \zeta'(t) B^{-\frac{1}{2}+\delta} c_{\varepsilon} \\ &= \zeta(t) B^{-\frac{1}{2}+\delta} \left\{ -Bc_{\varepsilon} + \frac{n_{\varepsilon}}{1 + \varepsilon n_{\varepsilon}} - \nabla \cdot (c_{\varepsilon} u_{\varepsilon}) \right\} + \zeta'(t) B^{-\frac{1}{2}+\delta} c_{\varepsilon} \\ &= -Bw_{\varepsilon} + \zeta(t) B^{-\frac{1}{2}+\delta} \frac{n_{\varepsilon}}{1 + \varepsilon n_{\varepsilon}} - \zeta(t) B^{-\frac{1}{2}+\delta} \nabla \cdot (c_{\varepsilon} u_{\varepsilon}) + \zeta'(t) B^{-\frac{1}{2}+\delta} c_{\varepsilon} \quad \text{in } \Omega \times (0, T), \end{aligned}$$

so that (3.36) applies so as to warrant that

$$\begin{aligned} \int_0^T \int_{\Omega} \zeta^p(t) |B^{\frac{1}{2}+\delta} c_{\varepsilon}|^p &= \int_0^T \int_{\Omega} |Bw_{\varepsilon}|^p \\ &\leq C_4 \int_0^T \int_{\Omega} \left| \zeta(t) B^{-\frac{1}{2}+\delta} \frac{n_{\varepsilon}}{1 + \varepsilon n_{\varepsilon}} - \zeta(t) B^{-\frac{1}{2}+\delta} \nabla \cdot (c_{\varepsilon} u_{\varepsilon}) + \zeta'(t) B^{-\frac{1}{2}+\delta} c_{\varepsilon} \right|^p \end{aligned}$$

$$\begin{aligned}
&\leq 3^p C_4 \int_0^T \int_{\Omega} \left| B^{-\frac{1}{2}+\delta} \frac{n_{\varepsilon}}{1+\varepsilon n_{\varepsilon}} \right|^p \\
&\quad + 3^p C_4 \int_0^T \int_{\Omega} \left| B^{-\frac{1}{2}+\delta} \nabla \cdot (c_{\varepsilon} u_{\varepsilon}) \right|^p \\
&\quad + 3^p C_4 \|\zeta'\|_{L^{\infty}((0,T))}^p \int_0^T \int_{\Omega} |B^{-\frac{1}{2}+\delta} c_{\varepsilon}|^p \quad \text{for all } \varepsilon \in (0, 1),
\end{aligned} \tag{3.37}$$

because  $0 \leq \zeta \leq 1$ . Here by (3.35), Young's inequality and the third restriction in (3.32),

$$\begin{aligned}
\int_0^T \int_{\Omega} \left| B^{-\frac{1}{2}+\delta} \frac{n_{\varepsilon}}{1+\varepsilon n_{\varepsilon}} \right|^p &\leq C_3 \int_0^T \int_{\Omega} \left| \frac{n_{\varepsilon}}{1+\varepsilon n_{\varepsilon}} \right|^p \\
&\leq C_3 \int_0^T \int_{\Omega} n_{\varepsilon}^p \\
&\leq C_3 \int_0^T \int_{\Omega} n_{\varepsilon}^{\alpha} + C_3 |\Omega| T \quad \text{for all } \varepsilon \in (0, 1),
\end{aligned} \tag{3.38}$$

whereas (3.35) together with Young's inequality and the second requirement in (3.32) shows that

$$\begin{aligned}
\int_0^T \int_{\Omega} |B^{-\frac{1}{2}+\delta} c_{\varepsilon}|^p &\leq C_3 \int_0^T \int_{\Omega} c_{\varepsilon}^p \\
&\leq C_3 \int_0^T \int_{\Omega} c_{\varepsilon}^{p^{(a)}} + C_3 |\Omega| T \\
&\leq C_3 T \cdot \sup_{t \in (0,T)} \int_{\Omega} c_{\varepsilon}^{p^{(a)}}(\cdot, t) + C_3 |\Omega| T \quad \text{for all } \varepsilon \in (0, 1).
\end{aligned} \tag{3.39}$$

Apart from that, applying Lemma 3.6 to  $\eta := \delta < \frac{1}{2}$  we obtain  $C_5 > 0$  such that for all  $\varepsilon \in (0, 1)$ ,

$$\int_0^T \int_{\Omega} \left| B^{-\frac{1}{2}+\delta} \nabla \cdot (c_{\varepsilon} u_{\varepsilon}) \right|^p \leq C_5 \int_0^T \left\| \nabla \cdot (c_{\varepsilon}(\cdot, t) u_{\varepsilon}(\cdot, t)) \right\|_{L^p(\Omega)}^{\frac{4p\delta}{1+2\delta}} \|c_{\varepsilon}(\cdot, t) u_{\varepsilon}(\cdot, t)\|_{L^p(\Omega)}^{\frac{(1-2\delta)p}{1+2\delta}} dt,$$

so that relying on the identity  $\nabla \cdot (c_{\varepsilon} u_{\varepsilon}) = u_{\varepsilon} \cdot \nabla c_{\varepsilon}$ , on the fact that  $\frac{4p\delta}{1+2\delta} < \lambda$  by the second condition in (3.33), and on (3.34), we may twice again employ Young's inequality to see that

$$\begin{aligned}
\int_0^T \int_{\Omega} \left| B^{-\frac{1}{2}+\delta} \nabla \cdot (c_{\varepsilon} u_{\varepsilon}) \right|^p &\leq C_5 \int_0^T \left\| u_{\varepsilon}(\cdot, t) \cdot \nabla c_{\varepsilon}(\cdot, t) \right\|_{L^p(\Omega)}^{\lambda} dt + C_5 \int_0^T \|c_{\varepsilon}(\cdot, t) u_{\varepsilon}(\cdot, t)\|_{L^p(\Omega)}^{\frac{(1-2\delta)p\lambda}{\lambda-(4p-2\lambda)\delta}} dt \\
&\leq C_5 \int_0^T \left\| u_{\varepsilon}(\cdot, t) \cdot \nabla c_{\varepsilon}(\cdot, t) \right\|_{L^p(\Omega)}^{\lambda} dt \\
&\quad + C_5 \int_0^T \|c_{\varepsilon}(\cdot, t) u_{\varepsilon}(\cdot, t)\|_{L^p(\Omega)}^{p_0} dt + C_5 T \quad \text{for all } \varepsilon \in (0, 1).
\end{aligned}$$

Since the first restriction in (3.32) ensures that due to the Hölder inequality we have

$$\|\varphi\|_{L^p(\Omega)} \leq |\Omega|^{\frac{p_0-p}{p_0 p}} \|\varphi\|_{L^{p_0}(\Omega)} \quad \text{for all } \varphi \in L^{p_0}(\Omega),$$



along with (3.30) and (3.31) this implies that for all  $\varepsilon \in (0, 1)$ ,

$$\begin{aligned} \int_0^T \int_{\Omega} \left| B^{-\frac{1}{2}+\delta} \nabla \cdot (c_{\varepsilon} u_{\varepsilon}) \right|^p &\leq C_5 |\Omega|^{\frac{(p_0-p)\lambda}{p_0 p}} \int_0^T \left\| u_{\varepsilon}(\cdot, t) \cdot \nabla c_{\varepsilon}(\cdot, t) \right\|_{L^{p_0}(\Omega)}^{\lambda} dt \\ &\quad + C_5 |\Omega|^{\frac{p_0-p}{p}} \int_0^T \|c_{\varepsilon}(\cdot, t) u_{\varepsilon}(\cdot, t)\|_{L^{p_0}(\Omega)}^{p_0} dt + C_5 T \\ &\leq C_6(T) := C_1(T) C_5 |\Omega|^{\frac{(p_0-p)\lambda}{p_0 p}} + C_2(T) C_5 |\Omega|^{\frac{p_0-p}{p}} + C_5 T, \end{aligned}$$

so that from (3.37)-(3.39) we infer that

$$\begin{aligned} \int_0^T \int_{\Omega} \zeta^p(t) |B^{\frac{1}{2}+\delta} c_{\varepsilon}|^p &\leq 3^p C_4 \cdot \left\{ C_3 C_7(T) + C_3 |\Omega| T \right\} \\ &\quad + 3^p C_4 C_6(T) \\ &\quad + 3^p C_4 \cdot \left\{ C_3 C_8(T) + C_3 |\Omega| T \right\} \cdot \|\zeta'\|_{L^{\infty}((0,T))}^p \quad \text{for all } \varepsilon \in (0, 1), \end{aligned}$$

where

$$C_7(T) := \sup_{\varepsilon \in (0,1)} \int_0^T \int_{\Omega} n_{\varepsilon}^{\alpha} \quad \text{and} \quad C_8(T) := \sup_{\varepsilon \in (0,1)} \sup_{t \in (0,T)} \int_{\Omega} c_{\varepsilon}^{p^{(a)}}(\cdot, t)$$

are both finite due to Lemma 2.2 and Lemma 3.1. It remains to recall that  $\zeta \equiv 1$  on  $[\tau, T]$  to conclude (3.29) from this upon an evident choice of  $C(\tau, T)$ .  $\square$

In preparation of an Aubin-Lions type argument, we supplement the above by some information on regularity of time derivatives.

**Lemma 3.8.** *Let  $\alpha > 1$ . Then there exists an integer  $m \geq 3$  such that for all  $T > 0$  one can find  $C(T) > 0$  fulfilling*

$$\int_0^T \|c_{\varepsilon t}(\cdot, t)\|_{(W_0^{m,2}(\Omega))^*} dt \leq C(T) \quad \text{for all } \varepsilon \in (0, 1). \quad (3.40)$$

*Proof.* We let  $p > 1$  be as provided by Lemma 3.5 and take  $m \in \{3, 4, \dots\}$  such that  $m \geq \frac{6-p}{2p}$ , which ensures that  $W_0^{m,2}(\Omega)$  is continuously embedded into both  $W^{2,\infty}(\Omega)$  and  $W^{1,\frac{p}{p-1}}(\Omega)$ , and that thus there exist positive constants  $C_1, C_2$  and  $C_3$  such that  $\|\Delta \psi\|_{L^{\infty}(\Omega)} \leq C_1 \|\psi\|_{W^{m,2}(\Omega)}$ ,  $\|\psi\|_{L^{\infty}(\Omega)} \leq C_2 \|\psi\|_{W^{m,2}(\Omega)}$  and  $\|\nabla \psi\|_{L^{\frac{p}{p-1}}(\Omega)} \leq C_3 \|\psi\|_{W^{m,2}(\Omega)}$  for all  $\psi \in C_0^{\infty}(\Omega)$ . Given any such  $\psi$  and an arbitrary  $t > 0$ , on the basis of (2.1) we can therefore estimate

$$\begin{aligned} \left| \int_{\Omega} c_{\varepsilon t}(\cdot, t) \psi \right| &= \left| \int_{\Omega} c_{\varepsilon} \Delta \psi - \int_{\Omega} c_{\varepsilon} \psi + \int_{\Omega} \frac{n_{\varepsilon}}{1 + \varepsilon n_{\varepsilon}} \psi + \int_{\Omega} c_{\varepsilon} u_{\varepsilon} \cdot \nabla \psi \right| \\ &\leq \|c_{\varepsilon}\|_{L^1(\Omega)} \|\Delta \psi\|_{L^{\infty}(\Omega)} + \|c_{\varepsilon}\|_{L^1(\Omega)} \|\psi\|_{L^{\infty}(\Omega)} + \|n_{\varepsilon}\|_{L^1(\Omega)} \|\psi\|_{L^{\infty}(\Omega)} \\ &\quad + \|c_{\varepsilon} u_{\varepsilon}\|_{L^p(\Omega)} \|\nabla \psi\|_{L^{\frac{p}{p-1}}(\Omega)} \\ &\leq \left\{ (C_1 + C_2) \|c_{\varepsilon}\|_{L^1(\Omega)} + C_2 \|n_{\varepsilon}\|_{L^1(\Omega)} + C_3 \|c_{\varepsilon} u_{\varepsilon}\|_{L^p(\Omega)} \right\} \|\psi\|_{W^{m,2}(\Omega)} \end{aligned}$$

for  $\varepsilon \in (0, 1)$ . Therefore,

$$\int_0^T \|c_{\varepsilon t}(\cdot, t)\|_{(W_0^{m,2}(\Omega))^*} dt \leq (C_1 + C_2) T \cdot \sup_{t \in (0,T)} \|c_{\varepsilon}(\cdot, t)\|_{L^1(\Omega)} + C_2 T \cdot \sup_{t \in (0,T)} \|n_{\varepsilon}(\cdot, t)\|_{L^1(\Omega)}$$

$$+ C_3 \int_0^T \|c_\varepsilon(\cdot, t)u_\varepsilon(\cdot, t)\|_{L^p(\Omega)} dt \quad \text{for all } T > 0 \text{ and } \varepsilon \in (0, 1),$$

so that the claim results from Lemma 3.1, Lemma 2.2 and Lemma 3.5.  $\square$

We can thereby derive the main result of this section in quite a straightforward manner from Lemma 3.7:

**Lemma 3.9.** *Let  $\alpha > 1$ . Then for all  $T > 0$ ,*

$$(c_\varepsilon)_{\varepsilon \in (0,1)} \text{ is relatively compact with respect to the strong topology in } L^1((0, T); W^{1,1}(\Omega)). \quad (3.41)$$

*Proof.* According to Lemma 3.7, we can find  $p > 1$  and  $\delta > 0$  such that

$$(c_\varepsilon)_{\varepsilon \in (0,1)} \text{ is bounded in } L^p((0, T); D(B_p^{\frac{1}{2}+\delta})) \quad \text{for all } T > 0,$$

whereas Lemma 3.8 provides an integer  $m \geq 3$  with the property that

$$(c_{\varepsilon t})_{\varepsilon \in (0,1)} \text{ is bounded in } L^1((0, T); (W_0^{m,2}(\Omega))^*) \quad \text{for all } T > 0.$$

Since  $D(B_p^{\frac{1}{2}+\delta})$  is continuously embedded into  $W^{1,p}(\Omega)$  ([6, Theorem 1.6.1]), an Aubin-Lions lemma ([18]) becomes applicable so as to guarantee that for all  $T > 0$ ,

$$(c_\varepsilon)_{\varepsilon \in (0,1)} \text{ is relatively compact with respect to the strong topology in } L^p((0, T); W^{1,p}(\Omega)).$$

As  $p \geq 1$ , this clearly entails (3.41).  $\square$

## 4 Compactness properties of $((n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon})_{\varepsilon \in (0,1)}$ for $p > 0$ and large $\kappa$

This section is devoted to an essentially straightforward adaptation of the reasoning from [33, Section 6], pursuing the goal to derive relative compactness of  $((n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon})_{\varepsilon \in (0,1)}$  with respect to both the weak topology in  $L^2((0, T); W^{1,2}(\Omega))$  and the strong topology in  $L^2(\Omega \times (0, T))$  for arbitrary  $T > 0$ , each  $p > 0$  and any suitably large  $\kappa > 0$ . This will be achieved on the basis of Lemma 2.4, in which we will choose  $\phi$  and  $\psi$  as specified and described in the following statement imported from [33, Lemma 6.1].

**Lemma 4.1.** *Let  $p > 0$  and  $\kappa > 0$ , and define*

$$\phi(s) := (s+1)^{-p}, \quad \Phi(s) := -2\sqrt{\frac{p+1}{p}}(s+1)^{-\frac{p}{2}} \quad \text{and} \quad \psi(\bar{s}) := e^{-\kappa \bar{s}}, \quad s \geq 0, \bar{s} \geq 0. \quad (4.1)$$

Then

$$\Phi'(s) = \sqrt{\phi''(s)} \quad \text{for all } s \geq 0, \quad (4.2)$$

and for any  $s \geq 0$  and  $\bar{s} \geq 0$  we have

$$\frac{\phi'(s)}{\sqrt{\phi''(s)}} \cdot \frac{\psi'(\bar{s})}{\sqrt{\psi(\bar{s})}} - \frac{1}{2}\Phi(s) \frac{\psi'(\bar{s})}{\sqrt{\psi(\bar{s})}} - \frac{1}{2}s\sqrt{\phi''(s)} \cdot \sqrt{\psi(\bar{s})} = -\frac{2\kappa + p(p+1)\frac{s}{s+1}}{2\sqrt{p(p+1)}}(s+1)^{-\frac{p}{2}}e^{-\frac{\kappa \bar{s}}{2}} \quad (4.3)$$

and

$$\phi(s)\psi''(\bar{s}) - \frac{\phi'^2(s)}{\phi''(s)} \cdot \frac{\psi'^2(\bar{s})}{\psi(\bar{s})} - \frac{1}{4}s^2\phi''(s)\psi(\bar{s}) = \frac{4\kappa^2 - p(p+1)\frac{s^2}{(s+1)^2}}{4(p+1)}(s+1)^{-p}e^{-\kappa \bar{s}} \quad (4.4)$$

as well as

$$\frac{\phi'(s)}{\sqrt{\phi''(s)}}\sqrt{\psi(\bar{s})} = -\frac{p}{\sqrt{p(p+1)}}(s+1)^{-\frac{p}{2}}e^{-\frac{\kappa \bar{s}}{2}} \quad (4.5)$$

and

$$s\phi'(s)\psi(\bar{s}) - \phi(s)\psi'(\bar{s}) + \frac{1}{2}\frac{\Phi(s)\phi'(s)}{\sqrt{\phi''(s)}}\psi'(\bar{s}) = -ps(s+1)^{-p-1}e^{-\kappa \bar{s}}. \quad (4.6)$$

When substantiated according to the latter choices, for  $\varepsilon \in (0, 1)$  Lemma 2.4 indeed takes the following form.

**Corollary 4.2.** *Let  $p > 0$  and  $\kappa > 0$ . Then whenever  $\varphi \in C^\infty(\overline{\Omega} \times (0, \infty))$ ,*

$$\begin{aligned}
 & \int_{\Omega} \partial_t \left\{ (n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon} \right\} \cdot \varphi \\
 &= -\frac{4(p+1)}{p} \int_{\Omega} \left| \nabla \left\{ (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \right\} + \frac{2\kappa + p(p+1)\frac{n_\varepsilon}{n_\varepsilon+1}}{4(p+1)} (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \nabla c_\varepsilon \right|^2 \varphi \\
 & \quad - \int_{\Omega} \frac{4\kappa^2 - p(p+1)^2 \frac{n_\varepsilon^2}{(n_\varepsilon+1)^2}}{4(p+1)} (n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon} |\nabla c_\varepsilon|^2 \varphi \\
 & \quad - 2 \int_{\Omega} (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \nabla \left\{ (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \right\} \cdot \nabla \varphi \\
 & \quad - p \int_{\Omega} n_\varepsilon (n_\varepsilon + 1)^{-p-1} e^{-\kappa c_\varepsilon} \nabla c_\varepsilon \cdot \nabla \varphi \\
 & \quad + \int_{\Omega} (n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon} u_\varepsilon \cdot \nabla \varphi \\
 & \quad - p \int_{\Omega} (n_\varepsilon + 1)^{-p-1} (\rho n_\varepsilon - \mu n_\varepsilon^\alpha) e^{-\kappa c_\varepsilon} \varphi \\
 & \quad + \kappa \int_{\Omega} (n_\varepsilon + 1)^{-p} c_\varepsilon e^{-\kappa c_\varepsilon} \varphi - \kappa \int_{\Omega} \frac{n_\varepsilon}{1 + \varepsilon n_\varepsilon} (n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon} \varphi
 \end{aligned} \tag{4.7}$$

for all  $t > 0$  and  $\varepsilon \in (0, 1)$ .

*Proof.* We only need to combine Lemma 2.4 with Lemma 4.1. □

Using that the factor  $4\kappa^2 - p(p+1)^2 \frac{n_\varepsilon^2}{(n_\varepsilon+1)^2}$  appearing in the second integrand on the right-hand side of (4.7) has a uniform positive lower bound whenever  $\kappa^2 > \frac{p(p+1)^2}{4}$ , the following can readily be derived from the latter.

**Lemma 4.3.** *If  $p > 0$  and  $\kappa > 0$  satisfy*

$$\kappa > \frac{\sqrt{p} \cdot (p+1)}{2}, \tag{4.8}$$

*then for all  $T > 0$  there exists  $C = C(T, p, \kappa) > 0$  such that*

$$\int_0^T \int_{\Omega} \left| \nabla \left\{ (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \right\} \right|^2 \leq C \quad \text{for all } \varepsilon \in (0, 1) \tag{4.9}$$

and

$$\int_0^T \int_{\Omega} (n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon} |\nabla c_\varepsilon|^2 \leq C \quad \text{for all } \varepsilon \in (0, 1). \tag{4.10}$$

*Proof.* Upon choosing  $\varphi \equiv 1$  in Corollary 4.2, on the basis of Lemma 2.2 this can be seen by copying almost word by word the proof of Lemma 6.3 in [33]. □

In a straightforward manner, this also entails some time regularity feature of said coupled quantities:

**Lemma 4.4.** Let  $p > 0$  and  $\kappa > \frac{\sqrt{p \cdot (p+1)}}{2}$ . Then for all  $T > 0$  there exists  $C = C(T, p, \kappa, m) > 0$  such that

$$\int_0^T \left\| \partial_t \left\{ (n_\varepsilon(\cdot, t) + 1)^{-p} e^{-\kappa c_\varepsilon(\cdot, t)} \right\} \right\|_{(W^{2,2}(\Omega))^*} dt \leq C \quad \text{for all } \varepsilon \in (0, 1). \quad (4.11)$$

*Proof.* For  $\varepsilon \in (0, 1)$ , we abbreviate  $a_\varepsilon := \nabla \left\{ (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \right\}$  and  $b_\varepsilon := (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \nabla v_\varepsilon$  for  $\varepsilon \in (0, 1)$ . An application of Corollary 4.2 to  $\varphi(x, t) := \zeta(x)$ ,  $(x, t) \in \bar{\Omega} \times (0, \infty)$ , for fixed  $\zeta \in C^\infty(\bar{\Omega})$ , then shows that if we let  $C_1 = C_1(p, \kappa) := \frac{8(p+1)}{p} \cdot \left( \frac{2\kappa + p(p+1)}{4(p+1)} \right)^2 + \frac{4\kappa^2 + p(p+1)}{4(p+1)}$ , then

$$\begin{aligned} & \left| \int_\Omega \partial_t \left\{ (n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon} \right\} \cdot \zeta \right| \\ &= \left| -\frac{4(p+1)}{p} \int_\Omega \left| a_\varepsilon + \frac{2\kappa + p(p+1)}{4(p+1)} \frac{n_\varepsilon}{n_\varepsilon + 1} b_\varepsilon \right|^2 \zeta \right. \\ & \quad - \int_\Omega \frac{4\kappa^2 - p(p+1)^2 \frac{n_\varepsilon^2}{(n_\varepsilon + 1)^2}}{4(p+1)} |b_\varepsilon|^2 \zeta \\ & \quad - 2 \int_\Omega (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} a_\varepsilon \cdot \nabla \zeta \\ & \quad - p \int_\Omega n_\varepsilon (n_\varepsilon + 1)^{-\frac{p}{2}-1} e^{-\frac{\kappa c_\varepsilon}{2}} b_\varepsilon \cdot \nabla \zeta \\ & \quad - p \int_\Omega (n_\varepsilon + 1)^{-p-1} (\rho n_\varepsilon - \mu n_\varepsilon^\alpha) e^{-\kappa c_\varepsilon} \zeta \\ & \quad + \int_\Omega (n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon} u_\varepsilon \cdot \nabla \zeta \\ & \quad \left. + \kappa \int_\Omega (n_\varepsilon + 1)^{-p} c_\varepsilon e^{-\kappa c_\varepsilon} \zeta - \kappa \int_\Omega \frac{n_\varepsilon}{1 + \varepsilon n_\varepsilon} (n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon} \zeta \right| \\ &\leq \frac{8(p+1)}{p} \cdot \left\{ \int_\Omega |a_\varepsilon|^2 \right\} \cdot \|\zeta\|_{L^\infty(\Omega)} + c_5 \cdot \left\{ \int_\Omega |b_\varepsilon|^2 \right\} \cdot \|\zeta\|_{L^\infty(\Omega)} \\ & \quad + 2 \cdot \left\{ \int_\Omega |a_\varepsilon|^2 \right\}^{\frac{1}{2}} \cdot \|\nabla \zeta\|_{L^2(\Omega)} + p \cdot \left\{ \int_\Omega |b_\varepsilon|^2 \right\} \cdot \|\nabla \zeta\|_{L^2(\Omega)} \\ & \quad + p\rho \cdot \left\{ \int_\Omega n_\varepsilon \right\} \cdot \|\zeta\|_{L^\infty(\Omega)} + p\mu \cdot \left\{ \int_\Omega n_\varepsilon^\alpha \right\} \cdot \|\zeta\|_{L^\infty(\Omega)} + \left\{ \int_\Omega |u_\varepsilon|^2 \right\} \cdot \|\nabla \zeta\|_{L^2(\Omega)} \\ & \quad + \frac{|\Omega|}{e} \|\zeta\|_{L^\infty(\Omega)} + \kappa \cdot \left\{ \int_\Omega n_\varepsilon \right\} \cdot \|\zeta\|_{L^\infty(\Omega)} \end{aligned} \quad (4.12)$$

for all  $t > 0$  and  $\varepsilon \in (0, 1)$ , because  $\frac{n_\varepsilon}{n_\varepsilon + 1} \leq 1$ ,  $(n_\varepsilon + 1)^{-1} \leq 1$ ,  $e^{-\kappa c_\varepsilon} \leq 1$  and  $\kappa v_\varepsilon e^{-\kappa c_\varepsilon} \leq \frac{1}{e}$  in  $\Omega \times (0, \infty)$ . Since from Lemma 4.3, Lemma 2.2 and 2.3 we know that for all  $T > 0$  we have

$$\sup_{\varepsilon \in (0,1)} \left\{ \int_0^T \int_\Omega |a_\varepsilon|^2 + \int_0^T \int_\Omega |b_\varepsilon|^2 + \int_0^T \int_\Omega n_\varepsilon^\alpha + \int_0^T \int_\Omega |u_\varepsilon|^2 \right\} < \infty, \quad (4.13)$$

and since  $W^{2,2}(\Omega)$  is continuously embedded into  $L^\infty(\Omega)$ , from (4.12) we readily conclude (4.11) upon taking the supremum over all  $\zeta \in C^\infty(\bar{\Omega})$  fulfilling  $\|\zeta\|_{W^{2,2}(\Omega)} \leq 1$ , and then integrating over  $t \in (0, T)$  for fixed  $T > 0$ .  $\square$

In consequence, we infer the following.

**Corollary 4.5.** Suppose that  $p > 0$  and  $\kappa > \frac{\sqrt{p(p+1)}}{2}$ . Then for all  $T > 0$ ,  $((n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon})_{\varepsilon \in (0,1)}$  is relatively compact in  $L^2((0, T); W^{1,2}(\Omega))$  with respect to the weak topology, and relatively compact in  $L^2(\Omega \times (0, T))$  with respect to the strong topology.

*Proof.* This can be derived from Lemma 4.3 and Lemma 4.4 by verbatim copying a corresponding argument detailed in [33, Lemma 7.1].  $\square$

## 5 Passing to the limit. Proof of Theorem 1.1

Thanks to the boundedness and compactness features obtained so far, we are now in the position to construct a limit triple which satisfies the second and the third sub-problem in (1.4) in the spirit of Definition 2.5.

**Lemma 5.1.** Let  $\alpha > 1$ . Then there exist  $(\varepsilon_j)_{j \in \mathbb{N}} \subset (0, 1)$  and functions

$$\begin{cases} n \in L^{\alpha}_{loc}(\bar{\Omega} \times [0, \infty)), \\ c \in L^1_{loc}([0, \infty); W^{1,1}(\Omega)) \quad \text{and} \\ u \in L^1_{loc}([0, \infty); W^{1,1}_0(\Omega; \mathbb{R}^3)) \end{cases} \quad (5.1)$$

such that  $\varepsilon_j \searrow 0$  as  $j \rightarrow \infty$ , that  $n \geq 0$ ,  $c \geq 0$  and  $\nabla \cdot u = 0$  a.e. in  $\Omega \times (0, \infty)$ , that

$$n_\varepsilon \rightarrow n \quad \text{in } L^1_{loc}(\bar{\Omega} \times [0, \infty)) \text{ and a.e. in } \Omega \times (0, \infty), \quad (5.2)$$

$$c_\varepsilon \rightarrow c \quad \text{in } L^1_{loc}(\bar{\Omega} \times [0, \infty)) \text{ and a.e. in } \Omega \times (0, \infty), \quad (5.3)$$

$$\nabla c_\varepsilon \rightarrow \nabla c \quad \text{in } L^1_{loc}(\bar{\Omega} \times [0, \infty)) \text{ and a.e. in } \Omega \times (0, \infty) \quad \text{as well as} \quad (5.4)$$

$$u_\varepsilon \rightharpoonup u \quad \text{in } L^1_{loc}([0, \infty); W^{1,1}(\Omega)) \quad (5.5)$$

as  $\varepsilon = \varepsilon_j \searrow 0$ , and such that (2.9) holds, that (2.10) is satisfied for all  $\varphi \in C^\infty_0(\bar{\Omega} \times [0, \infty))$ , and that (2.11) is fulfilled for each  $\varphi \in C^\infty_0(\Omega \times [0, \infty); \mathbb{R}^3)$  such that  $\nabla \cdot \varphi = 0$ .

*Proof.* We fix any  $p > 0$  and  $\kappa > \frac{\sqrt{p(p+1)}}{2}$ , and let  $w_\varepsilon := (n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon}$  for  $\varepsilon \in (0, 1)$ . In view of Lemma 3.9 and Corollary 4.5, we can then find  $(\varepsilon_j)_{j \in \mathbb{N}} \subset (0, 1)$  and nonnegative functions  $w$  and  $c$  on  $\Omega \times (0, \infty)$  such that  $\varepsilon_j \searrow 0$  as  $j \rightarrow \infty$ , and that as  $\varepsilon = \varepsilon_j \searrow 0$  we have (5.3), (5.4) as well as

$$w_\varepsilon \rightarrow w \quad \text{a.e. in } \Omega \times (0, \infty).$$

Therefore,

$$n_\varepsilon = (e^{\kappa c_\varepsilon} w_\varepsilon)^{-\frac{1}{p}} - 1 \rightarrow n := (e^{\kappa c} w)^{-\frac{1}{p}} - 1 \quad \text{a.e. in } \Omega \times (0, \infty) \quad \text{as } \varepsilon = \varepsilon_j \searrow 0.$$

Recalling that (2.3) implies uniform integrability of  $(n_\varepsilon)_{\varepsilon \in (0,1)}$  over  $\Omega \times (0, T)$  for each  $T > 0$ , we obtain (5.2) as a consequence of the Vitali convergence theorem, while (5.5) directly results from Lemma 2.3, and while the inclusions in (5.1) follow from the boundedness properties in (3.41), (2.5), (2.6) and (2.3) when combined with (5.2)-(5.5) and Fatou's lemma.

Apart from that, taking a null set  $N \subset (0, \infty)$  such that in accordance with (5.2) and the Tonelli theorem we have  $n_\varepsilon(\cdot, t) \rightarrow n(\cdot, t)$  a.e. in  $\Omega$  for all  $t \in (0, \infty) \setminus N$  as  $\varepsilon = \varepsilon_j \searrow 0$  and hence

$$\int_{\Omega} n(\cdot, t) \leq \liminf_{\varepsilon = \varepsilon_j \searrow 0} \int_{\Omega} n_\varepsilon(\cdot, t) \quad \text{for all } t \in (0, \infty) \setminus N, \quad (5.6)$$

in the identity

$$\int_{\Omega} n_\varepsilon(\cdot, t) + \mu \int_0^t \int_{\Omega} n_\varepsilon^\alpha = \int_{\Omega} n_0 + \rho \int_0^t \int_{\Omega} n_\varepsilon,$$

valid for all  $t > 0$  and  $\varepsilon \in (0, 1)$  due to (2.1), we may again employ (5.2) along with Fatou's lemma to infer that the inequality in (2.9) indeed holds for each  $t \in (0, \infty) \setminus N$ .

Finally, given  $\varphi \in C_0^\infty(\bar{\Omega} \times [0, \infty))$  we see from the second equation in (2.1) that

$$\begin{aligned} & - \int_0^\infty \int_\Omega c_\varepsilon \varphi_t - \int_\Omega c_0 \varphi(\cdot, 0) \\ &= - \int_0^\infty \int_\Omega \nabla c_\varepsilon \cdot \nabla \varphi - \int_0^\infty \int_\Omega c_\varepsilon \varphi + \int_0^\infty \int_\Omega \frac{n_\varepsilon}{1+n_\varepsilon} \varphi + \int_0^\infty \int_\Omega c_\varepsilon u_\varepsilon \cdot \nabla \varphi \end{aligned} \quad (5.7)$$

for all  $\varepsilon \in (0, 1)$ , where clearly, by (5.3) and (5.4),

$$\int_0^\infty \int_\Omega c_\varepsilon \varphi_t \rightarrow \int_0^\infty \int_\Omega c \varphi_t, \quad \int_0^\infty \int_\Omega \nabla c_\varepsilon \cdot \nabla \varphi \rightarrow \int_0^\infty \int_\Omega \nabla c \cdot \nabla \varphi \quad \text{and} \quad \int_0^\infty \int_\Omega c_\varepsilon \varphi \rightarrow \int_0^\infty \int_\Omega c \varphi$$

as  $\varepsilon = \varepsilon_j \searrow 0$ . Furthermore, once more due to (5.2) we infer from the Vitali convergence theorem that also  $\frac{n_\varepsilon}{1+n_\varepsilon} \rightarrow n$  in  $L_{loc}^1(\bar{\Omega} \times [0, \infty))$  and thus

$$\int_0^\infty \int_\Omega \frac{n_\varepsilon}{1+n_\varepsilon} \varphi \rightarrow \int_0^\infty \int_\Omega n \varphi$$

as  $\varepsilon = \varepsilon_j \searrow 0$ , whereas Lemma 3.5 entails

$$\int_0^\infty \int_\Omega c_\varepsilon u_\varepsilon \cdot \nabla \varphi \rightarrow \int_0^\infty \int_\Omega c u \cdot \nabla \varphi$$

as  $\varepsilon = \varepsilon_j \searrow 0$ . The identity in (2.10) thus results from (5.7), and that in (2.11) can be verified in quite a similar way by relying on (5.2) and (5.5).  $\square$

Quite in the style of Lemma 8.2 in [33], we can now verify the remaining parts of Definition 2.5 by making use of Corollary 4.2 and the convergence properties gathered in Lemma 5.1:

**Lemma 5.2.** *Let  $\alpha > 1$ , and given  $p > 0$  and  $\kappa > \frac{\sqrt{p}(p+1)}{2}$ , let  $\phi$ ,  $\Phi$  and  $\psi$  be as accordingly defined by (4.1). Then (2.12)-(2.14) are satisfied, and (2.16) holds for any nonnegative  $\varphi \in C_0^\infty(\bar{\Omega} \times [0, \infty))$ .*

*Proof.* For fixed  $T > 0$ , Lemma 4.3 implies that

$$\left( (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \right)_{\varepsilon \in (0,1)} \text{ is bounded in } L^2((0, T); W^{1,2}(\Omega)),$$

and that both

$$\left( (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \nabla c_\varepsilon \right)_{\varepsilon \in (0,1)} \text{ and } \left( n_\varepsilon (n_\varepsilon + 1)^{-\frac{p}{2}-1} e^{-\frac{\kappa c_\varepsilon}{2}} \nabla c_\varepsilon \right)_{\varepsilon \in (0,1)} \text{ are bounded in } L^2(\Omega \times (0, T)).$$

In view of Lemma 5.1 and Egorov's theorem, this implies that as  $\varepsilon = \varepsilon_j \searrow 0$ ,

$$\nabla \left\{ (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \right\} \rightharpoonup \nabla \left\{ (n + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c}{2}} \right\} \quad \text{in } L^2(\Omega \times (0, T)), \quad (5.8)$$

and that

$$(n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \nabla c_\varepsilon \rightharpoonup (n + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c}{2}} \nabla c \quad \text{in } L^2(\Omega \times (0, T)) \quad (5.9)$$

and

$$n_\varepsilon (n_\varepsilon + 1)^{-\frac{p}{2}-1} e^{-\frac{\kappa c_\varepsilon}{2}} \nabla c_\varepsilon \rightharpoonup n (n + 1)^{-\frac{p}{2}-1} e^{-\frac{\kappa c}{2}} \nabla c \quad \text{in } L^2(\Omega \times (0, T)), \quad (5.10)$$

from which it follows that

$$\begin{aligned} & \nabla \left\{ (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \right\} + \frac{2\kappa + p(p+1) \frac{n_\varepsilon}{n_\varepsilon+1}}{4(p+1)} (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \nabla c_\varepsilon \\ & \rightharpoonup \nabla \left\{ (n+1)^{-\frac{p}{2}} e^{-\frac{\kappa c}{2}} \right\} + \frac{2\kappa + p(p+1) \frac{n}{n+1}}{4(p+1)} (n+1)^{-\frac{p}{2}} e^{-\frac{\kappa c}{2}} \nabla c \quad \text{in } L^2(\Omega \times (0, T)) \end{aligned} \quad (5.11)$$

and that, since

$$(n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \rightarrow (n+1)^{-\frac{p}{2}} e^{-\frac{\kappa c}{2}} \quad \text{in } L^2(\Omega \times (0, T)) \quad \text{as } \varepsilon = \varepsilon_j \searrow 0 \quad (5.12)$$

by the dominated convergence theorem, also

$$n_\varepsilon (n_\varepsilon + 1)^{-p-1} e^{-\kappa c_\varepsilon} \nabla c_\varepsilon \rightharpoonup n(n+1)^{-p-1} e^{-\kappa c} \nabla c \quad \text{in } L^1(\Omega \times (0, T)) \quad (5.13)$$

and

$$(n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \nabla \left\{ (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \right\} \rightharpoonup (n+1)^{-\frac{p}{2}} e^{-\frac{\kappa c}{2}} \nabla \left\{ (n+1)^{-\frac{p}{2}} e^{-\frac{\kappa c}{2}} \right\} \quad \text{in } L^1(\Omega \times (0, T)) \quad (5.14)$$

as  $\varepsilon = \varepsilon_j \searrow 0$ . Since  $\left( (n_\varepsilon + 1)^{-p-1} (\rho n_\varepsilon - \mu n_\varepsilon^\alpha) e^{-\kappa c_\varepsilon} \right)_{\varepsilon \in (0,1)}$  can readily be seen to be uniformly integrable over  $\Omega \times (0, T)$  according to (2.3), the Vitali convergence theorem ensures that furthermore

$$(n_\varepsilon + 1)^{-p-1} (\rho n_\varepsilon - \mu n_\varepsilon^\alpha) e^{-\kappa c_\varepsilon} \rightarrow (n+1)^{-p-1} (\rho n - \mu n^\alpha) e^{-\kappa c} \quad \text{in } L^1(\Omega \times (0, T)), \quad (5.15)$$

while, quite similarly,

$$(n_\varepsilon + 1)^{-p} c_\varepsilon e^{-\kappa c_\varepsilon} \rightarrow (n+1)^{-p} c e^{-\kappa c} \quad \text{in } L^1(\Omega \times (0, T)) \quad \text{as } \varepsilon = \varepsilon_j \searrow 0 \quad (5.16)$$

and

$$\frac{n_\varepsilon}{1 + \varepsilon n_\varepsilon} (n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon} \rightarrow n(n+1)^{-p} e^{-\kappa c} \quad \text{in } L^1(\Omega \times (0, T)) \quad \text{as } \varepsilon = \varepsilon_j \searrow 0, \quad (5.17)$$

as well as

$$(n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon} u_\varepsilon \rightharpoonup (n+1)^{-p} e^{-\kappa c} u \quad \text{in } L^1(\Omega \times (0, T)) \quad \text{as } \varepsilon = \varepsilon_j \searrow 0 \quad (5.18)$$

due to (5.5).

Now letting  $\phi$ ,  $\Phi$  and  $\psi$  be as in (4.1), we see that the properties in (2.12) and (2.13) are obvious, and that (2.14), (2.15) are immediate from (5.8)-(5.17). Moreover, given any nonnegative  $\varphi \in C_0^\infty(\bar{\Omega} \times [0, \infty))$ , in the corresponding identity from Corollary 4.2, upon a time integration implying that to see that

$$\begin{aligned} & \frac{4(p+1)}{p} \int_0^\infty \int_\Omega \left| \nabla \left\{ (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \right\} + \frac{2\kappa + p(p+1) \frac{n_\varepsilon}{n_\varepsilon+1}}{4(p+1)} (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \nabla c_\varepsilon \right|^2 \varphi \\ & + \int_0^\infty \int_\Omega \frac{4\kappa^2 - p(p+1)^2 \frac{n_\varepsilon^2}{(n_\varepsilon+1)^2}}{4(p+1)} (n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon} |\nabla c_\varepsilon|^2 \varphi \\ & = \int_0^\infty \int_\Omega (n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon} \varphi_t + \int_\Omega (n_0 + 1)^{-p} e^{-\kappa c_0} \varphi(\cdot, 0) \\ & - 2 \int_0^\infty \int_\Omega (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \nabla \left\{ (n_\varepsilon + 1)^{-\frac{p}{2}} e^{-\frac{\kappa c_\varepsilon}{2}} \right\} \cdot \nabla \varphi \\ & - p \int_0^\infty \int_\Omega n_\varepsilon (n_\varepsilon + 1)^{-p-1} e^{-\kappa c_\varepsilon} \nabla c_\varepsilon \cdot \nabla \varphi \\ & + \int_0^\infty \int_\Omega (n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon} u_\varepsilon \cdot \nabla \varphi - p \int_0^\infty \int_\Omega (n_\varepsilon + 1)^{-p-1} (\rho n_\varepsilon - \mu n_\varepsilon^\alpha) e^{-\kappa c_\varepsilon} \varphi \end{aligned}$$

$$+ \kappa \int_0^\infty \int_\Omega (n_\varepsilon + 1)^{-p} c_\varepsilon e^{-\kappa c_\varepsilon} \varphi + \kappa \int_0^\infty \int_\Omega \frac{n_\varepsilon}{1 + \varepsilon n_\varepsilon} (n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon} \varphi \quad \text{for all } \varepsilon \in (0, 1),$$

we may once again rely on our hypothesis  $\kappa > \frac{\sqrt{p(p+1)}}{2}$  to infer that since thus  $4\kappa^2 - p(p+1)^2 \frac{n_\varepsilon^2}{(n_\varepsilon+1)^2}$  is non-negative for all  $\varepsilon \in (0, 1)$ , from Lemma 5.1 and Fatou's lemma we obtain that

$$\begin{aligned} & \int_0^\infty \int_\Omega \frac{4\kappa^2 - p(p+1)^2 \frac{n_\varepsilon^2}{(n_\varepsilon+1)^2}}{4(p+1)} (n_\varepsilon + 1)^{-p} e^{-\kappa c} |\nabla c|^2 \varphi \\ & \leq \liminf_{\varepsilon=\varepsilon_j \searrow 0} \int_0^\infty \int_\Omega \frac{4\kappa^2 - p(p+1)^2 \frac{n_\varepsilon^2}{(n_\varepsilon+1)^2}}{4(p+1)} (n_\varepsilon + 1)^{-p} e^{-\kappa c_\varepsilon} |\nabla c_\varepsilon|^2 \varphi. \end{aligned}$$

Along with (5.11) and a standard argument based on lower semicontinuity property of  $L^2$  norms with respect to weak convergence, due to (5.13)-(5.18) this can readily be verified to entail (2.16).  $\square$

We can thereby complete the derivation of our main results:

PROOF of Theorem 1.1. The claim follows by combining Lemma 5.1 with Lemma 5.2.  $\square$

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