

# GLOBAL EXISTENCE OF ENTROPY-WEAK SOLUTIONS TO THE COMPRESSIBLE NAVIER-STOKES EQUATIONS WITH NON-LINEAR DENSITY DEPENDENT VISCOSITIES

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**ABSTRACT.** In this paper, we extend considerably the global existence results of entropy-weak solutions related to compressible Navier-Stokes system with density dependent viscosities obtained, independently (using different strategies), by Vasseur-Yu [*Inventiones mathematicae* (2016) and arXiv:1501.06803 (2015)] and by Li-Xin [arXiv:1504.06826 (2015)]. More precisely we are able to consider a physical symmetric viscous stress tensor  $\sigma = 2\mu(\rho)\mathbb{D}(u) + (\lambda(\rho)\operatorname{div}u - P(\rho))\operatorname{Id}$  where  $\mathbb{D}(u) = [\nabla u + \nabla^T u]/2$  with a shear and bulk viscosities (respectively  $\mu(\rho)$  and  $\lambda(\rho)$ ) satisfying the BD relation  $\lambda(\rho) = 2(\mu'(\rho)\rho - \mu(\rho))$  and a pressure law  $P(\rho) = a\rho^\gamma$  (with  $a > 0$  a given constant) for any adiabatic constant  $\gamma > 1$ . The nonlinear shear viscosity  $\mu(\rho)$  satisfies some lower and upper bounds for low and high densities (our mathematical result includes the case  $\mu(\rho) = \mu\rho^\alpha$  with  $2/3 < \alpha < 4$  and  $\mu > 0$  constant). This provides an answer to a longstanding mathematical question on compressible Navier-Stokes equations with density dependent viscosities as mentioned for instance by F. Rousset in the Bourbaki 69ème année, 2016–2017, no 1135.

## 1. INTRODUCTION

When a fluid is governed by the barotropic compressible Navier-Stokes equations, the existence of global weak solutions, in the sense of J. LERAY (see [35]), in space dimension greater than two remained for a long time without answer, because of the weak control of the divergence of the velocity field which may provide the possibility for the density to vanish (vacuum state) even if initially this is not the case.

There exists a huge literature on this question, in the case of constant shear viscosity  $\mu$  and constant bulk viscosity  $\lambda$ . Before 1993, many authors such as Hoff [27], Jiang-Zhang [29], Kazhikhov–Shelukhin [32], Serre [47], Veigant–Kazhikhov [48] (to cite just some of them) have obtained partial answers: We can cite, for instance, the works in dimension 1 in 1986 by Serre [47], the one by Hoff [27] in 1987, and the one in the spherical case in 2001 by Jiang-Zhang [29]. The first rigorous approach of this problem in its generality is due in 1993 by P.–L. Lions [38] when the pressure law in terms of the density is given by  $P(\rho) = a\rho^\gamma$  where  $a$  and  $\gamma$  are two strictly positive constants. He has presented in 1998 a complete theory for  $P(\rho) = a\rho^\gamma$  with  $\gamma \geq 3d/(d+2)$  (where  $d$  is the space dimension) allowing to obtain the result of global existence of weak solutions à la Leray in dimension  $d = 2$  and 3 and for general initial data belonging to the energy space. His result has been then extended in 2001 to the case  $P(\rho) = a\rho^\gamma$  with  $\gamma > d/2$  by Feireisl–Novotny–Petzeltova

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[23] introducing an appropriated method of truncation. Note also in 2014 the paper on compressible Navier-Stokes equations with constant viscosities by Plotnikov-Weigant [45] in dimension 2 for the linear pressure law that means  $\gamma = 1$ . In 2002, Feireisl [24] has also proved it is possible to consider a pressure  $P(\rho)$  law non-monotone on a compact set  $[0, \rho_*]$  (with  $\rho_*$  constant) and monotone elsewhere. This has been relaxed in 2018 by Bresch-Jabin [15] allowing to consider real non-monotone pressure laws. They have also proved that it is possible to consider some constant anisotropic viscosities. The Lions theory has also been extended recently by Vasseur-Wen-Yu [51] to pressure laws depending on two phases (see also Maltese & *al.* [39], Novotny [43] and Novotny-Pokorný [44]). The method introduced by Bresch-Jabin in [15] has also been recently developed in the bifluid framework by Bresch-Mucha-Zatorska in [17].

When the shear and the bulk viscosities (respectively  $\mu$  and  $\lambda$ ) are assumed to depend on the density  $\rho$ , the mathematical framework is completely different. It has been discussed, mathematically, initially in a paper by Bernardi-Pironneau [6] related to viscous shallow-water equations and by P.-L. Lions [38] in his second volume related to mathematics and fluid mechanics. The main ingredient in the constant case which is the compactness in space of the effective flux  $F = (2\mu + \lambda)\operatorname{div} u - P(\rho)$  is no longer true for density dependent viscosities. In space dimension greater than one, a new mathematical framework has been initiated with a series of papers by Bresch-Desjardins [8, 9, 10, 11], (started in 2003 with Lin [12] in the context of Navier-Stokes-Korteweg with linear shear viscosity case) who have identified an information related to the gradient of a function of the density if the viscosities satisfy what is called the Bresch-Desjardins constraint. This information is usually called the BD entropy in the literature with the introduction of the concept of entropy-weak solutions. Using such extra information, they obtained the global existence of entropy-weak solutions in the presence of appropriate drag terms or singular pressure close to vacuum. Concerning the one-dimensional in space case or the spherical case, many important results have been obtained for instance by Burtea-Haspot [18], Ducomet-Necasova-Vasseur [22], Constantin-Drivas-Nguyen-Pasqualotto [21], Guo-Jiu-Xin [25], Haspot [26], Jiang-Xin-Zhang [28], Jiang-Zhang [29], Kanel [33], Li-Li-Xin [36], Mellet-Vasseur [41], Shelukhin [47] without such kind of additional terms. Stability and construction of approximate solutions in space dimension two or three have been investigated during more than fifteen years with a first important stability result without drag terms or singular pressure by Mellet-Vasseur [40]. Several important works for instance by Bresch-Desjardins [8, 9, 10, 11] and Bresch-Desjardins-Lin [12], Bresch-Desjardins-Zatorska [13], Li-Xin [37], Mellet-Vasseur [40], Mucha-Pokorný-Zatorska [42], Vasseur-Yu [49, 50], and Zatorska [52] have also been written trying to find a way to construct approximate solutions. Recently a real breakthrough has been done in two important papers by Li-Xin [37] and Vasseur-Yu [50]: Using two different ways, they got the global existence of entropy-weak solutions for the compressible paper when  $\mu(\rho) = \rho$  and  $\lambda(\rho) = 0$ . Note that in the last paper [37] by Li-Xin, they also consider more general viscosities satisfying the BD relation but with a non-symmetric stress diffusion ( $\sigma = \mu(\rho)\nabla u + (\lambda(\rho)\operatorname{div} u - P(\rho))\operatorname{Id}$ ) and more restrictive conditions on the shear  $\mu(\rho)$  viscosity and bulk viscosity  $\lambda(\rho)$  and on the pressure law  $P(\rho)$  compared to the present paper.

The objective of this current paper is to extend the existence results of global entropy-weak solutions obtained independently (using different strategies) by Vasseur-Yu [50] and

Lin-Xin [37] to answer a longstanding mathematical question on compressible Navier-Stokes equations with density dependent viscosities as mentioned for instance by Rousset [46]. More precisely extending and coupling carefully the two-velocities framework by Bresch-Desjardins-Zatorska [13] with the generalization of the quantum Böhm identity found by Bresch-Couderc-Noble-Vila [7] (proving a generalization of the dissipation inequality used by Jüngel [30] for Navier-Stokes-Quantum system and established by Jüngel-Matthes in [31]) and with the renormalized solutions introduced in Lacroix-Violet and Vasseur [34], we can get global existence of entropy-weak solutions to the following Navier-Stokes equations:

$$\begin{aligned} \rho_t + \operatorname{div}(\rho u) &= 0 \\ (\rho u)_t + \operatorname{div}(\rho u \otimes u) + \nabla P(\rho) - 2\operatorname{div}(\sqrt{\mu(\rho)}\mathbb{S}_\mu + \frac{\lambda(\rho)}{2\mu(\rho)}\operatorname{Tr}(\sqrt{\mu(\rho)}\mathbb{S}_\mu)\operatorname{Id}) &= 0, \end{aligned} \quad (1.1)$$

where the shear stress are given by

$$\sqrt{\mu(\rho)}\mathbb{S}_\mu = \mu(\rho)\mathbb{D}(u)$$

in the regular setting (see below for the definition in the non-regular setting) and with data

$$\rho|_{t=0} = \rho_0(x) \geq 0, \quad \rho u|_{t=0} = m_0(x) = \rho_0 u_0, \quad (1.2)$$

and where  $P(\rho) = a\rho^\gamma$  denotes the pressure with the two constants  $a > 0$  and  $\gamma > 1$ ,  $\rho$  is the density of fluid,  $u$  stands for the velocity of fluid,  $\mathbb{D}u = [\nabla u + \nabla^T u]/2$  is the strain tensor. As usually, we consider

$$u_0 = \frac{m_0}{\rho_0} \text{ when } \rho_0 \neq 0 \text{ and } u_0 = 0 \text{ elsewhere,} \quad \frac{|m_0|^2}{\rho_0} = 0 \text{ a.e. on } \{x \in \Omega : \rho_0(x) = 0\}.$$

*Remark 1.1.* We remark the following identity

$$2\operatorname{div}(\sqrt{\mu(\rho)}\mathbb{S}_\mu + \frac{\lambda(\rho)}{2\mu(\rho)}\operatorname{Tr}(\sqrt{\mu(\rho)}\mathbb{S}_\mu)\operatorname{Id}) = 2\operatorname{div}(\mu(\rho)\mathbb{D}u) + \nabla(\lambda(\rho)\operatorname{div}u),$$

in the regular setting where system (1.1) will be the classical writing form.

The viscosity coefficients  $\mu = \mu(\rho)$  and  $\lambda = \lambda(\rho)$  satisfy the Bresch-Desjardins relation introduced in [10]

$$\lambda(\rho) = 2(\rho\mu'(\rho) - \mu(\rho)). \quad (1.3)$$

The relation between the stress tensor  $\mathbb{S}_\mu$  and the triple  $(\mu(\rho)/\sqrt{\rho}, \sqrt{\rho}u, \sqrt{\rho}v)$  where  $v = 2\nabla s(\rho)$  with  $s'(\rho) = \mu'(\rho)/\rho$  will be proved in the following way: The matrix value  $\mathbb{S}_\mu$  is the symmetric part of matrix value function  $\mathbb{T}_\mu$  namely

$$\mathbb{S}_\mu = \frac{(\mathbb{T}_\mu + \mathbb{T}_\mu^t)}{2} \quad (1.4)$$

where  $\mathbb{T}_\mu$  is defined through

$$\sqrt{\mu(\rho)}\mathbb{T}_\mu = \nabla(\sqrt{\rho}u \frac{\mu(\rho)}{\sqrt{\rho}}) - \sqrt{\rho}u \otimes \sqrt{\rho}\nabla s(\rho) \quad (1.5)$$

with

$$s'(\rho) = \mu'(\rho)/\rho. \quad (1.6)$$

and

$$\frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)} \mathbb{T}_\mu) \text{Id} = \left[ \text{div} \left( \frac{\lambda(\rho)}{\mu(\rho)} \sqrt{\rho} u \frac{\mu(\rho)}{\sqrt{\rho}} \right) - \sqrt{\rho} u \cdot \sqrt{\rho} \nabla s(\rho) \frac{\rho \mu''(\rho)}{\mu'(\rho)} \right] \text{Id}. \quad (1.7)$$

*Remark 1.2.* Compared to the case  $\mu(\rho) = \rho$ , the definition of  $\mathbb{T}_\mu$  is given through the two compatible identities (1.5) and (1.7).

For the sake of simplicity, we will consider the case of periodic boundary conditions in three dimension in space namely  $\Omega = \mathbb{T}^3$ . In the whole paper, we assume:

$$\mu \in C^0(\mathbb{R}_+; \mathbb{R}_+) \cap C^2(\mathbb{R}_+^*; \mathbb{R}), \quad (1.8)$$

where  $\mathbb{R}_+ = [0, \infty)$  and  $\mathbb{R}_+^* = (0, \infty)$ . We also assume that there exists two positive numbers  $\alpha_1, \alpha_2$  such that

$$\begin{aligned} \frac{2}{3} < \alpha_1 \leq \alpha_2 < 4, \\ \text{for any } \rho > 0, \quad 0 < \frac{1}{\alpha_2} \rho \mu'(\rho) \leq \mu(\rho) \leq \frac{1}{\alpha_1} \rho \mu'(\rho), \end{aligned} \quad (1.9)$$

and there exists a constant  $C > 0$  such that

$$\left| \frac{\rho \mu''(\rho)}{\mu'(\rho)} \right| \leq C < +\infty. \quad (1.10)$$

Note that if  $\mu(\rho)$  and  $\lambda(\rho)$  satisfying (1.3) and (1.9), then

$$\lambda(\rho) + 2\mu(\rho)/3 \geq 0$$

and thanks to (1.9)

$$\mu(0) = \lambda(0) = 0.$$

*Remark 1.3.* Note that the hypothesis (1.9)–(1.10) allow a shear viscosity of the form  $\mu(\rho) = \mu \rho^\alpha$  with  $\mu > 0$  a constant where  $2/3 < \alpha < 4$  and a bulk viscosity satisfying the BD relation:  $\lambda(\rho) = 2(\mu'(\rho)\rho - \mu(\rho))$ .

*Remark 1.4.* Note that the restriction  $2/3 < \alpha_1 \leq \alpha_2$  comes from the hypothesis that there exists  $\varepsilon > 0$  such that  $2\mu(\rho) + 3\lambda(\rho) \geq \varepsilon\mu(\rho)$  which will satisfy  $2\mu(\rho) + 3\lambda(\rho) > 0$  (far from vacuum) which is the usual physical restriction between the shear and bulk viscosities. Meanwhile, for technical reasons in the proof of Lemma 2.1, we need to restrict  $\alpha_2 < 4$  in hypothesis (1.9). More precisely, we get that  $\|\nabla \nabla Z(\rho)\|_{L^2((0,T) \times \Omega)}$  and  $\|\nabla Z_1(\rho)\|_{L^4((0,T) \times \Omega)}$ , for some functions  $Z$  and  $Z_1$ , are controlled if the two constants in front of them in Lemma 2.1 are positive. It is important to remark that in the recent paper [1], the authors have indicated how Lemma 2.1 may be used for the full range  $2/3 < \alpha < +\infty$  when  $\mu(\rho) = \rho^\alpha$  and  $\lambda(\rho) = 2(\alpha - 1)\rho^\alpha$ . It is enough to be able to compare  $\|\nabla \nabla Z(\rho)\|_{L^2((0,T) \times \Omega)}$  to  $\|\nabla Z_1(\rho)\|_{L^4((0,T) \times \Omega)}$  to relax the assumptions. This is based on the following uniform inequality: For any  $d \geq 1$  and any positive function  $\theta$  in  $H^2(\mathbb{T}^d)$  :

$$\int_{\mathbb{T}^d} |\nabla \theta^{1/2}|^4 dx \leq \frac{9}{16} \int_{\mathbb{T}^d} (\Delta \theta)^2 dx.$$

*Remark 1.5.* In [50] and [37] the case  $\mu(\rho) = \mu\rho$  and  $\lambda(\rho) = 0$  is considered, and in [37] more general cases have been considered but with a non-symmetric viscous term in the three-dimensional in space case, namely  $-\operatorname{div}(\mu(\rho)\nabla u) - \nabla(\lambda(\rho)\operatorname{div}u)$ . In [37] the viscosities  $\mu(\rho)$  and  $\lambda(\rho)$  satisfy (1.3) with  $\mu(\rho) = \mu\rho^\alpha$  where  $\alpha \in [3/4, 2)$  and with the following assumption on the value  $\gamma$  for the pressure  $p(\rho) = a\rho^\gamma$ :

$$\text{If } \alpha \in [3/4, 1], \quad \gamma \in (1, 6\alpha - 3)$$

and

$$\text{if } \alpha \in (1, 2), \quad \gamma \in [2\alpha - 1, 3\alpha - 1].$$

**Definitions.** Following [34] (based on the work in [50]), we will show the existence of renormalized solutions in  $u$ . Then, we will show that this renormalized solution is a weak solution. The renormalization provides weak stability of the advection terms  $\rho u \otimes u$  together and  $\rho u \otimes v$ . Let us first define the renormalized solution:

**Definition 1.1.** Consider  $\mu > 0$ ,  $3\lambda + 2\mu > 0$ ,  $r_0 \geq 0$ ,  $r_1 \geq 0$ ,  $r_2 \geq 0$ ,  $\delta \geq 0$  and  $r \geq 0$ . We say that  $(\sqrt{\rho}, \sqrt{\rho}u)$  is a renormalized weak solution in  $u$  of the compressible Navier-Stokes equations (with an extra capillarity term, with drag terms, with a supplementary pressure if respectively  $r \neq 0$ ,  $(r_0, r_1, r_2) \neq 0$  and  $\delta \neq 0$ ), if it verifies (1.23)-(1.26), and for any function  $\varphi \in W^{2,\infty}(\mathbb{R}^3)$ , there exists three measures  $R_\varphi, \bar{R}_\varphi^1, \bar{R}_\varphi^2 \in \mathcal{M}(\mathbb{R}^+ \times \Omega)$ , with

$$\|R_\varphi\|_{\mathcal{M}(\mathbb{R}^+ \times \Omega)} + \|\bar{R}_\varphi^1\|_{\mathcal{M}(\mathbb{R}^+ \times \Omega)} + \|\bar{R}_\varphi^2\|_{\mathcal{M}(\mathbb{R}^+ \times \Omega)} \leq C \|\nabla \nabla \varphi\|_{L^\infty(\mathbb{R}^3)},$$

where the constant  $C$  depends only on the solution  $(\sqrt{\rho}, \sqrt{\rho}u)$ , and for any function  $\psi \in C_c^\infty(\mathbb{R}^+ \times \Omega)$ ,

$$\begin{aligned} & \int_0^T \int_\Omega (\rho \psi_t + \sqrt{\rho} \sqrt{\rho} u \cdot \nabla \psi) dx dt = 0, \\ & \int_0^T \int_\Omega (\rho \varphi(u) \psi_t + \rho \varphi(u) \otimes u : \nabla \psi) dx dt \\ & - \int_0^T \int_\Omega \left( 2(\sqrt{\mu(\rho)} \mathbb{S}_\mu + \frac{\lambda(\rho)}{2\mu(\rho)} \operatorname{Tr}(\sqrt{\mu(\rho)} \mathbb{S}_\mu) \operatorname{Id}) \varphi'(u) \right) \cdot \nabla \psi dx dt \\ & - r \int_0^T \int_\Omega \left( 2(\sqrt{\mu(\rho)} \mathbb{S}_r + \frac{\lambda(\rho)}{2\mu(\rho)} \operatorname{Tr}(\sqrt{\mu(\rho)} \mathbb{S}_r) \operatorname{Id}) \varphi'(u) \right) \cdot \nabla \psi dx dt \\ & + F(\rho, u) \varphi'(u) \psi dx dt = \langle R_\varphi, \psi \rangle, \\ & \int_0^T \int_\Omega (\mu(\rho) \psi_t + \frac{\mu(\rho)}{\sqrt{\rho}} \sqrt{\rho} u \cdot \nabla \psi) dx dt - \int_0^T \int_\Omega \frac{\lambda(\rho)}{2\mu(\rho)} \operatorname{Tr}(\sqrt{\mu(\rho)} \mathbb{T}_\mu) \psi dx dt = 0, \end{aligned}$$

where  $\mathbb{S}_\mu$  is given in (1.4) and  $\mathbb{T}_\mu$  is given in (1.7). The matrix  $\mathbb{S}_r$  is compatible in (1.19), (1.20), and (1.21).

The vector valued function  $F$  is given by

$$\begin{aligned} F(\rho, u) = & \sqrt{\frac{P'(\rho)\rho}{\mu'(\rho)}} \nabla \int_0^\rho \sqrt{\frac{P'(s)\mu'(s)}{s}} ds \\ & + \delta \sqrt{\frac{P'_\delta(\rho)\rho}{\mu'(\rho)}} \nabla \int_0^\rho \sqrt{\frac{P'_\delta(s)\mu'(s)}{s}} ds - r_0 u - r_1 \rho |u| u - \frac{r_2}{\mu'(\rho)} \rho |u|^2 u. \end{aligned} \quad (1.11)$$

For every  $i, j, k$  between 1 and  $d$ :

$$\sqrt{\mu(\rho)} \varphi'_i(u) [\mathbb{T}_\mu]_{jk} = \partial_j(\mu(\rho) \varphi'_i(u) u_k) - \sqrt{\rho} u_k \varphi'_i(u) \sqrt{\rho} \partial_j s(\rho) + \bar{R}_\varphi^1, \quad (1.12)$$

$$r \varphi'_i(u) [\nabla(\sqrt{\mu(\rho)} \nabla Z(\rho))]_{jk} = r \partial_j(\sqrt{\mu(\rho)} \varphi'_i(u) \partial_k Z(\rho)) + \bar{R}_\varphi^2, \quad (1.13)$$

and

$$\|\bar{R}_\varphi^1\|_{\mathcal{M}(\mathbb{R}^+ \times \Omega)} + \|\bar{R}_\varphi^2\|_{\mathcal{M}(\mathbb{R}^+ \times \Omega)} + \|R_\varphi\|_{\mathcal{M}(\mathbb{R}^+ \times \Omega)} \leq C \|\nabla \nabla \varphi\|_{L^\infty}.$$

and for any  $\bar{\psi} \in C_c^\infty(\Omega)$ :

$$\begin{aligned} \lim_{t \rightarrow 0} \int_\Omega \rho(t, x) \bar{\psi}(x) dx &= \int_\Omega \rho_0(x) \bar{\psi}(x) dx, \\ \lim_{t \rightarrow 0} \int_\Omega \rho(t, x) u(t, x) \bar{\psi}(x) dx &= \int_\Omega m_0(x) \bar{\psi}(x) dx, \\ \lim_{t \rightarrow 0} \int_\Omega \mu(\rho)(t, x) \bar{\psi}(x) dx &= \int_\Omega \mu(\rho_0)(x) \bar{\psi}(x) dx \end{aligned}$$

*Remark 1.6.* The notion of renormalized solutions was introduced by R. DiPerna and P.-L. Lions in [20], and it was adopted to study the compressible Navier-Stokes equations by P.-L. Lions [38]. In Lions' framework, this notation allows to handle the issue of low regularity of density. However, in our paper, we have more uniform bounds on density and less regularity of velocity. With our definition of renormalized solution in velocity, it allows us to get the weak stability of the solution sequence even we are not able to have extra control on  $\rho|u|^2$ . It allows us to get rid of the Mellet-Vasseur type inequality for passing to the limits and allows us to establish the existence result for any  $\gamma > 1$ .

We define a global weak solution of the approximate system or the compressible Navier-Stokes equation (when  $r = r_0 = r_1 = r_2 = \delta = 0$ ) as follows

**Definition 1.2.** Let  $\mathbb{S}_\mu$  the symmetric part of  $\mathbb{T}_\mu$  in  $L^2((0, T) \times \Omega)$  verifying (1.4)–(1.7) and  $\mathbb{S}_r$  the capillary quantity in  $L^2((0, T) \times \Omega)$  given by (1.19)–(1.21). Let us denote  $P(\rho) = a\rho^\gamma$  and  $P_\delta(\rho) = \delta\rho^{10}$ . We say that  $(\rho, u)$  is a weak solution to (1.17)–(1.20), if it satisfies the *a priori* estimates (1.23)–(1.26) and for any function  $\psi \in \mathcal{C}_c^\infty((0, T) \times \Omega)$

verifying

$$\begin{aligned}
& \int_0^T \int_{\Omega} (\rho \partial_t \psi + \rho u \cdot \nabla \psi) dx dt = 0, \\
& \int_0^T \int_{\Omega} (\rho u \partial_t \psi + \rho u \otimes u : \nabla \psi) dx dt \\
& \quad - \int_0^T \int_{\Omega} 2(\sqrt{\mu(\rho)} \mathbb{S}_{\mu} + \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)} \mathbb{S}_{\mu}) \text{Id}) \cdot \nabla \psi dx dt \\
& \quad - r \int_0^T \int_{\Omega} 2(\sqrt{\mu(\rho)} \mathbb{S}_r + \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)} \mathbb{S}_r) \text{Id}) \cdot \nabla \psi dx dt \\
& \quad + F(\rho, u) \psi dx dt = 0, \\
& \int_0^{\infty} \int_{\Omega} \left( \mu(\rho) \psi_t + \frac{\mu(\rho)}{\sqrt{\rho}} \sqrt{\rho} u \cdot \nabla \psi \right) dx dt \\
& \quad - \int_0^T \int_{\Omega} \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)} \mathbb{T}_{\mu}) \psi dx dt = 0,
\end{aligned} \tag{1.14}$$

with  $F$  given through (1.11) and for any  $\bar{\psi} \in \mathcal{C}_c^{\infty}(\Omega)$ :

$$\begin{aligned}
\lim_{t \rightarrow 0} \int_{\Omega} \rho(t, x) \bar{\psi}(x) dx &= \int_{\Omega} \rho_0(x) \bar{\psi}(x) dx, \\
\lim_{t \rightarrow 0} \int_{\Omega} \rho(t, x) u(t, x) \bar{\psi}(x) dx &= \int_{\Omega} m_0(x) \bar{\psi}(x) dx, \\
\lim_{t \rightarrow 0} \int_{\Omega} \mu(\rho)(t, x) \bar{\psi}(x) dx &= \int_{\Omega} \mu(\rho_0)(x) \bar{\psi}(x) dx.
\end{aligned}$$

*Remark 1.7.* As mentioned in [16], the equation on  $\mu(\rho)$  is important: By taking  $\psi = \text{div} \varphi$  for all  $\varphi \in \mathcal{C}_0^{\infty}$ , we can write the equation satisfied by  $\nabla \mu(\rho)$  namely

$$\begin{aligned}
\partial_t \nabla \mu(\rho) + \text{div}(\nabla \mu(\rho) \otimes u) &= \text{div}(\nabla \mu(\rho) \otimes u) - \nabla \text{div}(\mu(\rho) u) \\
&\quad - \nabla \left( \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)} \mathbb{T}_{\mu}) \right) \\
&= -\text{div}(\sqrt{\mu(\rho)} \mathbb{T}_{\mu}) - \nabla \left( \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)} \mathbb{T}_{\mu}) \right).
\end{aligned} \tag{1.15}$$

This will justify in some sense the two-velocities formulation introduced in [13] with the extra velocity linked to  $\nabla \mu(\rho)$ .

The main result of our paper reads as follows:

**Theorem 1.1.** *Let  $\mu(\rho)$  verify (1.8)–(1.10) and  $\mu$  and  $\lambda$  verify (1.3). Let us assume the initial data satisfy*

$$\begin{aligned}
& \int_{\Omega} \left( \frac{1}{2} \rho_0 |u_0 + 2\kappa \nabla s(\rho_0)|^2 + \kappa(1 - \kappa) \rho_0 \frac{|2\nabla s(\rho_0)|^2}{2} \right) dx \\
& \quad + \int_{\Omega} \left( a \frac{\rho_0^{\gamma}}{\gamma - 1} + \mu(\rho_0) \right) dx \leq C < +\infty.
\end{aligned} \tag{1.16}$$

with  $k \in (0, 1)$  given. Let  $T$  be given such that  $0 < T < +\infty$ , then, for any  $\gamma > 1$ , there exist a renormalized solution to (1.1)-(1.2) as defined in Definition 1.1 with  $r, r_0, r_1, r_2$  and  $\delta$  all zero. Moreover, this renormalized solution with initial data satisfying (1.16) is a weak solution to (1.1)-(1.2) in the sense of Definition 1.2.

Our result may be considered as an improvement of [37] for two reasons: First it takes into account a physical symmetric viscous tensor and secondly, it extends the range of coefficients  $\alpha$  and  $\gamma$ . The method is based on the consideration of an approximated system with an extra pressure quantity, appropriate non-linear drag terms and appropriate capillarity terms. This generalizes the Quantum-Navier-Stokes system with quadratic drag terms considered in [49, 50]. First we prove that weak solutions of the approximate system are renormalized solutions of the system, in the sense of [34]. Then we pass to the limit with respect to  $r_2, r_1, r_0, r, \delta$  to get renormalized solutions of the compressible Navier-Stokes system. The final step concerns the proof that a renormalized solution of the compressible Navier-Stokes system is a global weak solution of the compressible Navier-Stokes system. Note that, thanks to the technique of renormalized solution introduced in [34], it is not necessary to derive the Mellet-Vasseur type inequality in this paper: This allows us to cover all range  $\gamma > 1$ .

*First Step.* Motivated by the work of [34], the first step is to establish the existence of global  $\kappa$  entropy weak solution to the following approximation

$$\begin{aligned}
\rho_t + \operatorname{div}(\rho u) &= 0 \\
(\rho u)_t + \operatorname{div}(\rho u \otimes u) + \nabla P(\rho) + \nabla P_\delta(\rho) \\
&\quad - 2\operatorname{div}\left(\sqrt{\mu(\rho)}\mathbb{S}_\mu + \frac{\lambda(\rho)}{2\mu(\rho)}\operatorname{Tr}(\sqrt{\mu(\rho)}\mathbb{S}_\mu)\operatorname{Id}\right) \\
&\quad - 2r\operatorname{div}\left(\sqrt{\mu(\rho)}\mathbb{S}_r + \frac{\lambda(\rho)}{2\mu(\rho)}\operatorname{Tr}(\sqrt{\mu(\rho)}\mathbb{S}_r)\operatorname{Id}\right) \\
&\quad + r_0 u + r_1 \rho |u| u + r_2 \frac{\rho}{\mu'(\rho)} |u|^2 u = 0
\end{aligned} \tag{1.17}$$

where the barotropic pressure law and the extra pressure term are respectively

$$P(\rho) = a\rho^\gamma, \quad P_\delta(\rho) = \delta\rho^{10} \text{ with } \delta > 0. \tag{1.18}$$

The matrix  $\mathbb{S}_\mu$  is defined in (1.4) and  $\mathbb{T}_\mu$  is given in (1.5)-(1.7). The matrix  $\mathbb{S}_r$  is compatible in the following sense:

$$r\sqrt{\mu(\rho)}\mathbb{S}_r = 2r\left[2\sqrt{\mu(\rho)}\nabla\nabla Z(\rho) - \nabla(\sqrt{\mu(\rho)}\nabla Z(\rho))\right], \tag{1.19}$$

where

$$Z(\rho) = \int_0^\rho [(\mu(s))^{1/2}\mu'(s)]/s \, ds, \quad k(\rho) = \int_0^\rho [\lambda(s)\mu'(s)]/\mu(s)^{3/2} \, ds \tag{1.20}$$

and

$$r\frac{\lambda(\rho)}{2\mu(\rho)}\operatorname{Tr}(\sqrt{\mu(\rho)}\mathbb{S}_r)\operatorname{Id} = r\left(\frac{\lambda(\rho)}{\sqrt{\mu(\rho)}} + \frac{1}{2}k(\rho)\right)\Delta Z(\rho)\operatorname{Id} - \frac{r}{2}\operatorname{div}[k(\rho)\nabla Z(\rho)]\operatorname{Id}. \tag{1.21}$$

*Remark 1.8.* Note that the previous system is the generalization of the quantum viscous Navier-Stokes system considered by Lacroix-Violet and Vasseur in [34] (see also the interesting papers by Antonelli-Spirito [4, 5] and by Carles-Carrapatoso-Hillairet [19]). Indeed if we consider  $\mu(\rho) = \rho$  and  $\lambda(\rho) = 0$ , we can write  $\sqrt{\mu(\rho)}\mathbb{S}_r$  as

$$\sqrt{\mu(\rho)}\mathbb{S}_r = 4\sqrt{\rho}\left[\nabla\nabla\sqrt{\rho} - 4(\nabla\rho^{1/4} \otimes \nabla\rho^{1/4})\right],$$

using  $Z(\rho) = 2\sqrt{\rho}$ . The Navier-Stokes equations for quantum fluids was also considered by A. Jüngel in [30].

As the first step generalizing [50], we prove the following result.

**Theorem 1.2.** *Let  $\mu(\rho)$  verifies (1.8)–(1.10) and  $\lambda(\rho)$  is given by (1.3). If  $r_0 > 0$ , then we assume also that  $\inf_{s \in [0, +\infty)} \mu'(s) = \epsilon_1 > 0$ . Assume that  $r_1$  is small enough compared to  $\delta$ ,  $r_2$  is small enough compared to  $r$  and that the initial values verify*

$$\begin{aligned} \int_{\Omega} \rho_0 \left( \frac{|u_0 + 2\kappa\nabla s(\rho_0)|^2}{2} + (\kappa(1 - \kappa) + r) \frac{|2\nabla s(\rho_0)|^2}{2} \right) dx \\ + \int_{\Omega} \left( a \frac{\rho_0^\gamma}{\gamma - 1} + \mu(\rho_0) + \delta \frac{\rho_0^{10}}{9} + \frac{r_0}{\epsilon_1} |(\ln \rho_0)_-| \right) dx < +\infty, \end{aligned} \quad (1.22)$$

for a fixed  $\kappa \in (0, 1)$ . Then there exists a  $\kappa$  entropy weak solution  $(\rho, u, \mathbb{T}_\mu, \mathbb{S}_r)$  to (1.17)–(1.21) satisfying the initial conditions (1.2), in the sense that  $(\rho, u, \mathbb{T}_\mu, \mathbb{S}_r)$  satisfies the mass and momentum equations in a weak form, and satisfies the compatibility formula in the sense of definition 1.2. In addition, it verifies the following estimates:

$$\begin{aligned} \|\sqrt{\rho}(u + 2\kappa\nabla s(\rho))\|_{L^\infty(0, T; L^2(\Omega))}^2 &\leq C, & a\|\rho\|_{L^\infty(0, T; L^\gamma(\Omega))}^\gamma &\leq C, \\ \|\mathbb{T}_\mu\|_{L^2(0, T; L^2(\Omega))}^2 &\leq C, & (\kappa(1 - \kappa) + r)\|\sqrt{\rho}\nabla s(\rho)\|_{L^\infty(0, T; L^2(\Omega))}^2 &\leq C, \\ \kappa\|\sqrt{\mu'(\rho)}\rho^{\gamma-2}\nabla\rho\|_{L^2(0, T; L^2(\Omega))}^2 &\leq C, \end{aligned} \quad (1.23)$$

and

$$\begin{aligned} \delta\|\rho\|_{L^\infty(0, T; L^{10}(\Omega))}^{10} &\leq C, & \delta\|\sqrt{\mu'(\rho)}\rho^8\nabla\rho\|_{L^2(0, T; L^2(\Omega))}^2 &\leq C, \\ r_2\left(\frac{\rho}{\mu'(\rho)}\right)^{\frac{1}{4}}u\|_{L^4(0, T; L^4(\Omega))}^4 &\leq C, & r_1\|\rho^{\frac{1}{3}}|u|\|_{L^3(0, T; L^3(\Omega))}^3 &\leq C, \\ r_0\|u\|_{L^2(0, T; L^2(\Omega))}^2 &\leq C, & r\|\mathbb{S}_r\|_{L^2(0, T; L^2(\Omega))}^2 &\leq C. \end{aligned} \quad (1.24)$$

Note that the bounds (1.23) provide the following control on the velocity field

$$\|\sqrt{\rho}u\|_{L^\infty(0, T; L^2(\Omega))}^2 \leq C.$$

Moreover let

$$Z(\rho) = \int_0^\rho \frac{\sqrt{\mu(s)}\mu'(s)}{s} ds \quad \text{and} \quad Z_1(\rho) = \int_0^\rho \frac{\mu'(s)}{(\mu(s))^{1/4}s^{1/2}} ds,$$

we have the extra control

$$r \left[ \int_0^T \int_{\Omega} |\nabla^2 Z(\rho)|^2 dx dt + \int_0^T \int_{\Omega} |\nabla Z_1(\rho)|^4 dx dt \right] \leq C, \quad (1.25)$$

and

$$\begin{aligned} & \|\mu(\rho)\|_{L^\infty(0,T;W^{1,1}(\Omega))} + \|\mu(\rho)u\|_{L^\infty(0,T;L^{3/2}(\Omega)) \cap L^2(0,T;W^{1,1}(\Omega))} \leq C, \\ & \|\partial_t \mu(\rho)\|_{L^\infty(0,T;W^{-1,1}(\Omega))} \leq C, \\ & \|Z(\rho)\|_{L^\infty(0,T;L^{1+}(\Omega))} + \|Z_1(\rho)\|_{L^\infty(0,T;L^{1+}(\Omega))} \leq C, \end{aligned} \tag{1.26}$$

where  $C > 0$  is a constant which depends only on the initial data.

**Sketch of proof for Theorem 1.2.** To show Theorem 1.2, we need to build the smooth solution to an approximation associated to (1.17). Here, we adapt the ideas developed in [13] to construct this approximation. More precisely, we consider an augmented version of the system which will be more appropriate to construct approximate solutions. Let us explain the idea.

*First step: the augmented system.* Defining a new velocity field generalizing the one introduced in the BD entropy estimate namely

$$w = u + 2\kappa \nabla s(\rho)$$

and a drift velocity  $v = 2\nabla s(\rho)$  and  $s(\rho)$  defined in (1.6).

Assuming to have a smooth solution of (1.17) with damping terms, it follows that  $(\rho, w, v)$  satisfies the following system of equations

$$\rho_t + \operatorname{div}(\rho w) - 2\kappa \Delta \mu(\rho) = 0$$

and

$$\begin{aligned} & (\rho w)_t + \operatorname{div}(\rho u \otimes w) - 2(1 - \kappa) \operatorname{div}(\mu(\rho) \mathbb{D} w) - 2\kappa \operatorname{div}(\mu(\rho) \mathbf{A}(w)) \\ & - (1 - \kappa) \nabla(\lambda(\rho) \operatorname{div}(w - \kappa v)) + \nabla \rho^\gamma + \delta \nabla \rho^{10} + 4(1 - \kappa) \kappa \operatorname{div}(\mu(\rho) \nabla^2 s(\rho)) \\ & = -r_0(w - 2\kappa \nabla s(\rho)) - r_1 \rho |w - 2\kappa \nabla s(\rho)| (w - 2\kappa \nabla s(\rho)) \\ & - r_2 \frac{\rho}{\mu'(\rho)} |w - 2\kappa \nabla s(\rho)|^2 (w - 2\kappa \nabla s(\rho)) + r \rho \nabla \left( \sqrt{K(\rho)} \Delta \left( \int_0^\rho \sqrt{K(s)} ds \right) \right), \end{aligned}$$

and

$$(\rho v)_t + \operatorname{div}(\rho u \otimes v) - 2\kappa \operatorname{div}(\mu(\rho) \nabla v) + 2 \operatorname{div}(\mu(\rho) \nabla^t w) + \nabla(\lambda(\rho) \operatorname{div}(w - \kappa v)) = 0,$$

where

$$v = 2\nabla s(\rho), \quad w = u + \kappa v$$

and

$$K(\rho) = 4(\mu'(\rho))^2 / \rho.$$

This is the augmented version for which we will show that there exists global weak solutions, adding an hyperdiffusivity  $\varepsilon_2 [\Delta^{2s} w - \operatorname{div}((1 + |\nabla w|^2) \nabla w)]$  on the equation satisfied by  $w$ , and passing to the limit  $\varepsilon_2$  goes to zero.

**Important remark.** Note that recently Bresch-Couderc-Noble-Vila [7] showed the following interesting relation

$$\rho \nabla \left( \sqrt{K(\rho)} \Delta \left( \int_0^\rho \sqrt{K(s)} ds \right) \right) = \operatorname{div}(F(\rho) \nabla^2 \psi(\rho)) + \nabla ((F'(\rho) \rho - F(\rho)) \Delta \psi(\rho)),$$

with  $F'(\rho) = \sqrt{K(\rho)\rho}$  and  $\sqrt{\rho}\psi'(\rho) = \sqrt{K(\rho)}$ . Thus choosing

$$F(\rho) = 2\mu(\rho) \text{ and therefore } F'(\rho)\rho - F(\rho) = \lambda(\rho),$$

this gives  $\psi(\rho) = 2s(\rho)$  and thus

$$\rho \nabla \left( \sqrt{K(\rho)} \Delta \left( \int_0^\rho \sqrt{K(s)} ds \right) \right) = 2 \operatorname{div} \left( \mu(\rho) \nabla^2 (2s(\rho)) \right) + \nabla \left( \lambda(\rho) \Delta (2s(\rho)) \right). \quad (1.27)$$

This identity will play a crucial role in the proof, because it defines the appropriate capillarity term to consider in the approximate system to be compatible with the stress tensor. This form is compatible with the various multipliers which are used to get the  $\kappa$ -entropy estimates and to give regularity control on the density. Other identities will be used to define the weak solution for the Navier-Stokes-Korteweg system and to pass to the limit in it namely

$$\begin{aligned} 2\mu(\rho) \nabla^2 (2s(\rho)) + \lambda(\rho) \Delta (2s(\rho)) &= 4 \left[ 2\sqrt{\mu(\rho)} \nabla \nabla Z(\rho) - \nabla (\sqrt{\mu(\rho)} \nabla Z(\rho)) \right] \\ &+ \left( \frac{2\lambda(\rho)}{\sqrt{\mu(\rho)}} + k(\rho) \right) \Delta Z(\rho) \operatorname{Id} - \operatorname{div} [k(\rho) \nabla Z(\rho)] \operatorname{Id}. \end{aligned} \quad (1.28)$$

where  $Z(\rho) = \int_0^\rho [(\mu(s))^{1/2} \mu'(s)]/s ds$  and  $k(\rho) = \int_0^\rho \frac{\lambda(s) \mu'(s)}{\mu(s)^{3/2}} ds$ .

Note that the case considered in [34, 49, 50] is related  $\mu(\rho) = \rho$  and  $K(\rho) = 4/\rho$  which corresponds to the quantum Navier-Stokes system. Note that two very interesting papers have been written by Antonelli-Spirito in [2, 3] considering Navier-Stokes-Korteweg systems without such relation between the shear viscosity and the capillary coefficient.

*Remark 1.9.* The additional pressure  $\delta \rho^{10}$  is used in (2.17) thanks to  $3\alpha_2 - 2 \leq 10$ . It could be possible to take  $\rho^{3\alpha_2-2}$  but we have chosen  $\rho^{10}$  for the sake of simplicity.

*Second Step and main result concerning the compressible Navier-Stokes system.* To prove global existence of weak solutions of the compressible Navier-Stokes equations, we follow the strategy introduced in [34, 50]. To do so, first we approximate the viscosity  $\mu$  by a viscosity  $\mu_{\varepsilon_1}$  such that  $\inf_{s \in [0, +\infty)} \mu'_{\varepsilon_1}(s) \geq \varepsilon_1 > 0$ . Then we use Theorem 1.2 to construct a  $\kappa$  entropy weak solution to the approximate system (1.17). We then show that this  $\kappa$  entropy weak solution is a renormalized solution of (1.17) in the sense introduced in [34]. More precisely we prove the following theorem:

**Theorem 1.3.** *Let  $\mu(\rho)$  verifies (1.8)–(1.10),  $\lambda(\rho)$  given by (1.3). If  $r_0 > 0$ , then we assume also that  $\inf_{s \in [0, +\infty)} \mu'(s) = \varepsilon_1 > 0$ . Assume that  $r_1$  is small enough compared to  $\delta$  and  $r_2$  is small enough compared to  $r$ , (same to Theorem 1.2) the initial values verify*

$$\begin{aligned} \int_{\Omega} \left( \rho_0 \left( \frac{|u_0 + 2\kappa \nabla s(\rho_0)|^2}{2} + (\kappa(1 - \kappa) + r) \frac{|2\nabla s(\rho_0)|^2}{2} \right) \right) dx \\ + \int_{\Omega} \left( a \frac{\rho_0^\gamma}{\gamma - 1} + \mu(\rho_0) + \delta \frac{\rho_0^{10}}{9} + \frac{r_0}{\varepsilon_1} |(\ln \rho_0)_-| \right) dx < +\infty. \end{aligned} \quad (1.29)$$

*Then the  $\kappa$  entropy weak solutions is a renormalized solution of (1.17) in the sense of Definition 1.1.*

We then pass to the limit with respect to the parameters  $r, r_0, r_1, r_2$  and  $\delta$  to recover a renormalized weak solution of the compressible Navier-Stokes equations and prove our main theorem.

## 2. THE FIRST LEVEL OF APPROXIMATION PROCEDURE

The goal of this section is to construct a sequence of approximated solutions satisfying the compactness structure to prove Theorem 1.2 namely the existence of weak solutions of the approximation system with capillarity and drag terms. Here we present the first level of approximation procedure.

### 1. The continuity equation

$$\rho_t + \operatorname{div}(\rho[w]_{\varepsilon_3}) = 2\kappa \operatorname{div}([\mu'(\rho)]_{\varepsilon_4} \nabla \rho), \quad (2.1)$$

with modified initial data

$$\rho(0, x) = \rho_0 \in C^{2+\nu}(\bar{\Omega}), \quad 0 < \underline{\rho} \leq \rho_0(x) \leq \bar{\rho}.$$

Here  $\varepsilon_3$  and  $\varepsilon_4$  denote the standard regularizations by mollification with respect to space and time. In particular,  $[f(t, x)]_{\varepsilon_i} = f * \eta_{\varepsilon_i}(t, x)$ , for any  $t > \varepsilon$  where

$$\eta_{\varepsilon_i}(t, x) = \frac{1}{\varepsilon_i^{N+1}} \eta\left(\frac{t}{\varepsilon_i}, \frac{x}{\varepsilon_i}\right),$$

for  $i = 3, 4$ , with  $\eta$  a smooth nonnegative even function compactly supported in the space time ball of radius 1, and with integral equal to 1. This is a parabolic equation recalling that in this part  $\inf_{[0, +\infty)} \mu'(s) > 0$ . Thus, we can apply the standard theory of parabolic equation to solve it when  $w$  is given smooth enough. In fact, the exact same equation was solved in paper [13]. In particular, we are able to get the following bound on the density at this level approximation

$$0 < \underline{\rho} \leq \rho(t, x) \leq \bar{\rho} < +\infty. \quad (2.2)$$

2. The momentum equation with drag terms is replaced by its Faedo-Galerkin approximation with the additional regularizing term  $\varepsilon_2[\Delta^{2s}w - \operatorname{div}((1 + |\nabla w|^2)\nabla w)]$  where  $s \geq 2$

$$\begin{aligned}
& \int_{\Omega} \rho w \cdot \psi \, dx - \int_0^t \int_{\Omega} \left( \rho([w]_{\varepsilon_3} - 2\kappa \frac{[\mu'(\rho)]_{\varepsilon_4}}{\rho} \nabla \rho) \otimes w \right) : \nabla \psi \, dx \, dt \\
& + 2(1 - \kappa) \int_0^t \int_{\Omega} \mu(\rho) \mathbb{D}w : \nabla \psi \, dx \, dt + 2\kappa \int_0^t \int_{\Omega} \mu(\rho) \mathbf{A}(w) : \nabla \psi \, dx \, dt \\
& + (1 - \kappa) \int_0^t \int_{\Omega} \lambda(\rho) \operatorname{div} w \operatorname{div} \psi \, dx \, dt - 2\kappa(1 - \kappa) \int_0^t \int_{\Omega} \mu(\rho) \nabla v : \nabla \psi \, dx \, dt \\
& - \kappa(1 - \kappa) \int_0^t \int_{\Omega} \lambda(\rho) \operatorname{div} v \operatorname{div} \psi \, dx \, dt - \int_0^t \int_{\Omega} \rho^\gamma \operatorname{div} \psi \, dx \, dt - \delta \int_0^t \int_{\Omega} \rho^{10} \operatorname{div} \psi \, dx \, dt \\
& + \varepsilon_2 \int_0^t \int_{\Omega} (\Delta^s w \cdot \Delta^s \psi + (1 + |\nabla w|^2) \nabla w : \nabla \psi) \, dx \, dt = - \int_0^t \int_{\Omega} r_0 (w - 2\kappa \nabla s(\rho)) \cdot \psi \, dx \, dt \\
& - r_1 \int_0^t \int_{\Omega} \rho |w - 2\kappa \nabla s(\rho)| (w - 2\kappa \nabla s(\rho)) \cdot \psi \, dx \, dt \\
& - r_2 \int_0^t \int_{\Omega} \frac{\rho}{\mu'(\rho)} |w - 2\kappa \nabla s(\rho)|^2 (w - 2\kappa \nabla s(\rho)) \cdot \psi \, dx \, dt \\
& - r \int_0^t \int_{\Omega} \sqrt{K(\rho)} \Delta \left( \int_0^\rho \sqrt{K(s)} \, ds \right) \operatorname{div}(\rho \psi) \, dx \, dt + \int_{\Omega} \rho_0 w_0 \cdot \psi \, dx
\end{aligned} \tag{2.3}$$

satisfied for any  $t > 0$  and any test function  $\psi \in C([0, T], X_n)$ , where  $\lambda(\rho) = 2(\mu'(\rho)\rho - \mu(\rho))$ , and  $s'(\rho) = \mu'(\rho)/\rho$ , and  $X_n = \operatorname{span}\{e_i\}_{i=1}^n$  is an orthonormal basis in  $W^{1,2}(\Omega)$  with  $e_i \in C^\infty(\Omega)$  for any integers  $i > 0$ .

3. The Faedo-Galerkin approximation for the equation on the drift velocity  $v$  reads

$$\begin{aligned}
& \int_{\Omega} \rho v \cdot \phi \, dx - \int_0^t \int_{\Omega} \left( \rho([w]_{\varepsilon_3} - 2\kappa \frac{[\mu'(\rho)]_{\varepsilon_4}}{\rho} \nabla \rho) \otimes v \right) : \nabla \phi \, dx \, dt \\
& + 2\kappa \int_0^t \int_{\Omega} \mu(\rho) \nabla v : \nabla \phi \, dx \, dt + \kappa \int_0^t \int_{\Omega} \lambda(\rho) \operatorname{div} v \operatorname{div} \phi \, dx \, dt \\
& - \int_0^t \int_{\Omega} \lambda(\rho) \operatorname{div} w \operatorname{div} \phi \, dx \, dt + 2 \int_0^t \int_{\Omega} \mu(\rho) \nabla^T w : \nabla \phi \, dx \, dt = \int_{\Omega} \rho_0 v_0 \cdot \phi \, dx
\end{aligned} \tag{2.4}$$

satisfied for any  $t > 0$  and any test function  $\phi \in C([0, T], Y_n)$ , where  $Y_n = \operatorname{span}\{b_i\}_{i=1}^n$  and  $\{b_i\}_{i=1}^\infty$  is an orthonormal basis in  $W^{1,2}(\Omega)$  with  $b_i \in C^\infty(\Omega)$  for any integers  $i > 0$ .

The above full approximation is similar to the ones in the papers [13]–[14] which are two parts dedicated to augmented systems similar to the one we consider. We can repeat the same argument as [14] to obtain the local existence of solutions to the Galerkin approximation. In order to extend the local solution to the global one, the uniform bounds are necessary so that the corresponding procedure can be iterated.

**2.1. The energy estimate if the solution is regular enough.** For any fixed  $n > 0$ , choosing test functions  $\psi = w$ ,  $\phi = v$  in (2.3) and (2.4), we find that  $(\rho, w, v)$  satisfies the

following  $\kappa$ -entropy equality

$$\begin{aligned}
& \int_{\Omega} \left( \rho \left( \frac{|w|^2}{2} + (1 - \kappa) \kappa \frac{|v|^2}{2} \right) + \frac{\rho^\gamma}{\gamma - 1} + \delta \frac{\rho^{10}}{9} \right) dx + 2(1 - \kappa) \int_0^t \int_{\Omega} \mu(\rho) |\mathbb{D}w - \kappa \nabla v|^2 dx dt \\
& + (1 - \kappa) \int_0^t \int_{\Omega} \lambda(\rho) (\operatorname{div} w - \kappa \operatorname{div} v)^2 dx dt + 2\kappa \int_0^t \int_{\Omega} \frac{\mu'(\rho) p'(\rho)}{\rho} |\nabla \rho|^2 dx dt \\
& + 2\kappa \int_0^t \int_{\Omega} \mu(\rho) |Aw|^2 dx dt + \varepsilon_2 \int_0^t \int_{\Omega} (|\Delta^s w|^2 + (1 + |\nabla w|^2) |\nabla w|^2) dx dt \\
& + r \int_0^t \int_{\Omega} \sqrt{K(\rho)} \Delta \left( \int_0^\rho \sqrt{K(s)} ds \right) \operatorname{div}(\rho w) dx dt + 20\kappa\delta \int_0^t \int_{\Omega} \mu'(\rho) \rho^8 |\nabla \rho|^2 dx dt \\
& + r_0 \int_0^t \int_{\Omega} (w - 2\kappa \nabla s(\rho)) \cdot w dx dt + r_1 \int_0^t \int_{\Omega} \rho |w - 2\kappa \nabla s(\rho)| (w - 2\kappa \nabla s(\rho)) \cdot w dx dt \\
& + r_2 \int_0^t \int_{\Omega} \frac{\rho}{\mu'(\rho)} |w - 2\kappa \nabla s(\rho)|^2 (w - 2\kappa \nabla s(\rho)) \cdot w dx dt \\
& = \int_{\Omega} \left( \rho_0 \left( \frac{|w_0|^2}{2} + (1 - \kappa) \kappa \frac{|v_0|^2}{2} \right) + \frac{\rho_0^\gamma}{\gamma - 1} + \delta \frac{\rho_0^{10}}{9} \right) dx - \int_0^T \int_{\Omega} \rho^\gamma \operatorname{div}([w]_{\varepsilon_3} - w) dx dt \\
& - \delta \int_0^T \int_{\Omega} \rho^{10} \operatorname{div}([w]_{\varepsilon_3} - w) dx dt,
\end{aligned} \tag{2.5}$$

where  $s' = \mu'(\rho)/\rho$  and  $p(\rho) = \rho^\gamma$ . Compared to the calculations made in [13], we have to take care of the capillary term and then to take care of the drag terms showing that they can be controlled using that  $\inf_{s \in [0, +\infty)} \mu'(s) \geq \varepsilon_1 > 0$  for the linear drag, using the extra pressure term  $\delta \rho^{10}$  for the quadratic drag term and using the capillary term  $r \rho \nabla(\sqrt{K(\rho)} \Delta(\int_0^\rho \sqrt{K(s)} ds))$  for the cubic drag term. To do so, let us provide some properties on the capillary term and rewrite the terms coming from the drag quantities.

**2.1.1. Some properties on the capillary term.** Using the mass equation, the capillary term in the entropy estimates reads

$$\begin{aligned}
& r \int_{\Omega} \sqrt{K(\rho)} \Delta \left( \int_0^\rho \sqrt{K(s)} ds \right) \operatorname{div}(\rho w) = \frac{r}{2} \frac{d}{dt} \int_{\Omega} |\nabla \int_0^\rho \sqrt{K(s)} ds|^2 \\
& + 2\kappa r \int_{\Omega} \sqrt{K(\rho)} \Delta \left( \int_0^\rho \sqrt{K(s)} ds \right) \Delta \mu(\rho) = I_1 + I_2.
\end{aligned} \tag{2.6}$$

In fact, we write term  $I_1$  as follows

$$\frac{r}{2} \frac{d}{dt} \int_{\Omega} |\nabla \int_0^\rho \sqrt{K(s)} ds|^2 = \frac{r}{2} \frac{d}{dt} \int_{\Omega} \rho |\nabla s(\rho)|^2 dx.$$

By (1.27), we have

$$\begin{aligned}
I_2 &= 2\kappa r \int_{\Omega} \sqrt{K(\rho)} \Delta \left( \int_0^{\rho} \sqrt{K(s)} ds \right) \Delta \mu(\rho) \\
&= -2\kappa r \int_{\Omega} \rho \nabla \left( \sqrt{K(\rho)} \Delta \left( \int_0^{\rho} \sqrt{K(s)} ds \right) \right) \cdot \nabla s(\rho) \\
&= 2\kappa r \int_{\Omega} 2\mu(\rho) |2\nabla^2 s(\rho)|^2 + \lambda(\rho) |2\Delta s(\rho)|^2.
\end{aligned} \tag{2.7}$$

*Control of norms using  $I_2$ .* Let us first recall that since

$$\lambda(\rho) = 2(\mu'(\rho)\rho - \mu(\rho)) > -2\mu(\rho)/3,$$

there exists  $\eta > 0$  such that

$$\begin{aligned}
&2 \int_0^T \int_{\Omega} \mu(\rho) |\nabla^2 s(\rho)|^2 dx dt + \int_0^T \int_{\Omega} \lambda(\rho) |\Delta s(\rho)|^2 dx dt \\
&\geq \eta \left[ 2 \int_0^T \int_{\Omega} \mu(\rho) |\nabla^2 s(\rho)|^2 dx dt + \frac{1}{3} \int_0^T \int_{\Omega} \mu(\rho) |\Delta s(\rho)|^2 dx dt \right].
\end{aligned}$$

As the second term in the right-hand side is positive, lower bound on the quantity

$$\int_0^T \int_{\Omega} \mu(\rho) |\nabla^2 s(\rho)|^2 dx dt \tag{2.8}$$

will provide the same lower bound on  $I_2$ .

Let us now precise the norms which are controlled by (2.8). To do so, we need to rely on the following lemma on the density. In this lemma, we prove a more general entropy dissipation inequality than the one introduced by Jüngel in [30] and more general than those by Jüngel-Matthes in [31].

**Lemma 2.1.** *Let  $\mu'(\rho)\rho < k\mu(\rho)$  for  $2/3 < k < 4$  and*

$$s(\rho) = \int_0^{\rho} \frac{\mu'(s)}{s} ds, \quad Z(\rho) = \int_0^{\rho} \frac{\sqrt{\mu(s)}}{s} \mu'(s) ds, \quad Z_1(\rho) = \int_0^{\rho} \frac{\mu'(s)}{(\mu(s))^{1/4} s^{1/2}} ds.$$

i) *Assume  $\rho > 0$  and  $\rho \in L^2(0, T; H^2(\Omega))$  then there exists  $\varepsilon(k) > 0$ , such that we have the following estimate*

$$\int_0^T \int_{\Omega} |\nabla^2 Z(\rho)|^2 dx dt + \varepsilon(k) \int_0^T \int_{\Omega} \frac{\rho^2}{\mu(\rho)^3} |\nabla Z(\rho)|^4 dx dt \leq \frac{C}{\varepsilon(k)} \int_0^T \int_{\Omega} \mu(\rho) |\nabla^2 s(\rho)|^2 dx dt,$$

where  $C$  is a universal positive constant.

ii) *Consider a sequence of smooth densities  $\rho_n > 0$  such that  $Z(\rho_n)$  and  $Z_1(\rho_n)$  converge strongly in  $L^1((0, T) \times \Omega)$  respectively to  $Z(\rho)$  and  $Z_1(\rho)$  and  $\sqrt{\mu(\rho_n)} \nabla^2 s(\rho_n)$  is uniformly bounded in  $L^2((0, T) \times \Omega)$ . Then*

$$\int_0^T \int_{\Omega} |\nabla^2 Z(\rho)|^2 dx dt + \varepsilon(k) \int_0^T \int_{\Omega} |\nabla Z_1(\rho)|^4 dx dt \leq C < +\infty$$

*Remark 2.1.* The case of  $Z = 2\sqrt{\rho}$  for the inequality was proved in [30], which is critical to derive the uniform bound on approximated velocity in  $L^2(0, T; L^2(\Omega))$  in [49, 50]. The above lemma will play a similar role in this paper.

*Proof.* Let us first prove the part i). Note that  $Z'(\rho) = \frac{\sqrt{\mu(\rho)}}{\rho}\mu'(\rho)$ , we get the following calculation:

$$\begin{aligned}\sqrt{\mu(\rho)}\nabla^2 s(\rho) &= \sqrt{\mu(\rho)}\nabla\left(\frac{\nabla\mu(\rho)}{\rho}\right) = \sqrt{\mu(\rho)}\nabla\left(\frac{1}{\sqrt{\mu(\rho)}}\nabla Z(\rho)\right) \\ &= \nabla^2 Z(\rho) - \frac{\nabla Z(\rho)}{\sqrt{\mu(\rho)}} \otimes \nabla\sqrt{\mu(\rho)} \\ &= \nabla^2 Z(\rho) - \frac{\rho\nabla Z(\rho) \otimes \nabla Z(\rho)}{2\mu(\rho)^{\frac{3}{2}}}.\end{aligned}$$

Thus, we have

$$\begin{aligned}\int_{\Omega} \mu(\rho)|\nabla^2 s(\rho)|^2 dx &= \int_{\Omega} |\nabla^2 Z(\rho)|^2 dx + \frac{1}{4} \int_{\Omega} \frac{\rho^2}{\mu(\rho)^3} |\nabla Z(\rho)|^4 dx \\ &\quad - \int_{\Omega} \frac{\rho}{\mu(\rho)^{\frac{3}{2}}} \nabla^2 Z(\rho) : (\nabla Z(\rho) \otimes \nabla Z(\rho)) dx.\end{aligned}\tag{2.9}$$

By integration by parts, the cross product term reads as follows

$$\begin{aligned}& - \int_{\Omega} \frac{\rho}{\mu(\rho)^{\frac{3}{2}}} \nabla^2 Z(\rho) : (\nabla Z(\rho) \otimes \nabla Z(\rho)) dx \\ &= - \int_{\Omega} \frac{\rho\sqrt{\mu(\rho)}}{\mu(\rho)} \nabla^2 Z(\rho) : \left(\frac{\nabla Z(\rho)}{\sqrt{\mu(\rho)}} \otimes \frac{\nabla Z(\rho)}{\sqrt{\mu(\rho)}}\right) dx \\ &= \int_{\Omega} \frac{\rho}{\mu(\rho)} \sqrt{\mu(\rho)} \nabla Z(\rho) \cdot \operatorname{div}\left(\frac{\nabla Z(\rho)}{\sqrt{\mu(\rho)}} \otimes \frac{\nabla Z(\rho)}{\sqrt{\mu(\rho)}}\right) dx \\ &\quad + \int_{\Omega} \nabla\left(\frac{\rho}{\sqrt{\mu(\rho)}}\right) \otimes \nabla Z(\rho) : \frac{\nabla Z(\rho) \otimes \nabla Z(\rho)}{\mu(\rho)} dx \\ &= I_1 + I_2.\end{aligned}\tag{2.10}$$

To this end, we are able to control  $I_1$  directly,

$$\begin{aligned}|I_1| &\leq \varepsilon \int_{\Omega} \frac{\rho^2}{\mu(\rho)^3} |\nabla Z(\rho)|^4 dx + \frac{C}{\varepsilon} \int_{\Omega} \mu(\rho) \left|\nabla\left(\frac{\nabla Z(\rho)}{\sqrt{\mu(\rho)}}\right)\right|^2 dx \\ &\leq \varepsilon \int_{\Omega} \frac{\rho^2}{\mu(\rho)^3} |\nabla Z(\rho)|^4 dx + \frac{C}{\varepsilon} \int_{\Omega} \mu(\rho) |\nabla^2 s(\rho)|^2 dx,\end{aligned}\tag{2.11}$$

where  $C$  is a universal positive constant. We calculate  $I_2$  to have

$$\begin{aligned}I_2 &= \int_{\Omega} \nabla\left(\frac{\rho}{\sqrt{\mu(\rho)}}\right) \otimes \nabla Z(\rho) : \frac{\nabla Z(\rho) \otimes \nabla Z(\rho)}{\mu(\rho)} dx \\ &= \int_{\Omega} \frac{\nabla\rho \otimes \nabla Z(\rho)}{\mu(\rho)^{\frac{3}{2}}} : (\nabla Z(\rho) \otimes \nabla Z(\rho)) dx \\ &\quad - \int_{\Omega} \frac{\rho}{\mu(\rho)^2} \nabla\sqrt{\mu(\rho)} \otimes \nabla Z(\rho) : (\nabla Z(\rho) \otimes \nabla Z(\rho)) dx \\ &= \int_{\Omega} \frac{\rho}{\mu(\rho)^2 \mu(\rho)'} |\nabla Z(\rho)|^4 dx - \frac{1}{2} \int_{\Omega} \frac{\rho^2}{\mu(\rho)^3} |\nabla Z(\rho)|^4 dx.\end{aligned}\tag{2.12}$$

Relying on (2.9)-(2.12), we have

$$\begin{aligned} & \int_{\Omega} |\nabla^2 Z(\rho)|^2 dx + \int_{\Omega} \frac{\rho}{\mu(\rho)^2 \mu'(\rho)} |\nabla Z(\rho)|^4 dx - \left(\frac{1}{4} + \varepsilon\right) \int_{\Omega} \frac{\rho^2}{\mu(\rho)^3} |\nabla Z(\rho)|^4 dx \\ & \leq \frac{C}{\varepsilon} \int_{\Omega} \mu(\rho) |\nabla^2 s(\rho)|^2 dx. \end{aligned}$$

Since  $k_1 \mu'(s)s \leq \mu(s)$ , we have

$$\frac{s}{\mu^2(s) \mu'(s)} - \left(\frac{1}{4} + \varepsilon\right) \frac{s^2}{\mu(s)^3} \geq \left(k_1 - \frac{1}{4} - \varepsilon\right) \frac{s^2}{\mu(s)^3} > \varepsilon \frac{s^2}{\mu(s)^3},$$

where we choose  $k_1 > \frac{1}{4}$ . This implies

$$\int_{\Omega} |\nabla^2 Z(\rho)|^2 dx + \varepsilon \int_{\Omega} \frac{\rho^2}{\mu(\rho)^3} |\nabla Z(\rho)|^4 dx \leq \frac{C}{\varepsilon} \int_{\Omega} \mu(\rho) |\nabla^2 s(\rho)|^2 dx.$$

This ends the proof of part i). Concerning part ii), it suffices to pass to the limit in the inequality proved previously using the lower semi continuity on the left-hand side.  $\square$

**2.1.2. Drag terms control.** We have to discuss three kind of drag terms: Linear drag term, quadratic drag term and finally cubic drag term.

a) *Linear drag terms.* As in previous works [8, 49, 52], we need to choose a linear drag with constant coefficient

$$\begin{aligned} & r_0 \int_0^t \int_{\Omega} (w - 2\kappa \nabla s(\rho)) \cdot w dx dt = r_0 \int_0^t \int_{\Omega} |w - 2\kappa \nabla s(\rho)|^2 dx dt \\ & + r_0 \int_0^t \int_{\Omega} (w - 2\kappa \nabla s(\rho)) \cdot (2\kappa \nabla s(\rho)) dx dt. \end{aligned} \tag{2.13}$$

The second term on the right side of (2.13) reads

$$\begin{aligned} & r_0 \int_0^t \int_{\Omega} (w - 2\kappa \nabla s(\rho)) \cdot (2\kappa \nabla s(\rho)) dx dt = r_0 \int_0^t \int_{\Omega} \rho(w - 2\kappa \nabla s(\rho)) \cdot \frac{2\kappa \nabla s(\rho)}{\rho} dx dt \\ & = r_0 \int_0^t \int_{\Omega} \rho(w - 2\kappa \nabla s(\rho)) \cdot 2\kappa \nabla g(\rho) dx dt \\ & = 2\kappa r_0 \int_0^t \int_{\Omega} \rho_t g(\rho) dx dt, \end{aligned}$$

where  $g'(\rho) = \frac{s'(\rho)}{\rho} = \frac{\mu'(\rho)}{\rho^2}$  and  $g(\rho) = \int_1^\rho \frac{\mu'(r)}{r^2} dr$ . Letting

$$G(\rho) = \int_1^\rho \int_1^r \frac{\mu'(\zeta)}{\zeta^2} d\zeta dr,$$

then

$$r_0 \int_{\Omega} \rho_t g(\rho) dx = r_0 \frac{\partial}{\partial t} \int_{\Omega} G(\rho) dx,$$

which implies

$$r_0 \int_0^t \int_{\Omega} \rho_t g(\rho) dx dt = r_0 \int_{\Omega} G(\rho) dx.$$

Meanwhile, since  $\lim_{\zeta \rightarrow 0} \mu'(\zeta) = \varepsilon_1 > 0$ , for any  $|\zeta| < \epsilon$  and any small number  $\epsilon > 0$ , we have  $\mu'(\zeta) \geq \frac{\varepsilon_1}{2}$ . Thus, we have further estimate on  $G(\rho)$  as follows

$$\begin{aligned} G(\rho) &= \int_1^\rho \int_1^r \frac{\mu'(\zeta)}{\zeta^2} d\zeta dr \geq \frac{\varepsilon_1}{2} \int_1^\rho \left(1 - \frac{1}{r}\right) dr \\ &= \frac{\varepsilon_1}{2} (\rho - 1 - \ln \rho) \\ &\geq -\frac{\varepsilon_1}{4} (\ln \rho)_-, \end{aligned}$$

for any  $\rho \leq \epsilon$ . Similarly, we can show that

$$G(\rho) \leq 4\varepsilon_1 (\ln \rho)_+$$

for any  $\rho \leq \epsilon$ . For given number  $\epsilon_0 > 0$ , if  $\rho \geq \epsilon_0$ , then we have

$$0 \leq G(\rho) \leq C \int_1^\rho \int_1^r \mu'(\zeta) d\zeta dr \leq C\mu(\rho)\rho.$$

b) *Quadratic drag term.* We use the same argument as in [13] to handle this term. The quadratic drag term gives

$$\begin{aligned} &r_1 \int_0^t \int_\Omega \rho |w - 2\kappa \nabla s(\rho)| (w - 2\kappa \nabla s(\rho)) \cdot w \, dx \, dt \\ &= r_1 \int_0^t \int_\Omega \rho |w - 2\kappa \nabla s(\rho)|^3 \, dx \, dt \\ &\quad + r_1 \int_0^t \int_\Omega \rho |w - 2\kappa \nabla s(\rho)| (w - 2\kappa \nabla s(\rho)) \cdot (2\kappa \nabla s(\rho)) \, dx \, dt. \end{aligned} \tag{2.14}$$

The second drag term of the right-hand side can be controlled as follows

$$\begin{aligned} &r_1 \left| \int_0^t \int_\Omega \rho |w - 2\kappa \nabla s(\rho)| (w - 2\kappa \nabla s(\rho)) \cdot (2\kappa \nabla s(\rho)) \, dx \, dt \right| \\ &\leq 2\kappa r_1 \int_0^t \int_\Omega \mu(\rho) |u| |\mathbb{D}u| \, dx \, dt \\ &\leq \kappa \int_0^t \int_\Omega \mu(\rho) |\mathbb{D}u|^2 \, dx \, dt + \kappa r_1^2 \int_0^t \int_\Omega \mu(\rho) |u|^2 \, dx \, dt, \end{aligned} \tag{2.15}$$

and

$$\|\sqrt{\mu(\rho)}|u|\|_{L^2(0,T;L^2(\Omega))} \leq C \|\rho^{\frac{1}{3}}|u|\|_{L^3(0,T;L^3(\Omega))} \left\| \frac{\sqrt{\mu(\rho)}}{\rho^{\frac{1}{3}}} \right\|_{L^6(0,T;L^6(\Omega))}.$$

Note that

$$\begin{aligned} &\int_0^t \int_\Omega \frac{\mu(\rho)^3}{\rho^2} \, dx \, dt = \int_0^t \int_{0 \leq \rho \leq 1} \frac{\mu(\rho)^3}{\rho^2} \, dx \, dt + \int_0^t \int_{\rho \geq 1} \frac{\mu(\rho)^3}{\rho^2} \, dx \, dt \\ &\leq C \int_0^t \int_{0 \leq \rho \leq 1} \mu(\rho) (\mu'(\rho))^2 \, dx \, dt + \int_0^t \int_{\rho \geq 1} \frac{\mu(\rho)^3}{\rho^2} \, dx \, dt \\ &\leq C + \int_0^t \int_{\rho \geq 1} \frac{\mu(\rho)^3}{\rho^2} \, dx \, dt. \end{aligned} \tag{2.16}$$

From (1.9), for any  $\rho \geq 1$ , we have

$$c' \rho^{\alpha_1} \leq \mu(\rho) \leq c \rho^{\alpha_2},$$

where  $2/3 < \alpha_1 \leq \alpha_2 < 4$ . This yields to

$$\int_0^t \int_{\rho \geq 1} \frac{\mu(\rho)^3}{\rho^2} dx dt \leq c \int_0^t \int_{\rho \geq 1} \rho^{3\alpha_2-2} dx dt \leq c \int_0^t \int_{\Omega} \rho^{10} dx \quad (2.17)$$

for any time  $t > 0$ .

c) *Cubic drag term.* The non-linear cubic drag term gives

$$\begin{aligned} & r_2 \int_0^t \int_{\Omega} \frac{\rho}{\mu'(\rho)} |w - 2\kappa \nabla s(\rho)|^2 (w - 2\kappa \nabla s(\rho)) \cdot w dx dt \\ &= r_2 \int_0^t \int_{\Omega} \frac{\rho}{\mu'(\rho)} |w - 2\kappa \nabla s(\rho)|^4 dx dt \\ &\quad + r_2 \int_0^t \int_{\Omega} \frac{\rho}{\mu'(\rho)} |w - 2\kappa \nabla s(\rho)|^2 (w - 2\kappa \nabla s(\rho)) \cdot (2\kappa \nabla s(\rho)) dx dt. \end{aligned} \quad (2.18)$$

The novelty now is to show that we control the second drag term of the right-hand side using the Korteweg-type information on the left-hand side

$$\begin{aligned} & r_2 \int_0^t \int_{\Omega} \frac{\rho}{\mu'(\rho)} |w - 2\kappa \nabla s(\rho)|^2 (w - 2\kappa \nabla s(\rho)) \cdot (2\kappa \nabla s(\rho)) dx dt \\ &\leq r_2 \left( \frac{3}{4} \int_0^t \int_{\Omega} \frac{\rho}{\mu'(\rho)} |w - 2\kappa \nabla s(\rho)|^4 + \frac{(2\kappa)^4}{4} \int_0^t \int_{\Omega} \frac{\rho}{\mu'(\rho)} |\nabla s(\rho)|^4 \right). \end{aligned} \quad (2.19)$$

Remark that the first term in the right-hand side may be absorbed using the first term in (2.18). Let us now prove that if  $r_2$  small enough, the second term in the right-hand side may be absorbed by the term coming from the capillary quantity in the energy. From Lemma 2.1, we have

$$\int_0^t \int_{\Omega} \frac{\rho^2}{\mu^3(\rho)} |\nabla Z(\rho)|^4 dx dt = \int_0^t \int_{\Omega} \frac{1}{\mu(\rho) \rho^2} |\nabla \mu(\rho)|^4 dx dt.$$

It remains to check that

$$\int_0^t \int_{\Omega} \frac{\rho}{\mu'(\rho)} |\nabla s(\rho)|^4 = \int_0^t \int_{\Omega} \frac{1}{\mu'(\rho) \rho^3} |\nabla \mu(\rho)|^4 dx dt \leq C \int_0^t \int_{\Omega} \frac{1}{\mu(\rho) \rho^2} |\nabla \mu(\rho)|^4 dx dt.$$

This concludes assuming  $r_2$  small enough compared to  $r$ .

2.1.3. *The  $\kappa$ -entropy estimate.* Using the previous calculations, assuming  $r_2$  small enough compared to  $r$ , and denoting

$$E[\rho, u + 2\kappa \nabla s(\rho), \nabla s(\rho)] = \int_{\Omega} \rho \left( \frac{|u + 2\kappa \nabla s(\rho)|^2}{2} + (1 - \kappa) \kappa \frac{|\nabla s(\rho)|^2}{2} \right) + \frac{\rho^\gamma}{\gamma - 1} + \frac{\delta \rho^{10}}{9} + G(\rho),$$

we get the following  $\kappa$ -entropy estimate

$$\begin{aligned}
& E[\rho, u + 2\kappa \nabla \mathbf{s}(\rho), \nabla \mathbf{s}(\rho)](t) + r_0 \int_0^t \int_\Omega |u|^2 dx dt \\
& + \frac{r}{2} \int_\Omega |\nabla \int_0^\rho \sqrt{K(s)} ds|^2 dx + 2(1 - \kappa) \int_0^t \int_\Omega \mu(\rho) |\mathbb{D}u|^2 dx dt + 20\kappa\delta \int_0^t \int_\Omega \mu'(\rho) \rho^8 |\nabla \rho|^2 dx dt \\
& + 2(1 - \kappa) \int_0^t \int_\Omega (\mu'(\rho)\rho - \mu(\rho)) (\operatorname{div} u)^2 dx dt + 2\kappa \int_0^t \int_\Omega \mu(\rho) |A(u + 2\kappa \nabla \mathbf{s}(\rho))|^2 dx dt \\
& + 2\kappa \int_0^t \int_\Omega \frac{\mu'(\rho)p'(\rho)}{\rho} |\nabla \rho|^2 dx dt + r_1 \int_0^t \int_\Omega \rho |u|^3 dx dt + \frac{r_2}{4} \int_0^t \int_\Omega \frac{\rho}{\mu'(\rho)} |u|^4 dx dt \\
& + \kappa r \int_0^t \int_\Omega \mu(\rho) |2\nabla^2 s(\rho)|^2 dx dt + \frac{1}{2} \kappa r \int_0^t \int_\Omega \lambda(\rho) |2\Delta s(\rho)|^2 dx dt \\
& \leq \int_\Omega \left( \rho_0 \left( \frac{|w_0|^2}{2} + (1 - \kappa) \kappa \frac{|v_0|^2}{2} \right) + \frac{\rho_0^\gamma}{\gamma - 1} + \frac{\delta \rho_0^{10}}{9} + \frac{r}{2} |\nabla \int_0^{\rho_0} \sqrt{K(s)} ds|^2 + G(\rho_0) \right) dx \\
& + C \frac{r_1}{\delta} \int_\Omega E[\rho, u + 2\kappa \nabla \mathbf{s}(\rho), \nabla \mathbf{s}(\rho)] dx dt.
\end{aligned} \tag{2.20}$$

It suffices now to remark that

$$\begin{aligned}
& \int_0^t \int_\Omega \mu(\rho) |\mathbb{D}u|^2 + \int_0^t \int_\Omega (\mu'(\rho)\rho - \mu(\rho)) |\operatorname{div} u|^2 \\
& = \int_0^t \int_\Omega \mu(\rho) |\mathbb{D}u - \frac{1}{3} \operatorname{div} u \operatorname{Id}|^2 dx dt + \int_0^t \int_\Omega (\mu'(\rho)\rho - \mu(\rho) + \frac{1}{3} \mu(\rho)) |\operatorname{div} u|^2.
\end{aligned}$$

Note that  $\alpha_1 > 2/3$ , there exists  $\varepsilon > 0$  such that

$$\mu'(\rho)\rho - \frac{2}{3}\mu(\rho) > \varepsilon\mu(\rho).$$

Such information and the control of  $\sqrt{\mu(\rho)}|A(u) + 2\kappa \nabla \mathbf{s}(\rho)|$  in  $L^2(0, T; L^2(\Omega))$  allow us, using the Grönwall Lemma and the constraints on the parameters, to get the uniform estimates (1.23)–(1.25).

Now we can show (1.26). First, we have

$$\nabla \mu(\rho) = \frac{\nabla \mu(\rho)}{\sqrt{\rho}} \sqrt{\rho} \in L^\infty(0, T; L^1(\Omega)),$$

due to the mass conservation and the uniform control on  $\nabla \mu(\rho)/\sqrt{\rho}$  given in (1.23). Let us now write the equation satisfied by  $\mu(\rho)$  namely

$$\partial_t \mu(\rho) + \operatorname{div}(\mu(\rho)u) + \frac{\lambda(\rho)}{2} \operatorname{div} u = 0.$$

Recalling that  $\lambda(\rho) = 2(\mu'(\rho)\rho - \mu(\rho))$  and the hypothesis on  $\mu(\rho)$ , we get

$$\frac{d}{dt} \int_\Omega \mu(\rho) \leq C \left( \int_\Omega |\lambda(\rho)| |\operatorname{div} u|^2 + \int_\Omega \mu(\rho) \right),$$

and therefore

$$\mu(\rho) \in L^\infty(0, T; L^1(\Omega)),$$

if  $\mu(\rho_0) \in L^1(\Omega)$  due to the fact that  $\sqrt{|\lambda(\rho)|} \operatorname{div} u \in L^2(0, T; L^2(\Omega))$ . Now, we observe that  $\mu(\rho)/\sqrt{\rho}$  is smaller than 1 for  $\rho \leq 1$  because  $\alpha_1 > 2/3$ , and smaller than  $\mu(\rho)$  for  $\rho_n > 1$ , then

$$\frac{\mu(\rho)}{\sqrt{\rho}} \in L^\infty(L^1).$$

Meanwhile, thanks to (1.9), we have

$$|\nabla(\mu(\rho)/\sqrt{\rho})| \leq \left| \frac{\nabla \mu(\rho)}{\sqrt{\rho}} \right| + \frac{\mu(\rho)}{2\rho\sqrt{\rho}} |\nabla \rho| \leq \left( 1 + \frac{1}{\alpha_1} \right) \left| \frac{\nabla \mu(\rho)}{\sqrt{\rho}} \right|.$$

By (1.23),  $\nabla(\mu(\rho)/\sqrt{\rho})$  is bounded in  $L^\infty(0, T; L^2(\Omega))$  and finally  $\mu(\rho)/\sqrt{\rho}$  is bounded in  $L^\infty(0, T; (L^6(\Omega)))$ . Thus, we have that

$$\mu(\rho)u = \frac{\mu(\rho)}{\sqrt{\rho}} \sqrt{\rho}u,$$

is uniformly bounded in  $L^\infty(0, T; L^{3/2}(\Omega))$ . Let us come back to the equation satisfied by  $\mu(\rho)$  which reads

$$\partial_t \mu(\rho) + \operatorname{div}(\mu(\rho)u) + \frac{\lambda(\rho)}{2} \operatorname{div} u = 0.$$

Recalling that  $\lambda(\rho) \operatorname{div} u \in L^\infty(0, T; L^1(\Omega))$ , then we get the conclusion on  $\partial_t \mu(\rho)$ . Let us now to prove that

$$Z(\rho) = \int_0^{\rho_n} \frac{\sqrt{\mu(s)}\mu'(s)}{s} ds \in L^{1+}((0, T) \times \Omega) \text{ uniformly.}$$

Note first that

$$0 \leq \frac{\sqrt{\mu(s)}\mu'(s)}{s} \leq \alpha_2 \frac{\mu(s)^{3/2}}{s^2} \leq c_2 \alpha_2 (s^{3\alpha_1/2-2} 1_{s \leq 1} + \frac{\mu(s)^{3/2-}}{s^{2-}} 1_{s \geq 1}).$$

There exists  $\varepsilon > 0$  such that  $\alpha_1 > 2/3 + \varepsilon$ , thus

$$0 \leq \frac{\sqrt{\mu(s)}\mu'(s)}{s} \leq c_2 \alpha_2 (s^{\varepsilon-1} 1_{s \leq 1} + \frac{\mu(s)^{3/2-}}{s^{2-}} 1_{s \geq 1}).$$

Note that  $\mu'(s) > 0$  for  $s > 0$  and the definition of  $Z(\rho)$ , we get

$$0 \leq Z(\rho) \leq C(\rho^\varepsilon + \mu(\rho)^{3/2-})$$

with  $C$  independent of  $n$ . Thus  $Z(\rho) \in L^\infty(0, T; L^{1+}(\Omega))$  uniformly with respect to  $n$ . Bound on  $Z_1(\rho)$  follows the similar lines.

**2.2. Compactness Lemmas.** In this subsection, we provide general compactness lemmas which will be used several times in this paper.

*Some uniform compactness.*

**Lemma 2.2.** *Assume we have a sequence  $\{\rho_n\}_{n \in \mathbb{N}}$  satisfying the estimates in Theorem 1.2, uniformly with respect to  $n$ . Then, there exists a function  $\rho \in L^\infty(0, T; L^\gamma(\Omega))$  such that, up to a subsequence,*

$$\mu(\rho_n) \rightarrow \mu(\rho) \text{ in } \mathcal{C}([0, T]; L^{3/2}(\Omega) \text{ weak}),$$

and

$$\rho_n \rightarrow \rho \text{ a.e. in } (0, T) \times \Omega.$$

Moreover

$$\rho_n \rightarrow \rho \text{ in } L^{(4\gamma/3)^+}((0, T) \times \Omega),$$

$$\sqrt{\frac{P'(\rho_n)\rho_n}{\mu'(\rho_n)}} \nabla \left( \int_0^{\rho_n} \sqrt{\frac{P'(s)\mu'(s)}{s}} ds \right) \rightharpoonup \sqrt{\frac{P'(\rho)\rho}{\mu'(\rho)}} \nabla \left( \int_0^\rho \sqrt{\frac{P'(s)\mu'(s)}{s}} ds \right) \text{ in } L^1((0, T) \times \Omega)$$

and

$$\sqrt{\frac{P'(\rho_n)\rho_n}{\mu'(\rho_n)}} \nabla \left( \int_0^{\rho_n} \sqrt{\frac{P'(s)\mu'(s)}{s}} ds \right) \in L^{1+}((0, T) \times \Omega).$$

If  $\delta_n > 0$  is such that  $\delta_n \rightarrow \delta \geq 0$ , then

$$\delta_n \rho_n^{10} \rightarrow \delta \rho^{10} \quad \text{in } L^{\frac{4}{3}}((0, T) \times \Omega).$$

**Proof.** From the estimate on  $\mu(\rho_n)$  and Aubin-Lions lemma, up to a subsequence, we have

$$\mu(\rho_n) \rightarrow \mu(\rho) \text{ in } \mathcal{C}([0, T]; L^{3/2}(\Omega) \text{ weak})$$

and therefore using that  $\mu'(s) > 0$  on  $(0, +\infty)$  with  $\mu(0) = 0$ , we get the conclusion on  $\rho_n$ . Let us now recall that

$$\frac{\alpha_1}{\rho_n} \leq \frac{\mu'(\rho_n)}{\mu(\rho)} \leq \frac{\alpha_2}{\rho_n} \quad (2.21)$$

and therefore

$$c_1 \rho_n^{\alpha_2} \leq \mu(\rho_n) \leq c_2 \rho_n^{\alpha_1} \quad \text{for } \rho_n \leq 1,$$

and

$$c_1 \rho_n^{\alpha_1} \leq \mu(\rho_n) \leq c_2 \rho_n^{\alpha_2} \quad \text{for } \rho_n \geq 1.$$

with  $c_1$  and  $c_2$  independent on  $n$ . Note that

$$\sqrt{\frac{p'(\rho_n)\mu'(\rho_n)}{\rho_n}} \nabla \rho_n \in L^\infty(0, T; L^2(\Omega)) \text{ uniformly.} \quad (2.22)$$

Let us prove that there exists  $\varepsilon$  such that

$$I_0 = \int_0^T \int_\Omega \rho_n^{\frac{4\gamma}{3} + \varepsilon} < C$$

with  $C$  independent on  $n$  and the parameters. We first remark that it suffices to look at it when  $\rho_n \geq 1$  and to remark there exists  $\varepsilon$  such that  $\varepsilon \leq (\gamma - 1)/3$ . Let us take such parameter then

$$\int_0^T \int_\Omega \rho_n^{\frac{4\gamma}{3} + \varepsilon} 1_{\rho \geq 1} \leq \int_0^T \int_\Omega \rho_n^{\frac{2\gamma}{3} + \gamma - \frac{1}{3}} 1_{\rho \geq 1} \leq \int_0^T \int_\Omega \rho_n^{\frac{2\gamma}{3} + \gamma + \alpha_1 - 1} 1_{\rho \geq 1}$$

recalling that  $\alpha_1 > 2/3$ . Following [37], it remains to prove that

$$I_1 = \int_0^T \int_\Omega [\rho_n^{[5\gamma + 3(\alpha_1 - 1)]/3} 1_{\rho \geq 1}] < +\infty$$

uniformly. Denoting

$$I_2 = \int_0^T \int_\Omega [\rho_n^{[5\gamma + 3(\alpha_2 - 1)]/3} 1_{\rho \leq 1}]$$

and using the bounds on  $\mu(\rho_n)$  in terms of power functions in  $\rho$ , which are different if  $\rho_n \geq 1$  or  $\rho_n \leq 1$ , we can write:

$$I_1 \leq I_1 + I_2 \leq C_a \int_0^T \int_{\Omega} \rho_n^{2\gamma/3} P'(\rho_n) \mu(\rho_n) \leq C_a \int_0^T \|\rho_n^\gamma\|_{L^1(\Omega)}^{2/3} \|P'(\rho_n) \mu(\rho_n)\|_{L^3(\Omega)}$$

where  $C$  does not depend on  $n$ . Using the Poincaré-Wirtinger inequality, one obtains that

$$\begin{aligned} \|P'(\rho_n) \mu(\rho_n)\|_{L^3(\Omega)} &= \|\sqrt{P'(\rho_n) \mu(\rho_n)}\|_{L^6(\Omega)}^2 \\ &\leq \|\sqrt{P'(\rho_n) \mu(\rho_n)}\|_{L^1(\Omega)} + \|\nabla [\sqrt{P'(\rho_n) \mu(\rho_n)}]\|_{L^2(\Omega)}^2. \end{aligned}$$

Let us now check that the two terms are uniformly bounded in time. First we calculate

$$\nabla [\sqrt{P'(\rho_n) \mu(\rho_n)}] = \frac{P''(\rho_n) \mu(\rho_n) + P'(\rho_n) \mu'(\rho_n)}{\sqrt{P'(\rho_n) \mu(\rho_n)}} \nabla \rho_n$$

and using (2.21), we can check that

$$\frac{P''(\rho_n) \mu(\rho_n) + P'(\rho_n) \mu'(\rho_n)}{\sqrt{P'(\rho_n) \mu(\rho_n)}} \leq \sqrt{\frac{P'(\rho_n) \mu'(\rho_n)}{\rho_n}}.$$

Therefore, using (2.22), uniformly with respect to  $n$ , we get

$$\sup_{t \in [0, T]} \|\nabla [\sqrt{P'(\rho_n) \mu(\rho_n)}]\|_{L^2(\Omega)}^2 < +\infty.$$

Let us now check that uniformly with respect to  $n$

$$\sup_{t \in [0, T]} \|\sqrt{P'(\rho_n) \mu(\rho_n)}\|_{L^1(\Omega)} < +\infty. \quad (2.23)$$

Using the bounds on  $\mu(\rho_n)$ , we have

$$\int_{\Omega} \sqrt{P'(\rho_n) \mu(\rho_n)} \leq C \int_{\Omega} \left[ \rho_n^{(\gamma-1+\alpha_1)/2} 1_{\rho_n \leq 1} + \rho_n^{(\gamma-1+\alpha_2)/2} 1_{\rho_n \geq 1} \right]$$

with  $C$  independent on  $n$ . Recalling that  $\alpha_1 \geq 2/3$  and  $\alpha_2 < 4$ , we can check that

$$\int_{\Omega} \sqrt{P'(\rho_n) \mu(\rho_n)} \leq C \int_{\Omega} \left[ \rho_n^{\gamma/3} + \rho_n^{\frac{\gamma}{2}} \rho_n^{\frac{3}{2}} \right],$$

and therefore using that  $\rho_n^\gamma \in L^\infty(0, T; L^1(\Omega))$  and  $\rho_n \in L^\infty(0, T; L^{10}(\Omega))$ , we get (2.23).

This ends the proof of the convergence of  $\rho_n$  to  $\rho$  in  $L^{(4\gamma/3)^+}((0, T) \times \Omega)$ .

Let us now focus on the convergence of

$$\sqrt{\frac{P'(\rho_n) \rho_n}{\mu'(\rho_n)}} \nabla \left( \int_0^{\rho_n} \sqrt{\frac{P'(s) \mu'(s)}{s}} ds \right). \quad (2.24)$$

First let us recall that

$$\nabla \left( \int_0^{\rho_n} \sqrt{\frac{P'(s) \mu'(s)}{s}} ds \right) \in L^\infty(0, T; L^2(\Omega)) \text{ uniformly.}$$

Let us now prove that

$$\sqrt{\frac{P'(\rho_n) \rho_n}{\mu'(\rho_n)}} \in L^{2^+}((0, T) \times \Omega). \quad (2.25)$$

Recall first that  $\alpha_1 > \frac{2}{3}$ , we just have to consider  $\rho_n \geq 1$ . We write

$$\frac{P'(\rho_n)\rho_n}{\mu'(\rho_n)} 1_{\rho_n \geq 1} \leq C \rho_n^{\gamma - \alpha_1 + 1} 1_{\rho_n \geq 1} \leq C \rho_n^{\gamma + 1/3} 1_{\rho_n \geq 1} \leq C \rho_n^{\frac{4\gamma}{3}} 1_{\rho_n \geq 1}.$$

We can use the fact that  $\rho_n^{(4\gamma/3)^+} \in L^1((0, T) \times \Omega)$  uniformly to conclude on (2.25). Thanks to

$$\sqrt{\frac{P'(\rho_n)\rho_n}{\mu'(\rho_n)}} \rightarrow \sqrt{\frac{P'(\rho)\rho}{\mu'(\rho)}} \text{ in } L^2((0, T) \times \Omega)$$

and

$$\nabla \left( \int_0^{\rho_n} \sqrt{\frac{P'(s)\mu'(s)}{s}} ds \right) \rightarrow \nabla \left( \int_0^\rho \sqrt{\frac{P'(s)\mu'(s)}{s}} ds \right) \text{ weakly in } L^2((0, T) \times \Omega),$$

we have the weak convergence of (2.24) in  $L^1((0, T) \times \Omega)$ .

We now investigate limits on  $u$  independent of the parameters. We need to differentiate the case with hyper-viscosity  $\varepsilon_2 > 0$ , from the case without. In the case with hyper-viscosity, the estimate depends on  $\varepsilon_1$  because of the drag force  $r_1$ , while the estimate in the case  $\varepsilon_2 = 0$  is independent of all the other parameters. This is why we will consider the limit  $\varepsilon_2$  converges to 0 first.

**Lemma 2.3.** *Assume that  $\varepsilon_1 > 0$  is fixed. Then, there exists a constant  $C > 0$  depending on  $\varepsilon_1$  and  $C_{in}$ , but independent of all the other parameters (as long as they are bounded), such that for any initial values  $(\rho_0, \sqrt{\rho_0}u_0)$  verifying (1.29) for  $C_{in} > 0$  we have*

$$\begin{aligned} \|\partial_t(\rho u)\|_{L^{1+}(0, T; W^{-s, 2}(\Omega))} &\leq C, \\ \|\nabla(\rho u)\|_{L^2(0, T; L^1(\Omega))} &\leq C. \end{aligned}$$

Assume now that  $\varepsilon_2 = 0$ . Let  $\Phi : \mathbb{R}^+ \rightarrow \mathbb{R}$  be a smooth function, positive for  $\rho > 0$ , such that

$$\begin{aligned} \Phi(\rho) + |\Phi'(\rho)| &\leq C e^{-\frac{1}{\rho}}, & \text{for } \rho \leq 1, \\ \Phi(\rho) + |\Phi'(\rho)| &\leq C e^{-\rho}, & \text{for } \rho \geq 2. \end{aligned}$$

Assume that the initial values  $(\rho_0, \sqrt{\rho_0}u_0)$  verify (1.29) for a fixed  $C_{in} > 0$ . Then, there exists a constant  $C > 0$  independent of  $\varepsilon_1, r_0, r_1, r_2, \delta$  (as long as they are bounded), such that

$$\begin{aligned} \|\partial_t [\Phi(\rho)u]\|_{L^{1+}(0, T; W^{-2, 1}(\Omega))} &\leq C, \\ \|\nabla [\Phi(\rho)u]\|_{L^2(0, T; L^1(\Omega))} &\leq C. \end{aligned}$$

*Proof.* We split the proof into the two cases.

**Case 1:** Assume that  $\varepsilon_1 > 0$ . From the equation on  $\rho u$  and the *a priori* estimates, we find directly that

$$\|\partial_t(\rho u)\|_{L^{1+}(0, T; W^{-s, 2}(\Omega))} \leq C + \left(\frac{r_1}{\varepsilon_1}\right)^{\frac{1}{4}} \|\rho\|_{L^1(0, T) \times \Omega}^{\frac{1}{4}} \left( r_1 \int_0^T \int_{\Omega} \frac{\rho}{\mu'(\rho)} |u|^4 dx dt \right)^{3/4} \leq C(1 + 1/\varepsilon_1).$$

We have  $\mu(\rho) \geq \varepsilon_1 \rho$ , and from (1.23), we have the *a priori* estimate

$$\|\nabla \sqrt{\rho}\|_{L^\infty(0,T;L^2(\Omega))}^2 \leq \frac{C}{\varepsilon_1}.$$

Hence

$$\begin{aligned} \|\nabla(\rho u)\|_{L^2(0,T;L^1(\Omega))} &\leq \left\| \frac{\rho}{\sqrt{\mu}(\rho)} \right\|_{L^\infty(0,T;L^2(\Omega))} \|\sqrt{\mu}(\rho) \nabla u\|_{L^2(0,T;L^2(\Omega))} \\ &\quad + 2\|\nabla \sqrt{\rho}\|_{L^\infty(0,T;L^2(\Omega))} \|\sqrt{\rho} u\|_{L^\infty(0,T;L^2(\Omega))} \\ &\leq C. \end{aligned}$$

**Case 2:** Assume now that  $\varepsilon_2 = 0$ . Multiplying the equation on  $(\rho u)$  by  $\Phi(\rho)/\rho$ , we get, as for the renormalization, that

$$\|\partial_t [\Phi(\rho)u]\|_{L^{1+}(0,T;W^{-2,1}(\Omega))} \leq C.$$

Note that

$$\begin{aligned} \|\nabla [\Phi(\rho)u]\|_{L^2(0,T;L^1(\Omega))} &\leq \left\| \frac{\Phi(\rho)}{\sqrt{\mu}(\rho)} \right\|_{L^\infty} \|\sqrt{\mu}(\rho) \nabla u\|_{L^2(L^2)} \\ &\quad + 2\left\| \frac{\Phi'(\rho)}{\mu'(\rho)} \right\|_{L^\infty((0,T)\times\Omega)} \|\mu'(\rho) \nabla \sqrt{\rho}\|_{L^\infty(0,T;L^2(\Omega))} \|\sqrt{\rho} u\|_{L^\infty(0,T;L^2(\Omega))} \\ &\leq C. \end{aligned}$$

□

**Lemma 2.4.** Assume either that  $\varepsilon_{2,n} = 0$ , or  $\varepsilon_{1,n} = \varepsilon_1 > 0$ . Let  $(\rho_n, \sqrt{\rho_n} u_n)$  be a sequence of solutions for a family of bounded parameters with uniformly bounded initial values verifying (1.29) with a fixed  $C_{in}$ . Assume that there exists  $\alpha > 0$ , and a smooth function  $h : \mathbb{R}^+ \times \mathbb{R}^3 \rightarrow \mathbb{R}$  such that  $\rho_n^\alpha$  is uniformly bounded in  $L^p((0,T)\times\Omega)$  and  $h(\rho_n, u_n)$  is uniformly bounded in  $L^q((0,T)\times\Omega)$ , with

$$\frac{1}{p} + \frac{1}{q} < 1.$$

Then, up to a subsequence,  $\rho_n$  converges to a function  $\rho$  strongly in  $L^1$ ,  $\sqrt{\rho_n} u_n$  converges weakly to a function  $q$  in  $L^2$ . We define  $u = q/\sqrt{\rho}$  whenever  $\rho \neq 0$ , and  $u = 0$  on the vacuum where  $\rho = 0$ . Then  $\rho_n^\alpha h(\rho_n, u_n)$  converges strongly in  $L^1$  to  $\rho^\alpha h(\rho, u)$ .

*Proof.* Thanks to the uniform bound on the kinetic energy  $\int \rho_n |u_n|^2$ , and to Lemma 2.2, up to a subsequence,  $\rho_n$  converges strongly in  $L^1((0,T)\times\Omega)$  to a function  $\rho$ , and  $\sqrt{\rho_n} u_n$  converges weakly in  $L^2((0,T)\times\Omega)$  to a function  $q$ .

We want to show that, up to a subsequence,  $u_n \mathbf{1}_{\{\rho > 0\}}$  converges almost everywhere to  $u \mathbf{1}_{\{\rho > 0\}}$ . We consider the two cases. First, if  $\varepsilon_{1,n} = \varepsilon_1 > 0$ , then from Lemma 2.3 and the Aubin-Lions Lemma,  $\rho_n u_n$  converges strongly in  $C^0(0,T;L^1(\Omega))$  to  $\sqrt{\rho} q = \rho u$ . Up to a subsequence, both  $\rho_n$  and  $\rho_n u_n$  converges almost everywhere to, respectively,  $\rho$  and  $\rho u$ . For almost every  $(t,x) \in \{\rho > 0\}$ , for  $n$  big enough,  $\rho_n(t,x) > 0$ , so  $u_n = \rho_n u_n / \rho_n$  at this point converges  $u$ . If  $\varepsilon_{2,n} = 0$  we use the second part of Lemma 2.3 and thanks to the Aubin-Lions Lemma,  $\Phi(\rho_n) u_n$  converges strongly in  $C^0(0,T;L^1(\Omega))$  to  $\Phi(\rho) u$ . We still have, up to a subsequence, both  $\rho_n$  and  $\Phi(\rho_n) u_n$  converging almost everywhere to,

respectively,  $\rho$  and  $\phi(\rho)u$  (we used the fact that  $\Phi(r)/\sqrt{r} = 0$  at  $r = 0$ ). Since  $\Phi(r) \neq 0$  for  $r \neq 0$ , for almost every  $(t, x) \in \{\rho > 0\}$ , for  $n$  big enough,  $\Phi(\rho_n)(t, x) > 0$ , so  $u_n = \Phi(\rho_n)u_n/\Phi(\rho_n)$  at this point converges  $u$ .

Note that

$$\rho_n^\alpha h(\rho_n, u_n) = \rho_n^\alpha h(\rho_n, u_n) \mathbf{1}_{\{\rho_n > 0\}} + \rho_n^\alpha h(\rho_n, u_n) \mathbf{1}_{\{\rho_n = 0\}}.$$

The first term converges almost everywhere to  $\rho^\alpha h(\rho, u) \mathbf{1}_{\{\rho > 0\}}$ , and therefore to  $\rho^\alpha h(\rho, u)$  in  $L^1$  by the Lebesgue's theorem. The second part can be estimated as follows

$$\|\rho_n^\alpha h(\rho_n, u_n) \mathbf{1}_{\{\rho_n = 0\}}\|_{L^1} \leq \|h(\rho_n, u_n)\|_{L^q} \|\rho_n^\alpha \mathbf{1}_{\{\rho = 0\}}\|_{L^{p-\varepsilon}}.$$

But  $\rho_n^\alpha \mathbf{1}_{\{\rho = 0\}}$  converges almost everywhere to 0, by the Lebesgue's theorem, the last term converges to 0.  $\square$

*Some compactness when the parameters are fixed.* For any positive fixed  $\delta, r_0, r_1, r_2$  and  $r$ , to recover a weak solution to (1.17), we only need to handle the compactness of the terms

$$r\rho_n \nabla \left( \sqrt{K(\rho_n)} \Delta \left( \int_0^{\rho_n} \sqrt{K(s)} ds \right) \right)$$

and

$$r_1 \frac{\rho_n}{\mu'(\rho_n)} |u_n|^2 u_n.$$

Indeed due to the term  $r_2 \rho_n |u_n| u_n$  and the fact that  $\inf_{s \in [0, +\infty)} \mu'(s) > \varepsilon_1 > 0$ , one obtains the compactness for all other terms in the same way as in [13, 40].

*Capillarity term.* To pass to the limits in

$$r\rho_n \nabla \left( \sqrt{K(\rho_n)} \Delta \left( \int_0^{\rho_n} \sqrt{K(s)} ds \right) \right),$$

we use the identity

$$\begin{aligned} & \rho \nabla \left( \sqrt{K(\rho)} \Delta \left( \int_0^{\rho} \sqrt{K(s)} ds \right) \right) \\ &= 4 \left[ 2 \operatorname{div}(\sqrt{\mu(\rho)} \nabla \nabla Z(\rho)) - \Delta(\sqrt{\mu(\rho)} \nabla Z(\rho)) \right] \\ &+ \left[ \nabla \left[ \left( \frac{2\lambda(\rho)}{\sqrt{\mu(\rho)}} + k(\rho) \right) \Delta Z(\rho) \right] - \nabla \operatorname{div}[k(\rho) \nabla Z(\rho)] \right] \end{aligned} \quad (2.26)$$

where  $Z(\rho_n) = \int_0^{\rho_n} [(\mu(s))^{1/2} \mu'(s)]/s \, ds$  and  $k(\rho_n) = \int_0^{\rho_n} \frac{\lambda(s) \mu'(s)}{\mu(s)^{3/2}} ds$ . It allows us to rewrite the weak form coming for the capillarity term as follows

$$\begin{aligned} & \int_0^t \int_{\Omega} \sqrt{K(\rho_n)} \Delta \left( \int_0^{\rho_n} \sqrt{K(s)} \, ds \right) \operatorname{div}(\rho_n \psi) \, dx \, dt \\ &= 4 \int_0^t \int_{\Omega} (2\sqrt{\mu(\rho_n)} \nabla \nabla Z(\rho_n) : \nabla \psi + \sqrt{\mu(\rho_n)} \nabla Z(\rho_n) \cdot \Delta \psi) \\ & \quad + \int_0^t \int_{\Omega} \left( \frac{2\lambda(\rho_n)}{\sqrt{\mu(\rho_n)}} + k(\rho_n) \right) \Delta Z(\rho_n) \operatorname{div} \psi + k(\rho_n) \nabla Z(\rho_n) \cdot \nabla \operatorname{div} \psi \\ &= A_1 + A_2. \end{aligned}$$

In fact, with Lemma 2.2 at hand, we are able to have compactness of  $A_1$  and  $A_2$  easily. Concerning  $A_1$ , we know that

$$\sqrt{\mu(\rho_n)} \rightarrow \sqrt{\mu(\rho)} \text{ in } L^p((0, T); L^q(\Omega)) \text{ for all } p < +\infty \text{ and } q < 3.$$

Note that  $\nabla \nabla Z(\rho_n)$  is uniformly bounded in  $L^2(0, T; L^2(\Omega))$ , we have  $\nabla Z(\rho_n)$  is uniformly bounded in  $L^2(0, T; L^6(\Omega))$ , because  $\int_{\Omega} \nabla Z(\rho_n) = 0$  due to the periodic condition. Thus we have following weak convergence

$$\int_{\Omega} \sqrt{\mu(\rho_n)} \nabla Z(\rho_n) \cdot \Delta \psi \, dx \rightarrow \int_{\Omega} \sqrt{\mu} \nabla Z \cdot \Delta \psi \, dx,$$

and

$$\int_{\Omega} \sqrt{\mu(\rho_n)} \nabla \nabla Z(\rho_n) \nabla \psi \, dx \rightarrow \int_{\Omega} \sqrt{\mu} \nabla \nabla Z : \nabla \psi \, dx,$$

thanks to Lemma 2.2. We conclude that  $Z = Z(\rho)$ , thanks to the bound on  $Z(\rho_n)$  and the strong convergence on  $\rho_n$ . Thus using the compactness on  $\rho_n$ , the passage to the limit in  $A_1$  is done. Concerning  $A_2$ , we just have to look at the coefficients

$$k(\rho_n) = \int_0^{\rho_n} \lambda(s) \mu'(s) / \mu(s)^{3/2} \, ds, \quad j(\rho_n) = 2\lambda(\rho_n) / \sqrt{\mu(\rho_n)}.$$

Recalling the assumptions on  $\mu(s)$  and the relation  $\lambda(s) = 2(\mu'(s)s - \mu(s))$ , we have

$$2(\alpha_1 - 1)\mu(s) \leq \lambda(s) \leq 2(\alpha_2 - 1)\mu(s),$$

and

$$\frac{\alpha_1}{\sqrt{\mu(s)}s} \leq \frac{\mu'(s)}{\mu(s)^{3/2}} \leq \frac{\alpha_2}{\sqrt{\mu(s)}s}.$$

This means that the coefficients  $k(\rho_n)$  and  $j(\rho_n)$  are comparable to  $\sqrt{\mu(\rho_n)}$ . Using the compactness of the density  $\rho_n$  and the informations on  $\mu(\rho_n)$  given in Corollary 2.2, we conclude the compactness of  $A_2$  doing as for  $A_1$ .

*Cubic non-linear drag term.* We will use Lemma 2.4 to show the compactness of

$$\frac{\rho_n}{\mu'(\rho_n)} |u_n|^2 u_n.$$

More precisely, we write

$$\frac{\rho_n}{\mu'(\rho_n)} |u_n|^2 u_n = \rho_n^{\frac{1}{6}} \sqrt{\frac{\rho_n}{\mu'(\rho_n)}} |u_n|^2 \rho_n^{\frac{1}{3}} |u_n| \frac{1}{\sqrt{\mu'(\rho_n)}} = \rho_n^{1/6} h(\rho_n, |u_n|), \quad (2.27)$$

By Lemma 2.2, there exists  $\varepsilon > 0$  such that  $\rho_n^{\frac{1}{6}}$  is uniformly bounded in  $L^\infty(0, T; L^{6\gamma+\varepsilon}(\Omega))$  and  $\rho_n \rightarrow \rho$  a.e., so

$$\rho_n^{\frac{1}{6}} \rightarrow \rho^{\frac{1}{6}} \quad \text{in } L^{6\gamma+\varepsilon}((0, T) \times \Omega). \quad (2.28)$$

Note that  $\sqrt{\frac{\rho_n}{\mu'(\rho_n)}}|u_n|^2$  is uniformly bounded in  $L^2(0, T; L^2(\Omega))$ , and  $\inf_{s \in [0, +\infty)} \mu'(s) \geq \varepsilon_1 > 0$ ,  $\rho_n^{\frac{1}{3}}|u_n|\frac{1}{\sqrt{\mu'(\rho_n)}}$  is uniformly bounded in  $L^3(0, T; L^3(\Omega))$ , thus

$$h(\rho_n, |u_n|) = \sqrt{\frac{\rho_n}{\mu'(\rho_n)}}|u_n|^2 \rho_n^{\frac{1}{3}}|u_n|\frac{1}{\sqrt{\mu'(\rho_n)}} \in L^{\frac{6}{5}}(0, T; L^{\frac{6}{5}}(\Omega)) \text{ uniformly.} \quad (2.29)$$

By Lemma 2.4 and (2.27)–(2.29), we deduce that

$$\int_0^t \int_\Omega \frac{\rho_n}{\mu'(\rho_n)}|u_n|^2 u_n \, dx \, dt \rightarrow \int_0^t \int_\Omega \frac{\rho}{\mu'(\rho)}|u|^2 u \, dx \, dt. \quad \square$$

Relying on the compactness stated in this section and the compactness in [40], we are able to follow the argument in [13] to show Theorem 1.2. Thanks to term  $r_1 \rho_n |u_n| u_n$ , we have

$$\int_0^T \int_\Omega r_1 \rho_n |u_n|^3 \, dx \, dt \leq C.$$

This gives us that

$$\sqrt{\rho_n} u_n \rightarrow \sqrt{\rho} u \text{ strongly in } L^2(0, T; L^2(\Omega)).$$

With above compactness of this section, we are able to pass to the limits for recovering a weak solution. In fact, to recover a weak solution to (1.17), we have to pass to the limits as the order of  $\varepsilon_4 \rightarrow 0$ ,  $n \rightarrow \infty$ ,  $\varepsilon_3 \rightarrow 0$  and  $\varepsilon \rightarrow 0$  respectively. In particular, when passing to the limit  $\varepsilon_3$  tends to zero, we also need to handle the identification of  $v$  with  $2\nabla s(\rho)$ . Following the same argument in [13], one shows that  $v$  and  $2\nabla s(\rho)$  satisfy the same moment equation. By the regularity and compactness of solutions, we can show the uniqueness of solutions. By the uniqueness, we have  $v = 2\nabla s(\rho)$ . This ends the proof of Theorem 1.2.

### 3. FROM WEAK SOLUTIONS TO RENORMALIZED SOLUTIONS TO THE APPROXIMATION

This section is dedicated to show that a weak solution is a renormalized solution for our last level of approximation namely to show Theorem 1.3. First, we introduce a new function

$$[f(t, x)]_\varepsilon = f * \eta_\varepsilon(t, x), \text{ for any } t > \varepsilon, \quad \text{and } [f(t, x)]_\varepsilon^x = f * \eta_\varepsilon(x)$$

where

$$\eta_\varepsilon(t, x) = \frac{1}{\varepsilon^{N+1}} \eta\left(\frac{t}{\varepsilon}, \frac{x}{\varepsilon}\right), \quad \text{and } \eta_\varepsilon(x) = \frac{1}{\varepsilon^N} \eta\left(\frac{x}{\varepsilon}\right),$$

with  $\eta$  a smooth nonnegative even function compactly supported in the space time ball of radius 1, and with integral equal to 1. In this section, we will rely on the following two lemmas to proceed our ideas. Let  $\partial$  be a partial derivative in one direction (space or time) in these two lemmas. The first one is the commutator lemma of DiPerna and Lions, see [38].

**Lemma 3.1.** *Let  $f \in W^{1,p}(\mathbb{R}^N \times \mathbb{R}^+)$ ,  $g \in L^q(\mathbb{R}^N \times \mathbb{R}^+)$  with  $1 \leq p, q \leq \infty$ , and  $\frac{1}{p} + \frac{1}{q} \leq 1$ . Then, we have*

$$\|[\partial(fg)]_\varepsilon - \partial(f([g]_\varepsilon))\|_{L^r(\mathbb{R}^N \times \mathbb{R}^+)} \leq C \|f\|_{W^{1,p}(\mathbb{R}^N \times \mathbb{R}^+)} \|g\|_{L^q(\mathbb{R}^N \times \mathbb{R}^+)}$$

for some  $C \geq 0$  independent of  $\varepsilon$ ,  $f$  and  $g$ ,  $r$  is determined by  $\frac{1}{r} = \frac{1}{p} + \frac{1}{q}$ . In addition,

$$[\partial(fg)]_\varepsilon - \partial(f([g]_\varepsilon)) \rightarrow 0 \quad \text{in } L^r(\mathbb{R}^N \times \mathbb{R}^+)$$

as  $\varepsilon \rightarrow 0$  if  $r < \infty$ . Moreover, in the same way if  $f \in W^{1,p}(\mathbb{R}^N)$ ,  $g \in L^q(\mathbb{R}^N)$  with  $1 \leq p, q \leq \infty$ , and  $\frac{1}{p} + \frac{1}{q} \leq 1$ . Then, we have

$$\|[\partial(fg)]_\varepsilon^x - \partial(f([g]_\varepsilon^x))\|_{L^r(\mathbb{R}^N)} \leq C \|f\|_{W^{1,p}(\mathbb{R}^N)} \|g\|_{L^q(\mathbb{R}^N)}$$

for some  $C \geq 0$  independent of  $\varepsilon$ ,  $f$  and  $g$ ,  $r$  is determined by  $\frac{1}{r} = \frac{1}{p} + \frac{1}{q}$ . In addition,

$$[\partial(fg)]_\varepsilon^x - \partial(f([g]_\varepsilon^x)) \rightarrow 0 \quad \text{in } L^r(\mathbb{R}^N)$$

as  $\varepsilon \rightarrow 0$  if  $r < \infty$ .

We also need another very standard lemma as follows.

**Lemma 3.2.** *If  $f \in L^p(\Omega \times \mathbb{R}^+)$  and  $g \in L^q(\Omega \times \mathbb{R}^+)$  with  $\frac{1}{p} + \frac{1}{q} = 1$  and  $H \in W^{1,\infty}(\mathbb{R})$ , then*

$$\begin{aligned} \int_0^T \int_\Omega [f]_\varepsilon g \, dx \, dt &= \int_0^T \int_\Omega f [g]_\varepsilon \, dx \, dt, \\ \lim_{\varepsilon \rightarrow 0} \int_0^T \int_\Omega [f]_\varepsilon g \, dx \, dt &= \int_0^T \int_\Omega f g \, dx \, dt, \\ \partial[f]_\varepsilon &= [\partial f]_\varepsilon, \\ \lim_{\varepsilon \rightarrow 0} \|H([f]_\varepsilon) - H(f)\|_{L_{loc}^s(\Omega \times \mathbb{R}^+)} &= 0, \quad \text{for any } 1 \leq s < \infty. \end{aligned}$$

We define a nonnegative cut-off functions  $\phi_m$  for any fixed positive  $m$  as follows.

$$\phi_m(y) \begin{cases} = 0, & \text{if } 0 \leq y \leq \frac{1}{2m}, \\ = 2my - 1, & \text{if } \frac{1}{2m} \leq y \leq \frac{1}{m}, \\ = 1, & \text{if } \frac{1}{m} \leq y \leq m, \\ = 2 - \frac{y}{m}, & \text{if } m \leq y \leq 2m, \\ = 0, & \text{if } y \geq 2m. \end{cases} \quad (3.1)$$

It enables to define an approximated velocity for the density bounded away from zero and bounded away from infinity. It is crucial to process our procedure, since the approximated velocity gradient is bounded in  $L^2((0, T) \times \Omega)$ . In particular, we introduce  $u_m = u\phi_m(\rho)$  for any fixed  $m > 0$ . Thus, we can show  $\nabla u_m$  is bounded in  $L^2(0, T; L^2(\Omega))$  due to (3.1). In fact,

$$\begin{aligned} \nabla u_m &= \phi'_m(\rho)u \otimes \nabla \rho + \phi_m(\rho) \frac{1}{\sqrt{\mu(\rho)}} \mathbb{T}_\mu \\ &= (\phi'_m(\rho) \frac{(\mu(\rho)\rho)^{1/4}}{(\mu'(\rho))^{\frac{3}{4}}}) ((\frac{\rho}{\mu'(\rho)})^{\frac{1}{4}} u) \otimes (\frac{\mu'(\rho)}{\rho^{\frac{1}{2}} \mu(\rho)^{\frac{1}{4}}} \nabla \rho) + \phi_m(\rho) \frac{1}{\sqrt{\mu(\rho)}} \mathbb{T}_\mu. \end{aligned}$$

Similarly to [34], thanks to the cut-off function (3.1) and for  $m$  fixed,  $\phi'_m(\rho)(\mu(\rho)\rho)^{\frac{1}{4}}/(\mu'(\rho))^{\frac{3}{4}}$  and  $\phi_m(\rho)/\sqrt{\mu(\rho)}$  are bounded. Then  $\nabla u_m$  is bounded in  $L^2((0, T) \times \Omega)$  using the estimates with  $r > 0$  and  $r_2 > 0$ , and hence for  $\varphi \in W^{2,+\infty}(\mathbb{R})$ , we get  $\nabla \varphi'((u_m)_j)$  is bounded in  $L^2((0, T) \times \Omega)$  for  $j = 1, 2, 3$ .

The following estimates are necessary. We state them in the lemma as follows.

**Lemma 3.3.** *There exists a constant  $C > 0$  depending only on the fixed solution  $(\sqrt{\rho}, \sqrt{\rho}u)$ , and  $C_m$  depending also on  $m$  such that*

$$\begin{aligned} & \|\rho\|_{L^\infty(0,T;L^{10}(\Omega))} + \|\rho u\|_{L^3(0,T;L^{\frac{5}{2}}(\Omega))} + \|\rho|u|^2\|_{L^2(0,T;L^{\frac{10}{7}}(\Omega))} \\ & + \|\sqrt{\mu}(|\mathbb{S}_\mu| + r|\mathbb{S}_r|)\|_{L^2(0,T;L^{\frac{10}{7}}(\Omega))} + \left\|\frac{\lambda(\rho)}{\mu(\rho)}\right\|_{L^\infty((0,T)\times\Omega)} \\ & + \left\|\sqrt{\frac{P'(\rho_n)\rho_n}{\mu'(\rho_n)}}\nabla\left(\int_0^{\rho_n}\sqrt{\frac{P'(s)\mu'(s)}{s}}ds\right)\right\|_{L^1((0,T)\times\Omega)} \\ & + \left\|\sqrt{\frac{P'_\delta(\rho_n)\rho_n}{\mu'(\rho_n)}}\nabla\left(\int_0^{\rho_n}\sqrt{\frac{P'_\delta(s)\mu'(s)}{s}}ds\right)\right\|_{L^1((0,T)\times\Omega)} + \|r_0u\|_{L^2((0,T)\times\Omega)} \leq C, \end{aligned}$$

and

$$\|\nabla\phi_m(\rho)\|_{L^4((0,T)\times\Omega)} + \|\partial_t\phi_m(\rho)\|_{L^2((0,T)\times\Omega)} \leq C_m.$$

*Proof.* By (1.24), we have  $\rho \in L^\infty(0, T; L^{10}(\Omega))$ . Now we have  $\nabla\sqrt{\rho} \in L^\infty(0, T; L^2(\Omega))$  because  $\mu'(s) \geq \varepsilon_1$  and  $\mu'(\rho)\nabla\rho/\sqrt{\rho} \in L^\infty((0, T); L^2(\Omega))$ . Note that

$$\rho u = \rho^{\frac{2}{3}}\rho^{\frac{1}{3}}u,$$

$\rho^{\frac{2}{3}} \in L^\infty(0, T; L^{15}(\Omega))$  and  $\rho^{\frac{1}{3}}u \in L^3(0, T; L^3(\Omega))$ ,  $\rho u$  is bounded in  $L^3(0, T; L^{\frac{5}{2}}(\Omega))$ .

By (1.24), we have  $(\frac{\rho}{\mu'(\rho)})^{1/2}|u|^2 \in L^2((0, T) \times \Omega)$ . Note that

$$\rho|u|^2 = (\rho\mu'(\rho))^{1/2}(\frac{\rho}{\mu'(\rho)})^{1/2}|u|^2,$$

it is bounded in  $L^2(0, T; L^{\frac{10}{7}}(\Omega))$ , where we used facts that  $\mu(\rho) \in L^\infty(0, T; L^{5/2}(\Omega))$  (recalling that for  $\rho \geq 1$  we have  $\mu(\rho) \leq c\rho^4$  and  $\rho \in L^\infty(0, T; L^{10}(\Omega))$ ) and  $\mu'(\rho)\rho \leq \alpha_2\mu(\rho)$ .

Similarly, we get  $\sqrt{\mu}(|\mathbb{S}_\mu| + r|\mathbb{S}_r|) \in L^2(0, T; L^{10/7}(\Omega))$  by (1.23). The  $L^\infty((0, T) \times \Omega)$  bound for  $\lambda(\rho)/\mu(\rho)$  may be obtained easily due to (1.3) and (1.9).

Concerning the estimates related to the pressures, we just have to look at the proof in Lemma 2.2. Note that

$$\nabla\phi_m(\rho) = \phi'_m(\rho)\nabla\rho = \phi'_m(\rho)\frac{\rho^{1/2}\mu(\rho)^{1/4}}{\mu'(\rho)}\left[\frac{\mu'(\rho)}{\rho^{1/2}\mu(\rho)^{1/4}}\nabla\rho\right]$$

by (1.25), we conclude that  $\nabla\phi_m(\rho)$  is bounded in  $L^4((0, T) \times \Omega)$ . It suffices to recall that thanks to the cut-off function  $\phi_m$ , we have  $\phi'_m(\rho)\rho^{1/2}\mu(\rho)^{1/4}/\mu'(\rho)$  bounded in  $L^\infty((0, T) \times \Omega)$ .

$\Omega$ ). Similarly, we write

$$\begin{aligned}\partial_t \phi_m(\rho) &= \phi'_m(\rho) \partial_t \rho = -\phi'_m(\rho) \operatorname{div}(\rho u) \\ &= -\phi'_m(\rho) \frac{\rho}{\sqrt{\mu}} \operatorname{Tr}(\mathbb{T}_\mu) - (\phi'_m(\rho) \frac{(\mu(\rho)\rho)^{\frac{1}{4}}}{(\mu'(\rho))^{\frac{3}{4}}}) (\frac{\rho^{\frac{1}{4}}}{(\mu'(\rho))^{\frac{1}{4}}} u) \cdot (\frac{\mu'(\rho)}{\rho^{1/2}\mu(\rho)^{1/4}} \nabla \rho),\end{aligned}$$

which provides  $\partial_t \phi_m(\rho)$  bounded in  $L^2(0, T; L^2(\Omega))$  thanks to (1.23), (1.24) and (1.25). and using the cut-off function property to bound the extra quantities in  $L^\infty((0, T) \times \Omega)$  as previously.

□

**Lemma 3.4.** *The  $\kappa$ -entropy weak solution constructed in Theorem 1.2 is a renormalized solution, in particular, we have*

$$\begin{aligned}& \int_0^T \int_\Omega (\rho \varphi(u) \psi_t + (\rho \varphi(u) \otimes u) \nabla \psi) \\ & - \int_0^T \int_\Omega \nabla \psi \varphi'(u) [2(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r \mathbb{S}_r) + \frac{\lambda(\rho)}{2\mu(\rho)} \operatorname{Tr}(\sqrt{\mu(\rho)} \mathbb{S}_\mu + r \sqrt{\mu(\rho)} \mathbb{S}_r) \operatorname{Id})] \\ & - \int_0^T \int_\Omega \psi \varphi''(u) \mathbb{T}_\mu [2((\mathbb{S}_\mu + r \mathbb{S}_r) + \frac{\lambda(\rho)}{2\mu(\rho)} \operatorname{Tr}(\mathbb{S}_\mu + r \mathbb{S}_r) \operatorname{Id})] \\ & + \int_0^T \int_\Omega \psi \varphi'(u) F(\rho, u) \, dx \, dt = 0,\end{aligned}\tag{3.2}$$

where

$$\begin{aligned}\sqrt{\mu(\rho)} \varphi'_i(u) [\mathbb{T}_\mu]_{jk} &= \partial_j(\mu \varphi'_i(u) u_k) - \sqrt{\rho} u_k \varphi'_i(u) \frac{\nabla \mu}{\sqrt{\rho}} + \bar{R}_\varphi^1, \\ \sqrt{\mu(\rho)} \varphi'_i(u) [\mathbb{S}_r]_{jk} &= 2\sqrt{\mu(\rho)} \varphi'_i(u) \partial_j \partial_k Z(\rho) - 2\partial_j(\sqrt{\mu(\rho)} \partial_k Z(\rho) \varphi'_i(u)) + \bar{R}_\varphi^2 \\ \frac{\lambda(\rho)}{2\mu(\rho)} \varphi'_i(u) \operatorname{Tr}(\sqrt{\mu(\rho)} \mathbb{T}_\mu) &= \operatorname{div}(\frac{\lambda(\rho)}{\mu(\rho)} \sqrt{\rho} u \frac{\mu(\rho)}{\sqrt{\rho}} \varphi'(u)) \\ &\quad - \sqrt{\rho} u \cdot \sqrt{\rho} \nabla s(\rho) \frac{\rho \mu''(\rho)}{\mu(\rho)} \varphi'(u) + \bar{R}_\varphi^3 \\ \frac{\lambda(\rho)}{\mu(\rho)} \varphi'(u) \operatorname{Tr}(\sqrt{\mu(\rho)} \mathbb{S}_r) &= \varphi'_i(u) (\frac{\lambda(\rho)}{\sqrt{\mu(\rho)}} + \frac{1}{2} k(\rho)) \Delta Z(\rho) \\ &\quad - \frac{1}{2} \operatorname{div}(k(\rho) \varphi'_i(u) \nabla Z(\rho)) + \bar{R}_\varphi^4\end{aligned}\tag{3.3}$$

where

$$\begin{aligned}\bar{R}_\varphi^1 &= \varphi''_i(u) \mathbb{T}_\mu \sqrt{\mu(\rho)} u \\ \bar{R}_\varphi^2 &= 2\varphi''_i(u) \mathbb{T}_\mu \nabla Z(\rho) \\ \bar{R}_\varphi^3 &= -\varphi''_i(u) \mathbb{T}_\mu \cdot \sqrt{\mu(\rho)} u \frac{\lambda(\rho)}{2\mu(\rho)} \\ \bar{R}_\varphi^4 &= \frac{k(\rho)}{2\sqrt{\mu(\rho)}} \varphi''_i(u) \mathbb{T}_\mu \cdot \nabla Z(\rho)\end{aligned}\tag{3.4}$$

*Proof.* We choose a function  $\left[\phi'_m([\rho]_\varepsilon)\psi\right]_\varepsilon$  as a test function for the continuity equation with  $\psi \in C_c^\infty((0, T) \times \Omega)$ . Using Lemma 3.2, we have

$$\begin{aligned} 0 &= \int_0^T \int_\Omega (\partial_t [\phi'_m([\rho]_\varepsilon)\psi]_\varepsilon \rho + \rho u \cdot \nabla [\phi'_m([\rho]_\varepsilon)\psi]_\varepsilon) dx dt \\ &= - \int_0^T \int_\Omega (\phi'_m([\rho]_\varepsilon)\psi \partial_t [\rho]_\varepsilon + \operatorname{div}([\rho u]_\varepsilon) \phi'_m([\rho]_\varepsilon)\psi) dx dt \\ &= \int_0^T \int_\Omega \left( \psi_t \phi_m([\rho]_\varepsilon) - \psi \phi'_m([\rho]_\varepsilon) \left[ \frac{\rho}{\sqrt{\mu(\rho)}} \operatorname{Tr}(\mathbb{T}_\mu) + 2\sqrt{\rho} u \cdot \nabla \sqrt{\rho} \right]_\varepsilon \right) dx dt. \end{aligned} \quad (3.5)$$

Using Lemma 3.3 and Lemma 3.2, and passing into the limit as  $\varepsilon$  goes to zero, from (3.5), we get:

$$\begin{aligned} 0 &= \int_0^T \int_\Omega (\psi_t \phi_m(\rho) - \psi \phi'_m(\rho) \left[ \frac{\rho}{\sqrt{\mu}} \operatorname{Tr}(\mathbb{T}_\mu) + 2\sqrt{\rho} u \cdot \nabla \sqrt{\rho} \right]) dx dt \\ &= \int_0^T \int_\Omega (\psi_t \phi_m(\rho) - \psi [\phi'_m(\rho) \frac{\rho}{\sqrt{\mu}} \operatorname{Tr}(\mathbb{T}_\mu) + u \cdot \nabla \phi_m(\rho)]) dx dt, \end{aligned} \quad (3.6)$$

thanks to  $\psi \nabla \phi_m(\rho) \in L^4((0, T) \times \Omega)$ ,  $u \in L^2((0, T) \times \Omega)$ , and  $\psi$  compactly supported.

Similarly, we can choose  $[\psi \phi_m(\rho)]_\varepsilon$  as a test function for the momentum equation. In particular, we have the following lemma.

**Lemma 3.5.**

$$\int_0^T \int_\Omega [\psi \phi_m(\rho)]_\varepsilon (\partial_t(\rho u) + \operatorname{div}(\rho u \otimes u)) dx dt$$

tends to

$$- \int_0^T \int_\Omega \psi_t \rho u_m + \nabla \psi \cdot (\rho u \otimes u_m + \psi (\partial_t \phi_m(\rho) + u \cdot \nabla \phi_m(\rho)) \rho u) dx dt$$

as  $\varepsilon \rightarrow 0$ .

*Proof.* By Lemma 3.1, we can show that

$$\int_0^T \int_\Omega [\psi \phi_m(\rho)]_\varepsilon \partial_t(\rho u) dx dt \rightarrow - \int_0^T \int_\Omega \partial_t \psi \rho u_m + \psi \partial_t \phi_m(\rho) \rho u dx dt.$$

For the second term, we have

$$\begin{aligned} &\int_0^T \int_\Omega [\psi \phi_m(\rho)]_\varepsilon \operatorname{div}(\rho u \otimes u) dx dt = \int_0^T \int_\Omega \psi \phi_m(\rho) [\operatorname{div}(\rho u \otimes u)]_\varepsilon dx dt \\ &= \left( \int_0^T \int_\Omega \psi \phi_m(\rho) [\operatorname{div}(\rho u \otimes u)]_\varepsilon dx dt - \int_0^T \int_\Omega \psi \phi_m(\rho) [\operatorname{div}(\rho u \otimes u)]_\varepsilon^x dx dt \right) \\ &\quad + \int_0^T \int_\Omega \psi \phi_m(\rho) [\operatorname{div}(\rho u \otimes u)]_\varepsilon^x dx dt \\ &= R_1 + R_2, \end{aligned}$$

where  $[f(t, x)]_\varepsilon = f(t, x) * \eta_\varepsilon(t, x)$  and  $[f(t, x)]_\varepsilon^x = f * \eta_\varepsilon(x)$  with  $\varepsilon > 0$  a small enough number. We write  $R_1$  in the following way

$$\begin{aligned} R_1 &= \int_0^T \int_\Omega \psi \phi_m(\rho) [\operatorname{div}(\rho u \otimes u)]_\varepsilon dx dt - \int_0^T \int_\Omega \psi \phi_m(\rho) [\operatorname{div}(\rho u \otimes u)]_\varepsilon^x dx dt \\ &= \int_0^T \int_\Omega \psi \nabla \phi_m(\rho) : [\rho u \otimes u]_\varepsilon dx dt - \int_0^T \int_\Omega \psi \nabla \phi_m(\rho) : [\rho u \otimes u]_\varepsilon^x dx dt. \end{aligned}$$

Thanks to Lemma 3.3,  $\rho|u|^2 \in L^2(0, T; L^{10/7}(\Omega))$  and  $\psi \nabla \phi_m(\rho) \in L^4((0, T) \times \Omega)$ , we conclude that  $R_1 \rightarrow 0$  as  $\varepsilon \rightarrow 0$ . Meanwhile, we can apply Lemma 3.1 to  $R_2$  directly, thus

$$\begin{aligned} &\int_0^T \int_\Omega \psi \phi_m(\rho) [\operatorname{div}(\rho u \otimes u)]_\varepsilon^x dx dt \\ &= \left( \int_0^T \int_\Omega \psi \phi_m(\rho) [\operatorname{div}(\rho u \otimes u)]_\varepsilon^x dx dt - \int_0^T \int_\Omega \psi \phi_m(\rho) \operatorname{div}(\rho u \otimes [u]_\varepsilon^x) dx dt \right) \\ &+ \int_0^T \int_\Omega \psi \phi_m(\rho) \operatorname{div}(\rho u \otimes [u]_\varepsilon^x) dx dt \\ &= R_{21} + R_{22}. \end{aligned}$$

By Lemma 3.1, we have  $R_{21} \rightarrow 0$  as  $\varepsilon \rightarrow 0$ . The term  $R_{22}$  will be calculated in the following way,

$$\begin{aligned} &\int_0^T \int_\Omega \psi \phi_m(\rho) \operatorname{div}(\rho u \otimes [u]_\varepsilon^x) dx dt \\ &= \int_0^T \int_\Omega \psi \phi_m(\rho) \operatorname{div}(\rho u) [u]_\varepsilon^x dx dt + \int_0^T \int_\Omega \psi \phi_m(\rho) \rho u \cdot \nabla [u]_\varepsilon^x dx dt \\ &= \int_0^T \int_\Omega \psi \operatorname{div}(\rho u) [u_m]_\varepsilon^x dx dt + \int_0^T \int_\Omega \psi \rho u \nabla(\phi_m(\rho) [u]_\varepsilon^x) dx dt - \\ &\int_0^T \int_\Omega \psi [u]_\varepsilon^x \cdot \nabla \phi_m(\rho) \rho u dx dt \\ &= - \int_0^T \int_\Omega \nabla \psi \rho u \otimes [u_m]_\varepsilon^x dx dt - \int_0^T \int_\Omega \psi \cdot [u]_\varepsilon^x \nabla \phi_m(\rho) \rho u dx dt, \end{aligned}$$

which tends to

$$- \int_0^T \int_\Omega \nabla \psi \rho u \otimes u_m dx dt - \int_0^T \int_\Omega \psi \cdot u \nabla \phi_m(\rho) \rho u dx dt,$$

as  $\varepsilon \rightarrow 0$ .

□

For the other terms in the momentum equation, we can follow the same way as above method for (3.6) to have

$$\begin{aligned}
& \int_0^T \int_{\Omega} (\psi_t \rho u_m + \nabla \psi \cdot (\rho u \otimes u_m - 2\phi_m(\rho)(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r) + \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)}\mathbb{S}_\mu + r\mathbb{S}_r)\text{Id})) \\
& + \int_0^T \int_{\Omega} \psi(\partial_t \phi_m(\rho) + u \cdot \nabla \phi_m(\rho)) \rho u \\
& - \int_0^T \int_{\Omega} 2\psi(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r) + \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)}\mathbb{S}_\mu + r\mathbb{S}_r)\text{Id}) \nabla \phi_m(\rho) + \psi \phi_m(\rho) F(\rho, u) \, dx \, dt \\
& = 0.
\end{aligned}$$

Thanks to (3.6), we have

$$\begin{aligned}
& \int_0^T \int_{\Omega} (\psi_t \rho u_m + \nabla \psi \cdot (\rho u \otimes u_m - 2\phi_m(\rho)(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r) + \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r))\text{Id}) \\
& - \int_0^T \int_{\Omega} \psi \phi'_m(\rho) \frac{\rho}{\sqrt{\mu(\rho)}} \text{Tr}(\mathbb{T}_\mu) \rho u - \psi \phi_m(\rho) F(\rho, u) \\
& - \int_0^T \int_{\Omega} 2\psi(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r) + \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r))\text{Id}) \nabla \phi_m(\rho) \, dx \, dt = 0.
\end{aligned} \tag{3.7}$$

The goal of this subsection is to derive the formulation of renormalized solution following the idea in [34]. We choose the function  $[\psi \varphi'([u_m]_\varepsilon)]_\varepsilon$  as a test function in (3.7). As the same argument of Lemma 3.5, we can show that

$$\begin{aligned}
& \int_0^T \int_{\Omega} (\partial_t [\psi \varphi'([u_m]_\varepsilon)]_\varepsilon \rho u_m + \nabla [\psi \varphi'([u_m]_\varepsilon)]_\varepsilon : (\rho u \otimes u_m)) \, dx \, dt \\
& \rightarrow \int_0^T \int_{\Omega} (\rho \varphi(u_m) \psi_t + \rho u \otimes \varphi(u_m) \nabla \psi) \, dx \, dt,
\end{aligned}$$

and

$$\begin{aligned}
& \int_0^T \int_{\Omega} \nabla [\psi \varphi'([u_m]_\varepsilon)]_\varepsilon \left( -2\phi_m(\rho)(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r) + \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)}\mathbb{S}_\mu + r\mathbb{S}_r))\text{Id} \right) \\
& + [\psi \varphi'([u_m]_\varepsilon)]_\varepsilon \left( -\phi'_m(\rho) \frac{\rho}{\sqrt{\mu(\rho)}} \text{Tr}(\mathbb{T}_\mu) \rho u \right. \\
& \left. - 2(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r) + \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r)\text{Id})) \nabla \phi_m(\rho) + \phi_m(\rho) F(\rho, u) \right) \, dx \, dt \\
& \rightarrow \int_0^T \int_{\Omega} \nabla (\psi \varphi'(u_m)) \left( -2\phi_m(\rho)(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r) + \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r))\text{Id}) \right) \\
& + \psi \varphi'(u_m) \left( -\phi'_m(\rho) \frac{\rho}{\sqrt{\mu(\rho)}} \text{Tr}(\mathbb{T}_\mu) \rho u \right. \\
& \left. - 2(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r) + \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)}\mathbb{S}_\mu + r\mathbb{S}_r)) \nabla \phi_m(\rho) + \phi_m(\rho) F(\rho, u) \right) \, dx \, dt
\end{aligned}$$

as  $\varepsilon$  goes to zero. Putting these two limits together, we have

$$\begin{aligned}
& \int_0^T \int_{\Omega} (\rho \varphi(u_m) \psi_t + \rho u \otimes \varphi(u_m) \nabla \psi) \\
& + \nabla \psi \varphi'(u_m) (-2\phi_m(\rho)(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r) + \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)}\mathbb{S}_\mu + r\mathbb{S}_r))) \\
& + \psi \varphi''(u_m) \nabla u_m (-\phi_m(\rho)2(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r) + \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)}\mathbb{S}_\mu + r\mathbb{S}_r))) \quad (3.8) \\
& + \psi \varphi'(u_m) (-\phi'_m(\rho) \frac{\rho}{\sqrt{\mu(\rho)}} \text{Tr}(\mathbb{T}_\mu) \rho u - 2(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r) \\
& + \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)}\mathbb{S}_\mu + r\mathbb{S}_r)) \nabla \phi_m(\rho) + \phi_m(\rho) F(\rho, u)) \, dx \, dt = 0.
\end{aligned}$$

Now we should pass to the limit in (3.8) as  $m$  goes to infinity. To this end, we should keep the following convergences in mind:

$$\begin{aligned}
& \phi_m(\rho) \text{ converges to } 1, \quad \text{for almost every } (t, x) \in \mathbb{R}^+ \times \Omega, \\
& u_m \text{ converges to } u, \quad \text{for almost every } (t, x) \in \mathbb{R}^+ \times \Omega, \quad (3.9) \\
& |\rho \phi'_m(\rho)| \leq 2, \quad \text{and converges to 0 for almost every } (t, x) \in \mathbb{R}^+ \times \Omega.
\end{aligned}$$

We can find that

$$\begin{aligned}
& \sqrt{\mu(\rho)} \nabla u_m = \sqrt{\mu(\rho)} \nabla (\phi_m(\rho) u) = \phi_m(\rho) \sqrt{\mu(\rho)} \nabla u + \phi'_m(\rho) \sqrt{\mu(\rho)} u \nabla \rho \\
& = \frac{\phi_m(\rho)}{\sqrt{\mu(\rho)}} (\nabla(\mu(\rho) u) - \sqrt{\rho} u \cdot \frac{\nabla \mu(\rho)}{\sqrt{\rho}}) + \frac{\sqrt{\rho}}{\mu(\rho)^{\frac{3}{4}}} (\frac{\sqrt{\mu(\rho)}}{\rho} \mu'(\rho) \nabla \rho) (\frac{\rho^{\frac{1}{4}}}{(\mu'(\rho))^{\frac{1}{4}}} u) (\phi'_m(\rho) \frac{\mu(\rho)^{\frac{3}{4}} \rho^{\frac{1}{4}}}{(\mu'(\rho))^{\frac{3}{4}}}) \\
& = \phi_m(\rho) \mathbb{T}_\mu + \frac{\sqrt{\rho}}{\mu(\rho)^{\frac{3}{4}}} (\frac{\sqrt{\mu(\rho)}}{\rho} \mu'(\rho) \nabla \rho) (\frac{\rho^{\frac{1}{4}}}{(\mu'(\rho))^{\frac{1}{4}}} u) (\phi'_m(\rho) \frac{\mu(\rho)^{\frac{3}{4}} \rho^{\frac{1}{4}}}{(\mu'(\rho))^{\frac{3}{4}}}) \\
& = A_{1m} + A_{2m}.
\end{aligned}$$

Note that

$$|\phi'_m(\rho) \frac{\mu(\rho)^{\frac{3}{4}} \rho^{\frac{1}{4}}}{(\mu'(\rho))^{\frac{3}{4}}}| \leq C |\phi'_m(\rho) \rho|,$$

thus  $\phi'_m(\rho) \mu(\rho)^{\frac{3}{4}} \rho^{\frac{1}{4}} / (\mu(\rho)')^{\frac{3}{4}}$  converges to zero for almost every  $(t, x)$ . Thus, the Dominated convergence theorem yields that  $A_{2m}$  converges to zero as  $m \rightarrow \infty$ . Meanwhile, the Dominated convergence theorem also gives us  $A_{1m}$  converges to  $\mathbb{T}_\mu$  in  $L^2_{t,x}$ . Hence, with (3.9) at hand, letting  $m \rightarrow \infty$  in (3.8), one obtains that

$$\begin{aligned}
& \int_0^T \int_{\Omega} (\rho \varphi(u) \psi_t + \rho u \otimes \varphi(u) \nabla \psi) - 2 \nabla \psi \varphi'(u) ((\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r) \\
& + \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}(\sqrt{\mu(\rho)}(\mathbb{S}_\mu + r\mathbb{S}_r)) \text{Id}) - 2 \psi \varphi''(u) \mathbb{T}_\mu ((\mathbb{S}_\mu + r\mathbb{S}_r) \\
& + \frac{\lambda(\rho)}{2\mu(\rho)} \text{Tr}((\mathbb{S}_\mu + r\mathbb{S}_r) \text{Id}) + \psi \varphi'(u) F(\rho, u)) \, dx \, dt = 0.
\end{aligned}$$

From now, we denote  $R_\varphi = 2\psi\varphi''(u)\mathbb{T}_\mu((\mathbb{S}_\mu + r\mathbb{S}_r) + \frac{\lambda(\rho)}{2\mu(\rho)}\text{Tr}((\mathbb{S}_\mu + r\mathbb{S}_r)\text{Id}))$ . This ends the proof of Theorem 1.3.  $\square$

#### 4. RENORMALIZED SOLUTIONS AND WEAK SOLUTIONS

The main goal of this section is the proof of Theorem 1.1 that obtains the existence of renormalized solutions of the Navier-Stokes equations without the additional terms, thus the existence of weak solutions of the Navier-Stokes equations.

**4.1. Renormalized solutions.** In this subsection, we will show the existence of renormalized solutions. To this end, we need the following lemma of stability.

**Lemma 4.1.** *For any fixed  $\alpha_1 < \alpha_2$  as in (1.9) and consider sequences  $\delta_n, r_{0n}, r_{1n}$  and  $r_{2n}$ , such that  $r_{i,n} \rightarrow r_i \geq 0$  with  $i = 0, 1, 2$  and then  $\delta_n \rightarrow \delta \geq 0$ . Consider a family of  $\mu_n : \mathbb{R}^+ \rightarrow \mathbb{R}^+$  verifying (1.9) and (1.10) for the fixed  $\alpha_1$  and  $\alpha_2$  such that*

$$\mu_n \rightarrow \mu \quad \text{in } C^0(\mathbb{R}^+).$$

*Then, if  $(\rho_n, u_n)$  verifies (1.23)-(1.26), up to a subsequence, still denoted  $n$ , the following convergences hold.*

1. *The sequence  $\rho_n$  converges strongly to  $\rho$  in  $C^0(0, T; L^p(\Omega))$  for any  $1 \leq p < \gamma$ .*
2. *The sequence  $\mu_n(\rho_n)u_n$  converges to  $\mu(\rho)u$  in  $L^\infty(0, T; L^p(\Omega))$  for  $p \in [1, 3/2)$ .*
3. *The sequence  $(\mathbb{T}_\mu)_n$  converges to  $\mathbb{T}_\mu$  weakly in  $L^2(0, T; L^2(\Omega))$ .*
4. *For every function  $H \in W^{2,\infty}(\mathbb{R}^d)$  and  $0 < \alpha < 2\gamma/\gamma + 1$ , we have that  $\rho_n^\alpha H(u_n)$  converges to  $\rho^\alpha H(u)$  strongly in  $L^p(0, T; \Omega)$  for  $1 \leq p < \frac{2\gamma}{(\gamma+1)\alpha}$ . In particular,  $\sqrt{\mu(\rho_n)}H(u_n)$  converges to  $\sqrt{\mu(\rho)}H(u)$  strongly in  $L^\infty(0, T; L^2(\Omega))$ .*

*Proof.* Using (1.26), the Aubin-Lions lemma gives us, up to a subsequence,

$$\mu_n(\rho_n) \rightarrow \tilde{\mu} \quad \text{in } C^0(0, T; L^q(\Omega))$$

for any  $q < \frac{3}{2}$ . But

$$\sup |\mu_n - \mu| \rightarrow 0$$

as  $n \rightarrow \infty$ . Thus, we have

$$\mu_n(\rho_n) \rightarrow \tilde{\mu}(t, x) \quad \text{in } C^0([0, T]; L^q(\Omega)), \quad (4.1)$$

so up to a subsequence,

$$\mu(\rho_n) \rightarrow \tilde{\mu}(t, x) \quad \text{a. e.}$$

Note that  $\mu$  is increasing function, so it is invertible, and  $\mu^{-1}$  is continuous. This implies that  $\rho_n \rightarrow \rho$  a.e. with  $\mu(\rho) = \tilde{\mu}(t, x)$ . Together with (4.1) and  $\rho_n$  is uniformly bounded in  $L^\infty(0, T; L^\gamma(\Omega))$ , thus we get part 1.

Note that

$$\nabla \frac{\mu(\rho_n)}{\sqrt{\rho_n}} = \frac{\sqrt{\rho_n} \nabla \mu(\rho_n)}{\rho_n} - \frac{\mu(\rho_n) \nabla \rho_n}{2\rho_n \sqrt{\rho_n}},$$

thus

$$\left| \nabla \frac{\mu(\rho_n)}{\sqrt{\rho_n}} \right| \leq C |\sqrt{\rho_n}| \left| \frac{\nabla \mu(\rho_n)}{\sqrt{\rho_n}} \right|,$$

so  $\nabla \frac{\mu(\rho_n)}{\sqrt{\rho_n}}$  is bounded in  $L^\infty(0, T; L^2(\Omega))$ , thanks to (1.23). Using (1.26), we have  $\frac{\mu(\rho_n)}{\sqrt{\rho_n}}$  is bounded in  $L^\infty(0, T; W^{1,2}(\Omega))$ , thus it is uniformly bounded in  $L^\infty(0, T; L^6(\Omega))$ .

On the other hand,  $\sqrt{\rho_n}u_n$  is uniformly bounded in  $L^\infty(0, T; L^2(\Omega))$ . From Lemma 2.4, we have

$$\mu(\rho_n)u_n = \frac{\mu(\rho_n)}{\sqrt{\rho_n}}\sqrt{\rho_n}u_n \rightarrow \mu(\rho)u \quad \text{in } L^\infty(0, T; L^q(\Omega))$$

for any  $1 \leq q < \frac{3}{2}$ . Since  $(\mathbb{T}_\mu)_n$  is bounded in  $L^2(0, T; L^2(\Omega))$ , and so, up to a subsequence, converges weakly in  $L^2(0, T; L^2(\Omega))$  to a function  $\mathbb{T}_\mu$ . Using Lemma 2.4, this gives part 4.  $\square$

With Lemma 4.1, we are able to recover the renormalized solutions of Navier-Stokes equations without any additional term by letting  $n \rightarrow \infty$  in (3). We state this result in the following Lemma. In this lemma, we fix  $\mu$  such that  $\varepsilon_1 > 0$ .

**Lemma 4.2.** *For any fixed  $\varepsilon_1 > 0$ , there exists a renormalized solution  $(\sqrt{\rho}, \sqrt{\rho}u)$  to the initial value problem (1.1)-(1.2).*

*Proof.* We can use Lemma 4.1 to pass to the limits for the extra terms. We will have to follow this order: let  $r_2$  goes to zero, then  $r_1$  tends to zero, after that  $r_0, \delta, r$  go to zero together.

– If  $r_2 = r_2(n) \rightarrow 0$ , we just write

$$r_2 \frac{\rho_n}{\mu'(\rho_n)} |u_n|^2 u_n = r_2^{\frac{1}{4}} \left( \frac{\rho_n}{\mu'(\rho_n)} \right)^{\frac{1}{4}} \left( \frac{\rho_n}{\mu'(\rho_n)} \right)^{\frac{3}{4}} |u_n|^2 u_n,$$

and  $\mu'(\rho_n) \geq \varepsilon_1 > 0$ , so  $\left( \frac{\rho_n}{\mu'(\rho_n)} \right)^{\frac{1}{4}} \leq C|\rho_n|^{\frac{1}{4}}$ , thus,

$$r_2 \frac{\rho_n}{\mu'(\rho_n)} |u_n|^2 u_n \rightarrow 0 \quad \text{in } L^{\frac{4}{3}}(0, T; L^{\frac{6}{5}}(\Omega)).$$

– For  $r_1 = r_1(n) \rightarrow 0$ ,

$$|r_1 \rho_n |u_n| u_n| \leq r^{\frac{1}{3}} \rho_n^{\frac{1}{3}} r^{\frac{2}{3}} \rho_n^{\frac{2}{3}} |u_n|^2,$$

which converges to zero in  $L^{\frac{3}{2}}(0, T; L^{\frac{9}{7}}(\Omega))$  using the drag term control in the energy and the information on the pressure law  $P(\rho) = a\rho^\gamma$ .

– For  $r_0 = r_0(n) \rightarrow 0$ , it is easy to conclude that

$$r_0 u_n \rightarrow 0 \quad \text{in } L^2((0, T) \times \Omega).$$

– We now consider the limit  $r \rightarrow 0$  of the term

$$r \rho_n \nabla \left( \sqrt{K(\rho_n)} \Delta \left( \int_0^{\rho_n} \sqrt{K(s)} ds \right) \right).$$

Note the following identity

$$\rho_n \nabla \left( \sqrt{K(\rho_n)} \Delta \left( \int_0^{\rho_n} \sqrt{K(s)} ds \right) \right) = 2 \operatorname{div} \left( \mu(\rho_n) \nabla^2 (2s(\rho_n)) \right) + \nabla \left( \lambda(\rho_n) \Delta (2s(\rho_n)) \right),$$

we only need to focus on  $\operatorname{div}(\mu(\rho_n)\nabla^2(2s(\rho_n)))$  since the same argument holds for the other term. Since

$$\begin{aligned} r \int_{\Omega} \operatorname{div}(\mu(\rho_n)\nabla^2(2s(\rho_n)))\psi \, dx \\ = r \int_{\Omega} \frac{\rho_n}{\mu_n} \nabla Z(\rho_n) \otimes \nabla Z(\rho_n) \nabla \psi \, dx + r \int_{\Omega} \mu_n \nabla s(\rho_n) \Delta \psi \, dx \\ = r \int_{\Omega} \frac{\rho_n}{\mu_n} \nabla Z(\rho_n) \otimes \nabla Z(\rho_n) \nabla \psi \, dx + r \int_{\Omega} \sqrt{\mu_n} \nabla Z(\rho_n) \Delta \psi \, dx, \end{aligned}$$

the first term can be controlled as

$$\left| r \int_{\Omega} \sqrt{\mu_n} \nabla Z(\rho_n) \Delta \psi \, dx \right| \leq Cr^{\frac{1}{2}} \|\sqrt{\mu(\rho_n)}\|_{L^2(0,T;L^2(\Omega))} \|\sqrt{r} \nabla Z(\rho_n)\|_{L^2(0,T;L^2(\Omega))} \rightarrow 0,$$

thanks to (1.25) and (1.26); and the second term as

$$\begin{aligned} \left| \int_{\Omega} \frac{\rho_n}{\mu_n} \nabla Z(\rho_n) \otimes \nabla Z(\rho_n) \nabla \psi \, dx \right| &\leq \sqrt{r} \sqrt{r} \int_{\Omega} \sqrt{\mu(\rho_n)} \frac{\rho_n}{\mu(\rho_n)^{\frac{3}{2}}} |\nabla Z(\rho_n)|^2 |\nabla \psi| \, dx \\ &\leq C \|\sqrt{r} \frac{\rho_n}{\mu(\rho_n)^{\frac{3}{2}}} |\nabla Z(\rho_n)|^2\|_{L^2(0,T;L^2(\Omega))} \|\sqrt{\mu(\rho_n)}\|_{L^2(0,T;L^2(\Omega))} r^{\frac{1}{2}} \rightarrow 0. \end{aligned}$$

– Concerning the quantity  $\delta \rho^{10}$ , thanks to  $\mu'_{\varepsilon_1}(\rho) \geq \varepsilon_1 > 0$ ,  $\sqrt{\delta} |\nabla \rho^5|$  is uniformly bounded in  $L^2(0,T;L^2(\Omega))$ . This gives us that  $\delta^{\frac{1}{30}} \rho$  is uniformly bounded in  $L^{10}(0,T;L^{30}(\Omega))$ . Thus, we have

$$\left| \int_0^T \int_{\Omega} \delta \rho^{10} \nabla \psi \, dx \, dt \right| \leq C(\psi) \delta^{\frac{2}{3}} \|\delta^{\frac{1}{3}} \rho^{10}\|_{L^1(0,T;L^3(\Omega))} \rightarrow 0$$

as  $\delta \rightarrow 0$ .

With Lemma 4.1 at hand, we are ready to recover the renormalized solutions to (1.1)-(1.2). By part 1 and part 2 of Lemma 4.1, we are able to pass to the limits on the continuity equation. Thanks to part 4 of Lemma 4.1,

$$\sqrt{\mu(\rho_n)} \varphi'(u_n) \rightarrow \sqrt{\mu(\rho)} \varphi'(u) \quad \text{in } L^\infty(0,T;L^2(\Omega)).$$

With the help of Lemma 2.2, we can pass to the limit on pressure, thus we can recover the renormalized solutions.  $\square$

**4.2. Recover weak solutions from renormalized solutions.** In this part, we can recover the weak solutions from the renormalized solutions constructed in Lemma 4.2. Now we show that Lemma 4.2 is valid without the condition  $\varepsilon_1 > 0$ . For such a  $\mu$ , we construct a sequence  $\mu_n$  converging to  $\mu$  in  $C^0(\mathbb{R}^+)$  and such that  $\varepsilon_{1n} = \inf \mu'_n > 0$ . Lemma 4.1 shows that, up to a subsequence,

$$\rho_n \rightarrow \rho \quad \text{in } C^0(0,T;L^p(\Omega))$$

and

$$\rho_n u_n \rightarrow \rho u \quad \text{in } L^\infty(0,T;L^{\frac{p+1}{2p}}(\Omega))$$

for any  $1 \leq p < \gamma$ , where  $(\rho, \sqrt{\rho} u)$  is a renormalized solution to (1.1).

Now, we want to show that this renormalized solution is also a weak solution in the sense of Definition 1.2. To this end, we introduce a non-negative smooth function  $\Phi : \mathbb{R} \rightarrow \mathbb{R}$  such that it has a compact support and  $\Phi(s) = 1$  for any  $-1 \leq s \leq 1$ . Let  $\tilde{\Phi}(s) = \int_0^s \Phi(r) dr$ , we define

$$\varphi_n(y) = n\tilde{\Phi}\left(\frac{y_1}{n}\right)\Phi\left(\frac{y_2}{n}\right)\Phi\left(\frac{y_3}{n}\right)$$

for any  $y = (y_1, y_2, y_3) \in \mathbb{R}^3$ . Note that  $\varphi_n$  is bounded in  $W^{2,\infty}(\mathbb{R}^3)$  for any fixed  $n > 0$ ,  $\varphi_n(y)$  converges everywhere to  $y_1$  as  $n$  goes to infinity,  $\nabla\varphi_n$  is uniformly bounded in  $n$  and converges everywhere to unit vector  $(1, 0, \dots, 0)$ , and we have the following control

$$\|\nabla\nabla\varphi_n\|_{L^\infty(\mathbb{R}^3)} \leq \frac{C}{n} \rightarrow 0$$

as  $n$  goes to infinity. This allows us to control the measures in Definition 1.1 as follows

$$\|R_{\varphi_n}\|_{\mathcal{M}(\mathbb{R}^+ \times \Omega)} + \|\overline{R}_{\varphi_n}^1\|_{\mathcal{M}(\mathbb{R}^+ \times \Omega)} + \|\overline{R}_{\varphi_n}^2\|_{\mathcal{M}(\mathbb{R}^+ \times \Omega)} \leq C\|\nabla\nabla\varphi_n\|_{L^\infty(\mathbb{R}^3)} \rightarrow 0$$

as  $n$  goes to infinity. Using this function  $\varphi_n$  in the equation of Definition 1.1, the Lebesgue's Theorem gives us the equation on  $\rho u_1$  in Definition 1.2 by passing limits as  $n$  goes to infinity. In this way, we are able to get full vector equation on  $\rho u$  by permuting the directions. Applying the Lebesgue's dominated convergence Theorem, one obtains (1.4) by passing to limit in (1.12) with  $i = 1$  and the function  $\varphi_n$ . Thus, we have shown that the renormalized solution is also a weak solution.

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