ERROR ESTIMATES FOR A NUMERICAL METHOD FOR THE COMPRESSIBLE NAVIER–STOKES SYSTEM ON SUFFICIENTLY SMOOTH DOMAINS *, **, ***

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Abstract. We derive an a priori error estimate for the numerical solution obtained by time and space discretization by the finite volume/finite element method of the barotropic Navier–Stokes equations. The numerical solution on a convenient polyhedral domain approximating a sufficiently smooth bounded domain is compared with an exact solution of the barotropic Navier–Stokes equations with a bounded density. The result is unconditional in the sense that there are no assumed bounds on the numerical solution. It is obtained by the combination of discrete relative energy inequality derived in [T. Gallouët, R. Herbin, D. Maltese and A. Novotný, IMA J. Numer. Anal. 36 (2016) 543–592.] and several recent results in the theory of compressible Navier–Stokes equations concerning blow up criterion established in [Y. Sun, C. Wang and Z. Zhang, J. Math. Pures Appl. 95 (2011) 36–47] and weak strong uniqueness principle established in [E. Feireisl, B.J. Jin and A. Novotný, J. Math. Fluid Mech. 14 (2012) 717–730].

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1. Introduction

We consider the compressible Navier–Stokes equations in the barotropic regime in a space-time cylinder \( Q_T = (0, T) \times \Omega \), where \( T > 0 \) is arbitrarily large and \( \Omega \subset \mathbb{R}^3 \) is a bounded domain:

\[
\begin{align*}
\partial_t \varrho + \text{div}_x(\varrho \mathbf{u}) & = 0, \\
\partial_t(\varrho \mathbf{u}) + \text{div}_x(\varrho \mathbf{u} \otimes \mathbf{u}) + \nabla_x p(\varrho) & = \text{div}_x S(\nabla_x \mathbf{u}).
\end{align*}
\]

In equations (1.1) and (1.2) \( \varrho = \varrho(t, x) \geq 0 \) and \( \mathbf{u} = \mathbf{u}(t, x) \in \mathbb{R}^3 \), \( t \in [0, T) \), \( x \in \Omega \) are the unknown density and velocity fields, while \( S \) and \( p \) are the viscous stress and pressure characterizing the fluid via the constitutive relations

\[
S(\nabla_x \mathbf{u}) = \mu \left( \nabla_x \mathbf{u} + \nabla_x^T \mathbf{u} - \frac{2}{3} \text{div}_x \mathbf{u} \mathbf{I} \right), \quad \mu > 0,
\]

\[
p \in C^2(0, \infty) \cap C^1[0, \infty), \quad p(0) = 0, \quad p'(\varrho) > 0 \quad \text{for all} \quad \varrho \geq 0, \quad \lim_{\varrho \to 0^+} \frac{p'(\varrho)}{\varrho^{\gamma - 1}} = p_\infty > 0,
\]

where \( \gamma \geq 1 \).

The assumption \( p'(0) > 0 \) in (1.4) excludes the constitutive laws for pressure behaving as \( \varrho^\gamma \) as \( \varrho \to 0^+ \). The error estimates stated in Theorem 3.2 however still hold in the case \( \lim_{\varrho \to 0^+} \frac{p'(\varrho)}{\varrho^{\gamma - 1}} = 0 \), in particular for the isentropic pressure laws \( p(\varrho) = \varrho^\gamma \). The proof contains some additional technical difficulties, see also Remark 3.2.

Equations (1.1) and (1.2) are completed with the no-slip boundary conditions

\[
\mathbf{u}|_{\partial \Omega} = 0,
\]

and initial conditions

\[
\varrho(0, \cdot) = \varrho_0, \quad \mathbf{u}(0, \cdot) = \mathbf{u}_0, \quad \varrho_0 > 0 \text{ in } \overline{\Omega}.
\]

We notice that under assumption (1.3), we may write

\[
\text{div}_x S(\nabla_x \mathbf{u}) = \mu \Delta \mathbf{u} + \frac{\mu}{3} \nabla_x \text{div}_x \mathbf{u}.
\]

The results on error estimates for numerical schemes for the compressible Navier–Stokes equations are in the mathematical literature on short supply. We refer the reader to papers of Liu [39,40], Jovanović [28], Gallouet et al. [22].

In [22] the authors have developed a methodology of deriving unconditional error estimates for the numerical schemes to the compressible Navier–Stokes equations (1.1)–(1.6) and applied it to the numerical scheme (3.5)–(3.7) discretizing the system on polyhedral domains. They have obtained error estimates for the discrete solution with respect to a classical solution of the system on the same (polyhedral) domain. In spite of the fact that [22] provides the first and to the best of our knowledge so far the sole error estimate for discrete solutions of a finite volume/finite element approximation to a model of compressible fluids that does not need any assumed bounds on the numerical solution itself, it has two weak points: 1) The existence of classical solutions on at least a short time interval to the compressible Navier–Stokes equations is known for smooth \( C^3 \) domains (see [43] or [4]) but may not be in general true on the polyhedral domains. 2) The numerical solutions are compared with the classical exact solutions (as is usual in any previous existing mathematical literature). In this paper we address both points raised above and to a certain extent remove the limitations of the theory presented in [22].

More precisely, we generalize the result of Gallouet et al. ([22], Thm. 3.1) in two directions:

(1) The physical domain \( \Omega \) filled by the fluid and the numerical domain \( \Omega_h, h > 0 \) approximating the physical domain do not need to coincide.
(2) If the physical domain is sufficiently smooth (at least of class \( C^3 \)) and the \( C^3 \)-initial data satisfy natural compatibility conditions, we are able to obtain the unconditional error estimates with respect to any weak exact solution with bounded density.

As in [22], and in contrast with any other literature dealing with finite volume or mixed finite volume/finite element methods for compressible fluids \([3, 10, 16–19, 23–25, 28, 29, 32–35, 44]\) and others) this result does not require any assumed bounds on the discrete solution: the sole bounds needed for the result are those provided by the numerical scheme. Moreover, in contrast with [22] and with all above mentioned papers, the exact solution is solely weak solution with bounded density. This seemingly weak hypothesis is compensated by the regularity and compatibility conditions imposed on initial data that make possible a (sophisticated) bootstrapping argument showing that weak solutions with bounded density are in fact strong solutions in the class investigated in [22]. These results are achieved by using the following tools:

(1) The technique introduced in [22] modified in order to accommodate non-zero velocity of the exact sample solution on the boundary of the numerical domain.

(2) Three fundamental recent results from the theory of compressible Navier–Stokes equations, namely

- Local in time existence of strong solutions in class \((2.11)\) and \((2.12)\) by Cho et al. [4].
- Weak strong uniqueness principle proved in [13] (see also [14]).
- Blow up criterion for strong solutions in the class \((2.11)\) and \((2.12)\) by Sun et al. [41].

The three above mentioned items allow to show that the weak solution with bounded density emanating from the sufficiently smooth initial data is in fact a strong solution defined on the large time interval \([0, T]\). The last item allows to bootstrap the strong solution in the classCho et al. [4] to the class needed for the error estimates in [22], provided a certain compatibility condition for the initial data is satisfied.

2. PRELIMINARIES

2.1. Weak and strong solutions to the Navier–Stokes system

We introduce the notion of the weak solution to system \((1.1)–(1.4)\):

**Definition 2.1 (Weak solutions).** Let \( \rho_0 : \Omega \to [0, +\infty) \) and \( u_0 : \Omega \to \mathbb{R}^3 \) with finite energy \( E_0 = \int_\Omega \frac{1}{2} \rho_0 |u_0|^2 + H(\rho_0) \, dx \) and finite mass \( 0 < M_0 = \int_\Omega \rho_0 \, dx \). We shall say that the pair \((\rho, u)\) is a weak solution to the problem \((1.1)–(1.6)\) emanating from the initial data \((\rho_0, u_0)\) if:

(a) \( \rho \in C^{\text{weak}}_{\text{weak}}([0, T]; L^a(\Omega)) \), for a certain \( a > 1 \), \( \rho \geq 0 \) a.e. in \((0, T)\), and \( u \in L^2(0, T; W^{1,2}_0(\Omega; \mathbb{R}^3))\).

(b) the continuity equation \((1.1)\) is satisfied in the following weak sense

\[
\int_0^T \int_\Omega \rho \varphi \, dx \, dt = \int_0^T \int_\Omega \left( \rho \varphi_t + \rho u \cdot \nabla \varphi \right) \, dx \, dt, \quad \forall \tau \in [0, T], \forall \varphi \in C^\infty_c([0, T] \times \overline{\Omega}).
\]  

(2.1)

(c) \( \rho u \in C^{\text{weak}}_{\text{weak}}([0, T]; L^b(\Omega; \mathbb{R}^3)) \), for a certain \( b > 1 \), and the momentum equation \((1.2)\) is satisfied in the weak sense,

\[
\int_0^T \int_\Omega \rho u \cdot \varphi \, dx \, dt = \int_0^T \int_\Omega \left( \rho u \partial_t \varphi + \rho u \cdot \nabla \varphi + p(\rho) \nabla \varphi \right) \, dx \, dt - \int_0^T \int_\Omega \left( \mu \nabla u : \nabla \varphi \right) \, dx \, dt + (\mu + \lambda) \text{div} u \text{div} \varphi \, dx \, dt, \quad \forall \tau \in [0, T], \forall \varphi \in C^\infty_c([0, T] \times \Omega; \mathbb{R}^3).
\]  

(2.2)
(d) The following energy inequality is satisfied

\[
\int_\Omega \left( \frac{1}{2} \rho |\mathbf{u}|^2 + H(\rho) \right) \, dx \bigg|_0^\tau + \int_0^\tau \int_\Omega \left( \mu |\nabla \mathbf{u}|^2 + (\mu + \lambda) \text{div} \mathbf{u} |^2 \right) \, dx \, dt \leq 0, \quad \text{for a.a. } \tau \in (0, T),
\]

with \( H(\rho) = \rho \int_1^\rho \frac{p(z)}{z^2} \, dz \).

Here and hereafter the symbol \( \int_\Omega g \, dx \bigg|_0^\tau \) is meant for \( \int_\Omega g(\tau, x) \, dx - \int_\Omega g_0(x) \, dx \).

In the above definition, we tacitly assume that all the integrals in the formulas (2.1)–(2.3) are defined and we recall that \( C_{\text{weak}}([0, T]; L^a(\Omega)) \) is the space of functions of \( L^\infty([0, T]; L^a(\Omega)) \) which are continuous as functions of time in the weak topology of the space \( L^a(\Omega) \).

We notice that the function \( \rho \mapsto H(\rho) \) is a solution of the ordinary differential equation \( \rho \frac{d}{dt} H'(\rho) - H(\rho) = p(\rho) \) with the constant of integration fixed such that \( H(1) = 0 \).

Note that the existence of weak solutions emanating from the finite energy initial data is well-known on bounded Lipschitz domains provided \( \gamma > 3/2 \), see Lions [38] for ‘large’ values of \( \gamma \), Feireisl and coauthors [12] for \( \gamma > 3/2 \).

**Proposition 2.2.** Suppose the \( \Omega \subset \mathbb{R}^3 \) is a bounded domain of class \( C^3 \). Let \( r, \mathbf{V} \) be a weak solution to problem (1.1)–(1.6) in \( (0, T) \times \Omega \), originating from the initial data

\[
r_0 \in C^3(\overline{\Omega}), \quad r_0 > 0 \text{ in } \overline{\Omega},
\]

\[
\mathbf{V}_0 \in C^3(\overline{\Omega}; \mathbb{R}^3),
\]

satisfying the compatibility conditions

\[
\mathbf{V}_0|_{\partial \Omega} = 0, \quad \nabla_x p(r_0)|_{\partial \Omega} = \text{div}_x \mathbf{V}(\nabla_x \mathbf{V}_0)|_{\partial \Omega},
\]

and such that

\[
0 \leq r \leq \overline{r} \text{ a.a. in } (0, T) \times \Omega.
\]

Then \( r, \mathbf{V} \) is a classical solution satisfying the bounds:

\[
\|1/r\|_{C([0, T] \times \overline{\Omega})} + \|r\|_{C^1([0, T] \times \overline{\Omega})} + \|\partial_t \mathbf{V}\|_{C([0, T]; L^6(\Omega; \mathbb{R}^3))} + \|\partial^2_{tt} r\|_{C([0, T]; L^6(\Omega))} \leq D,
\]

\[
\|\mathbf{V}\|_{C^1([0, T] \times \overline{\Omega}; \mathbb{R}^3)} + \|\mathbf{V}\|_{C([0, T]; C^2(\overline{\Omega}; \mathbb{R}^3))} + \|\partial_t \nabla_x \mathbf{V}\|_{C([0, T]; L^6(\Omega; \mathbb{R}^{3 \times 3}))} + \|\partial^2_{tt} \mathbf{V}\|_{L^2(0, T; L^6(\Omega))} \leq D,
\]

where \( D \) depends on \( \Omega, T, \overline{r}, \) and the initial data \( r_0, \mathbf{V}_0 \) (via \( \|r_0, \mathbf{V}_0\|_{C^3(\overline{\Omega}; \mathbb{R}^3)} \) and \( \min_{x \in \overline{\Omega}} r_0(x) \)).

**Proof.** The proof will be carried over in several steps.

**Step 1.** According to Cho et al. [4], problem (1.1)–(1.6) admits a strong solution unique in the class

\[
r \in C([0, T_M]; W^{1,6}(\Omega)), \quad \partial_t r \in C([0, T_M]; L^6(\Omega)), \quad 1/r \in L^\infty(Q_T),
\]

\[
\mathbf{V} \in C([0, T_M]; W^{2,2}(\Omega; \mathbb{R}^3)) \cap L^2(0, T_M; W^{2,6}(\Omega; \mathbb{R}^3)), \quad \partial_t \mathbf{V} \in L^2(0, T_M; W^{0,2}_{0,1,2}(\Omega; \mathbb{R}^3)).
\]
defined on a time interval $[0, T_M)$, where $T_M > 0$ is finite or infinite and depends on the initial data. Moreover, for any $T_M' < T_M$, there is a constant $c = c(T_M')$ such that
\begin{equation}
\|r\|_{L^\infty(0,T_M';W^{1,6}(\Omega))} + \|\partial_t r\|_{L^\infty(0,T_M';L^6(\Omega))} + \|1/r\|_{L^\infty(Q_T)}
\end{equation}
\begin{equation}
+ \|\nabla r\|_{L^\infty(0,T_M';W^{2,6}(\Omega; R^3))} + \|\nabla V\|_{L^2(0,T_M';W^{2,6}(\Omega; R^3))} + \|\partial_t V\|_{L^2(0,T_M';W^{1,2}(\Omega))}
\leq c \left( \|r_0\|_{W^{1,6}(\Omega)} + \|V_0\|_{W^{2,6}(\Omega)} \right).
\end{equation}

**Step 2.**
By virtue of the weak-strong uniqueness result stated in ([13], Thm. 4.1) (see also [14], Thm. 4.6), the weak solution $r$, $V$ coincides on the time interval $[0, T_M)$ with the strong solution, the existence of which is claimed in the previous step. According to Sun et al. ([41], Thm. 1.3) if $T_M < \infty$ then
\begin{equation}
\limsup_{t \to T_M^-} \|r(t)\|_{L^\infty(\Omega)} = \infty.
\end{equation}
Since (2.8) holds, we infer that $T_M = T$. At this point we conclude that couple $(r, V)$ possesses regularity (2.11) and (2.12) and that the bound (2.13) holds with $c$ dependent only on $T$.

**Step 3.**
Since the initial data enjoy the regularity and compatibility conditions stated in (2.5)–(2.7), a straightforward bootstrap argument gives rise to better bounds, specifically, the solution belongs to the Valli–Zajaczkowski class (see [43], Thm. 2.5) class
\begin{equation}
r \in C([0, T]; W^{3,2}(\Omega)), \quad \partial_t r \in L^2(0, T; W^{2,2}(\Omega)),
\end{equation}
\begin{equation}
V \in C([0, T]; W^{3,2}(\Omega)) \cap L^2(0, T; W^{4,2}(\Omega; R^3)), \quad \partial_t V \in L^2(0, T; W^{2,2}(\Omega; R^3)),
\end{equation}
where, similarly to the previous step, the norms depend only on the initial data, $\overline{\Omega}$, and $T$.

**Step 4.**
We write equation (1.2) in the form
\begin{equation}
\partial_t V - \frac{1}{r} \text{div}_x S(\nabla_x V) = -V \cdot \nabla_x V + \frac{1}{r} \nabla_x p(r),
\end{equation}
where, by virtue of (2.15) and a simple interpolation argument, $V \in C^{1+\nu}([0, T] \times \overline{\Omega}; R^{3 \times 3})$, and, by the same token $r \in C^{1+\nu}([0, T] \times \overline{\Omega})$ for some $\nu > 0$. Consequently, by means of the standard theory of parabolic equations, see for instance Ladyzhenskaya et al. [37], we may infer that $r$, $V$ is a classical solution,
\begin{equation}
\partial_t V, \ \nabla_x^2 V \text{ Hölder continuous in } [0, T] \times \overline{\Omega}.
\end{equation}
and, going back to (1.1),
\begin{equation}
\partial_t r \text{ Hölder continuous in } [0, T] \times \overline{\Omega}.
\end{equation}

**Step 5.**
We write
\begin{equation}
\nabla_x \partial_t r = -\nabla_x V \cdot \nabla_x r - V \cdot \nabla_x^2 r - \nabla_x r \text{div}_x V - r \nabla_x \text{div}_x V;
\end{equation}
whence, by virtue (2.14), (2.17), (2.18), and the Sobolev embedding $W^{1,2} \hookrightarrow L^6$, \begin{equation}
\partial_t r \in C([0, T]; W^{1,6}(\Omega)).
\end{equation}
Next, we differentiate (2.16) with respect to $t$. Denoting $Z = \partial_t V$ we therefore obtain
\[
\partial_t Z - \frac{1}{r} \text{div}_x S(\nabla_x Z) + V \cdot \nabla_x Z = \partial_t \left( \frac{1}{r} \right) \text{div}_x S(\nabla_x V) - \partial_t V \cdot \nabla_x V + \partial_t \left( \frac{1}{r} \nabla_x p(r) \right),
\]
(2.20)
where, in view of (2.19) and the previously established estimates, the expression on the right-hand side is bounded in $C([0, T]; L^6(\Omega; R^3))$. Thus using the $L^p$-maximal regularity (see Denk et al. [5], Krylov [36] or Danchin [8], Thm. 2.2), we deduce that
\[
\partial^2_{t,t} V = \partial_t Z \in L^2(0, T; L^6(\Omega; R^3)), \quad \partial_t V = Z \in C([0, T]; W^{1,6}(\Omega; R^3)).
\]
(2.21)
Finally, writing
\[
\partial^2_{t,t} r = -\partial_t V \cdot \nabla_x r - V \cdot \partial_t \nabla_x r - \partial_t r \text{div}_x V - r \partial_t \text{div}_x V,
\]
and using (2.19), (2.21), we obtain the desired conclusion
\[
\partial^2_{t,t} r \in C([0, T]; L^6(\Omega)).
\]
□

Here and hereafter, we shall use notation $a \lesssim b$ and $a \approx b$. the symbol $a \lesssim b$ means that there exists $c = c(\Omega, T, \mu, \gamma) > 0$ such that $a \leq cb$; $a \approx b$ means $a \lesssim b$ and $b \lesssim a$.

2.2. Extension lemma

Lemma 2.3. Under the hypotheses of Proposition 2.2, the functions $r$ and $V$ can be extended outside $\Omega$ in such a way that:

1. The extended functions (still denoted by $r$ and $V$) are such that $V$ is compactly supported in $[0, T] \times R^3$ and $r \geq a > 0$.

2. \[
\|V\|_{C^1([0, T] \times R^3)} + \|V\|_{C([0, T]; C^2(R^3; R^3))} + \|\partial_t V\|_{C([0, T]; L^6(R^3; R^3 \times 3))} + \|\partial^2_{t,t} V\|_{L^2(0, T; L^6(R^3))} \lesssim \|V\|_{C^1([0, T] \times \overline{\Omega}; R^3)} + \|\partial_t V\|_{C([0, T]; L^6(R^3))} + \|\partial^2_{t,t} V\|_{L^2(0, T; L^6(\Omega))};
\]
(2.22)

3. \[
\|r\|_{C^1([0, T] \times R^3)} + \|\partial_t V\|_{C([0, T]; L^6(R^3; R^3))} + \|\partial^2_{t,t} V\|_{C([0, T]; L^6(R^3))} \lesssim \|r\|_{C^1([0, T] \times \overline{\Omega})} + \|\partial_t V\|_{C([0, T]; L^6(\Omega; R^3))} + \|\partial^2_{t,t} V\|_{C([0, T]; L^6(\Omega))} + \|\partial^2_{t,t} V\|_{L^2(0, T; L^6(\Omega))};
\]
(2.23)
(4) \[
\partial_t r + \text{div}_x (r V) = 0 \text{ in } (0, T) \times R^3.
\]
(2.24)

Proof. We first construct the extension of the vector field $V$. To this end, we follow the standard construction in the flat domain, see Adams ([1], Chap. 5, Thm. 5.22) and combine it with the standard procedure of ‘flattening’ of the boundary and the partition of unity technique, we get (2.22) Once this is done, we solve on the whole space the transport equation (2.24). It is easy to show that the unique solution $r$ of this equation possesses regularity and estimates stated in (2.23). □
Remark 2.4. Here and hereafter, we denote $X_T(\mathbb{R}^3)$ a subset of $L^2((0, T) \times \mathbb{R}^3)$ of couples $(r, V)$, $r > 0$ with finite norm

$$\| (r, V) \|_{X_T(\mathbb{R}^3)} \equiv \| r \|_{C^1([0, T] \times \mathbb{R}^3)} + \| \partial_t \nabla_x r \|_{C([0, T]; L^6(R^3; R^3))} + \| \partial_t^2 r \|_{C([0, T]; L^6(R^3))}$$

(2.25)

$$\| V \|_{C^1([0, T] \times \mathbb{R}^3; R^3)} + \| \partial_t \nabla_x V \|_{C([0, T]; L^6(R^3; R^3))} + \| \partial_t^2 V \|_{L^2(0, T; L^6(R^3))}$$

(2.26)

We notice that if $r$, $V$ are interrelated through (2.7), then the first component of the couple belonging to $X_T(\mathbb{R}^3)$ is always strictly positive on $[0, T] \times \mathbb{R}^3$. We set

$$0 < \underline{r} = \min_{(t, x) \in [0, T] \times \mathbb{R}^3} r(t, x), \quad \overline{r} = \max_{(t, x) \in [0, T] \times \mathbb{R}^3} r(t, x) < \infty$$

2.3. Physical domain, mesh approximation

The physical space is represented by a bounded domain $\Omega \subset \mathbb{R}^3$ of class $C^3$. The numerical domains $\Omega_h$ are polyhedral domains,

$$\Omega_h = \bigcup_{K \in T} K,$$  

(2.27)

where $T$ is a set of tetrahedra which have the following property: If $K \cap L \neq \emptyset$, $K \neq L$, then $K \cap L$ is either a common face, or a common edge, or a common vertex. By $E(K)$, we denote the set of the faces $\sigma$ of the element $K \in T$. The set of all faces of the mesh is denoted by $E$; the set of faces included in the boundary $\partial \Omega_h$ of $\Omega_h$ is denoted by $E_{ext}$ and the set of internal faces (i.e. $E \setminus E_{ext}$) is denoted by $E_{int}$.

Further, we ask

$$V_h \subset \partial \Omega_h \text{ a vertex } \Rightarrow V_h \subset \partial \Omega.$$  

(2.28)

Furthermore, we suppose that each $K$ is a tetrahedron such that

$$\xi[K] \approx \text{diam}[K] \approx h,$$  

(2.29)

where $\xi[K]$ is the radius of the largest ball contained in $K$.

The properties of this mesh needed in the sequel are formulated in the following lemma, whose proof is left to the reader, see Johnson and Nedelec [27] for the 2D case, and [26] for the general 3D case.

Lemma 2.5. There exists a positive constant $d_\Omega$ depending solely on the geometric properties of $\partial \Omega$ such that

$$\text{dist}[x, \partial \Omega] \leq d_\Omega h^2,$$

for any $x \in \partial \Omega_h$. Moreover,

$$| (\Omega_h \setminus \Omega) \cup (\Omega \setminus \Omega_h) | \approx h^2.$$

We find important to emphasize that $\Omega_h \not\subset \Omega$, in general.

2.4. Numerical spaces

We denote by $Q_h(\Omega_h)$ the space of piecewise constant functions:

$$Q_h(\Omega_h) = \{ q \in L^2(\Omega_h) \mid \forall K \in T, \ q|_K \in \mathbb{R} \}. $$

(2.30)

For a function $v$ in $C(\Omega_h)$, we set

$$v_K = \frac{1}{|K|} \int_K v dx \text{ for } K \in T \text{ and } \Pi_h^Q v(x) = \sum_{K \in T} v_K 1_K(x), \ x \in \Omega.$$  

(2.31)

Here and in what follows, $1_K$ is the characteristic function of $K$. 
We define the Crouzeix–Raviart space with ‘zero traces’:

\[ V_{h,0}(\Omega_h) = \{ v \in L^2(\Omega_h), \forall K \in T, v|_K \in P_1(K), \} \]

\[ \forall \sigma \in E_{\text{int}}, \sigma = K|L, \int_{\sigma} v|_K \, dS = \int_{\sigma} v|_L \, dS, \forall \sigma' \in E_{\text{ext}}, \int_{\sigma'} v \, dS = 0 \}, \] (2.32)

and ‘with general traces’

\[ V_h(\Omega_h) = \{ v \in L^2(\Omega), \forall K \in T, v|_K \in P_1(K), \forall \sigma \in E_{\text{int}}, \sigma = K|L, \int_{\sigma} v|_K \, dS = \int_{\sigma} v|_L \, dS \}. \] (2.33)

We denote by \( \Pi^V_h \) the standard Crouzeix–Raviart projection, and \( \Pi^V_{h,0} \) the Crouzeix–Raviart projection with ‘zero trace’, specifically,

\[ \Pi^V_h : C(\Omega_h) \rightarrow V_h(\Omega_h), \int_{\sigma} \Pi^V_h[\phi] \, dS_x = \int_{\sigma} \phi \, dS_x \text{ for all } \sigma \in E, \]

\[ \Pi^V_{h,0} : C(\Omega_h) \rightarrow V_{h,0}(\Omega_h), \int_{\sigma} \Pi^V_{h,0}[\phi] \, dS_x = \int_{\sigma} \phi \, dS_x \text{ for all } \sigma \in E_{\text{int}}, \] (2.34)

\[ \int_{\sigma} \Pi^V_{h,0}[\phi] \, dS_x = 0 \text{ whenever } \sigma \in E_{\text{ext}}. \]

If \( v \in W^{1,1}(\Omega_h) \), we set

\[ v_{\sigma} = \frac{1}{|\sigma|} \int_{\sigma} v \, dS \text{ for } \sigma \in E. \] (2.35)

(See e.g. [9], Sect. 4.3) for the definition of traces of functions in \( W^{1,1} \).)

Each element \( v \in V_h(\Omega_h) \) can be written in the form

\[ v(x) = \sum_{\sigma \in E} v_{\sigma} \varphi_{\sigma}(x), \quad x \in \Omega_h, \] (2.36)

where the set \( \{ \varphi_{\sigma} \}_{\sigma \in E} \subset V_h(\Omega_h) \) is the classical Crouzeix–Raviart basis determined by

\[ \forall (\sigma, \sigma') \in E^2, \frac{1}{|\sigma'|} \int_{\sigma'} \varphi_{\sigma} \, dS = \delta_{\sigma,\sigma'}. \] (2.37)

Similarly, each element \( v \in V_{h,0}(\Omega_h) \) can be written in the form

\[ v(x) = \sum_{\sigma \in E_{\text{int}}} v_{\sigma} \varphi_{\sigma}(x), \quad x \in \Omega_h. \] (2.38)

We first recall in Lemmas 2.6)–(2.10 the standard properties of the projection \( \Pi^V_h \). The collection of their proofs in the requested generality can be found in the Appendix of [22] with exception of Lemma 2.11 and its Corollary 2.12. We refer to the monograph of Brezzi and Fortin [2], the Crouzeix’s and Raviart’s paper [6], Gallouet et al. [21] for the original versions of some of these proofs. We present the proof of Lemma 2.11 dealing with the comparison of projections \( \Pi^V_h \) and \( \Pi^V_{h,0} \) that we did not find in the literature.

**Lemma 2.6.** The following estimates hold true:

\[ \| \Pi^V_h[\phi] \|_{L^\infty(K)} + \| \Pi^V_{h,0}[\phi] \|_{L^\infty(K)} \lesssim \| \phi \|_{L^\infty(K)}, \] (2.39)
for all $K \in \mathcal{T}$ and $\phi \in C(K)$:

$$
\|\phi - \Pi^{V}_h[\phi]\|_{L^p(K)} \lesssim h^{s}\|\nabla^{s}\phi\|_{L^p(K;\mathbb{R}^{d})}, \quad s = 1, 2, \quad 1 \leq p \leq \infty,
$$

(2.40)

and

$$
\|\nabla(\phi - \Pi^{V}_h[\phi])\|_{L^p(K;\mathbb{R}^d)} \leq c h^{s-1}\|\nabla^{s}\phi\|_{L^p(K;\mathbb{R}^d)}, \quad s = 1, 2, \quad 1 \leq p \leq \infty,
$$

(2.41)

for all $K \in \mathcal{T}$ and $\phi \in C^{s}(K)$.

**Lemma 2.7.** Let $1 \leq p < \infty$. Then

$$
\sum_{\sigma \in \mathcal{E}} |\sigma| h|v_\sigma|^p \approx \|v\|^p_{L^p(\Omega_h)},
$$

(2.42)

with any $v \in V_h(\Omega_h)$.

**Lemma 2.8.** The following Sobolev-type inequality holds true:

$$
\|v\|^2_{L^p(\Omega_h)} \lesssim \sum_{K \in \mathcal{T}} \int_K |\nabla v|^2 dx,
$$

(2.43)

with any $v \in V_{h,0}(\Omega_h)$.

**Lemma 2.9.** There holds:

$$
\sum_{K \in \mathcal{T}} \int_K q \; \Pi^V_h[v] \, dx = \int_\Omega q \; \div v \, dx,
$$

(2.44)

for all $v \in C^1(\overline{\Omega_h}, \mathbb{R}^d)$ and all $q \in Q_h(\Omega_h)$.

**Lemma 2.10** (Jumps over faces in the Crouzeix–Raviart space). For all $v \in V_{h,0}(\Omega_h)$ there holds

$$
\sum_{\sigma \in \mathcal{E}} \frac{1}{h} \int_\sigma [v]_{\sigma,n_\sigma}^2 \, dS \lesssim \sum_{K \in \mathcal{T}} \int_K |\nabla v|^2 dx,
$$

(2.45)

where $[v]_{\sigma,n_\sigma}$ is a jump of $v$ with respect to a normal $n_\sigma$ to the face $\sigma$,

$$
\forall x \in \sigma = K|L \in \mathcal{E}_{\text{int}}, \quad [v]_{\sigma,n_\sigma}(x) = \begin{cases} 
v|\sigma|_K(x) - v|\sigma|_L(x) & \text{if } n_\sigma = n_{\sigma,K}, \\
v|\sigma|_L(x) - v|\sigma|_K(x) & \text{if } n_\sigma = n_{\sigma,L},
\end{cases}
$$

($n_{\sigma,K}$ is the normal of $\sigma$, that is outer w.r. to element $K$) and

$$
\forall x \in \sigma \in \mathcal{E}_{\text{ext}}, \quad [v]_{\sigma,n_\sigma}(x) = v(x), \text{ with } n_\sigma \text{ an exterior normal to } \partial \Omega.
$$

We will need to compare the projections $\Pi^V_h$ and $\Pi^V_{h,0}$. Clearly they coincide on ‘interior’ elements meaning $K \in \mathcal{T}$, $K \cap \partial \Omega_h = \emptyset$. We have the following lemma for the tetrahedra with non void intersection with the boundary.

**Lemma 2.11.** We have

$$
\|\Pi^V_h[\phi] - \Pi^V_{h,0}[\phi]\|_{L^\infty(K)} + h\|\nabla_x(\Pi^V_h[\phi] - \Pi^V_{h,0}[\phi])\|_{L^\infty(K;\mathbb{R}^d)} \lesssim \sup_{\sigma \in K \cap \partial \Omega_h} \|\phi\|_{L^\infty(\sigma)} \quad \text{if } K \in \mathcal{T}, \quad K \cap \partial \Omega_h \neq \emptyset,
$$

(2.46)

for any $\phi \in C(K)$. 
Proof. We recall the Crouzeix–Raviart basis (2.37) and the fact that \( \Pi_h^V \) and \( \Pi_{h,0}^V \) differ only in basis functions corresponding to \( \sigma \in \mathcal{E}_{\text{ext}} \). We have

\[
||\Pi_h^V[\phi] - \Pi_{h,0}^V[\phi]||_{L^\infty(K)} \leq \left\| \sum_{\sigma \in \mathcal{E}(K) \cap \mathcal{E}_{\text{ext}}} \varphi_{\sigma} \frac{1}{|\sigma|} \int_{\sigma} \phi \, dS \right\|_{L^\infty(K)} \leq c(K) \cdot \sup_{\sigma \in \mathcal{E}(K) \cap \mathcal{E}_{\text{ext}}} ||\phi||_{L^\infty(\sigma)}, \tag{2.47}
\]

and

\[
h ||\nabla_x (\Pi_h^V[\phi] - \Pi_{h,0}^V[\phi])||_{L^\infty(K)} \leq h \left\| \sum_{\sigma \in \mathcal{E}(K) \cap \mathcal{E}_{\text{ext}}} \nabla_x \varphi_{\sigma} \frac{1}{|\sigma|} \int_{\sigma} \phi \, dS \right\|_{L^\infty(K)} \leq ch \sup_{\sigma \subseteq K \cap \partial \Omega_h} ||\phi||_{L^\infty(\sigma)} \left\| \sum_{\sigma \in \mathcal{E}(K) \cap \mathcal{E}_{\text{ext}}} \nabla_x \varphi_{\sigma} \right\|_{L^\infty(K)}.
\]

The proof is completed by \( ||\sum_{\sigma \in \mathcal{E}(K) \cap \mathcal{E}_{\text{ext}}} \nabla_x \varphi_{\sigma}||_{L^\infty(K)} \leq c(K)h^{-1} \). \qedhere

In fact, in the derivation of the error estimates we will use the consequence of the above observations formulated in the following two corollaries.

**Corollary 2.12.** Let \( \phi \in C^1(\mathbb{R}^3) \) such that \( \phi|_{\partial \Omega} = 0 \). Then we have,

\[
||\Pi_h^V[\phi] - \Pi_{h,0}^V[\phi]||_{L^\infty(K)} = 0 \text{ if } K \in T_h, K \cap \partial \Omega_h = \emptyset, \tag{2.48}
\]

\[
||\Pi_h^V[\phi] - \Pi_{h,0}^V[\phi]||_{L^\infty(K)} + h ||\nabla_x (\Pi_h^V[\phi] - \Pi_{h,0}^V[\phi])||_{L^\infty(K;\mathbb{R}^3)} \lesssim h^2 ||\nabla_x \phi||_{L^\infty(\mathbb{R}^3;\mathbb{R}^3)}, \tag{2.49}
\]

if \( K \in T_h, K \cap \partial \Omega_h \neq \emptyset, \partial K \not\subseteq \partial \Omega \).

**Proof.** Relation (2.48) follows immediately from (2.46), as there is an empty sum on the right hand side for ‘interior’ elements (\( K \cap \partial \Omega_h = \emptyset \)).

For any \( x \in \partial \Omega_h \) there exists \( y \in \partial \Omega \) (and thus \( \phi(y) = 0 \)) such that

\[
|\phi(x)| \leq \text{dist}[x,y] ||\nabla_x \phi||_{L^\infty(\mathbb{R}^3;\mathbb{R}^3)} \lesssim h^2 ||\nabla_x \phi||_{L^\infty(\mathbb{R}^3;\mathbb{R}^3)}, \tag{2.50}
\]

where we used Lemma 2.5 for the latter inequality. The proof is completed by taking supremum over \( K \in T_h \) and combining with (2.50). Note that the mesh regularity property (2.29) supplies a uniform estimate of constants \( c(K) \) from the previous lemma, which enables to write the latter inequality in (2.50). \qedhere

**Corollary 2.13.** For any \( \phi \in C(\mathbb{R}^3) \),

\[
||\Pi_h^V[\phi] - \Pi_{h,0}^V[\phi]||_{L^p(\Omega_h)} \lesssim h^{1/p} ||\phi||_{L^\infty(\Omega_h)}, 1 \leq p < \infty. \tag{2.51}
\]

**Proof.** Apply inverse estimates (see e.g. [31], Lem. 2.9) to (2.46). \qedhere

We will frequently use the Poincaré, Sobolev and interpolation inequalities on tetrahedra reported in the following lemma.
Lemma 2.14. 

(1) We have,

$$
\|v - v_K\|_{L^p(K)} \lesssim h\|\nabla v\|_{L^p(K)},
$$

(2.52) 

for any $v \in W^{1,p}(K)$, where $1 \leq p \leq \infty$.

(2) There holds

$$
\|v - v_K\|_{L^p(K)} \lesssim h\|\nabla v\|_{L^p(K)},
$$

(2.53) 

for any $v \in W^{1,p}(K)$, where $p^* = \frac{dp}{d-p}$.

(3) We have,

$$
\|v - v_K\|_{L^p(K)} \leq ch^d\|\nabla v\|_{L^p(K;\mathbb{R}^d)},
$$

(2.54) 

for any $v \in W^{1,p}(K)$, $1 \leq p < d$, where $p^* = \frac{dp}{d-p}$, $p \leq q \leq p^*$.

We finish the section of preliminaries by recalling two algebraic inequalities: the ‘imbedding’ inequality

$$
\left(\sum_{i=1}^L |a_i|^p\right)^{1/p} \leq \left(\sum_{i=1}^L |a_i|^q\right)^{1/q},
$$

(2.58) 

for all $a = (a_1, \ldots, a_L) \in \mathbb{R}^L$, $1 \leq q \leq p < \infty$ and the discrete Hölder inequality

$$
\sum_{i=1}^L |a_i||b_i| \leq \left(\sum_{i=1}^L |a_i|^q\right)^{1/q} \left(\sum_{i=1}^L |a_i|^p\right)^{1/p},
$$

(2.59) 

for all $a = (a_1, \ldots, a_L) \in \mathbb{R}^L$, $b = (b_1, \ldots, b_L) \in \mathbb{R}^L$, $\frac{1}{q} + \frac{1}{p} = 1$.

3. Main result

Here and hereafter we systematically use the following abbreviated notation:

$$
\hat{\phi} = \Pi_h^Q[\phi], \quad \phi_h = \Pi_h^V[\phi], \quad \phi_{h,0} = \Pi_h^V[\phi],
$$

(3.1) 

where projections $\Pi_h^Q$, $\Pi_h^V$ and $\Pi_h^V(0)$ are defined in (2.31) and (2.34). For a function $v \in C([0,T],L^1(\Omega))$ we set

$$
v^n(x) = v(t_n,x),
$$

(3.2) 

where $t_0 = 0 < t_1 < \ldots < t_{n-1} < t_n < t_{n+1} < \ldots t_N = T$ is a partition of the interval $[0,T]$. Finally, for a function $v \in V_h(\Omega_h)$ we denote

$$
\nabla_h v(x) = \sum_{K \in \mathcal{T}} \nabla_x v(x) \mathbf{1}_K(x), \quad \text{div}_h v(x) = \sum_{K \in \mathcal{T}} \text{div}_x v(x) \mathbf{1}_K(x).
$$

(3.3)
In order to ensure the positivity of the approximate densities, we shall use an upwinding technique for the density in the mass equation. For \(q \in Q_h(\Omega_h)\) and \(u \in V_{h,0}(\Omega_h; \mathbb{R}^3)\), the upwinding of \(q\) with respect to \(u\) is defined, for \(\sigma = K|L \in \mathcal{E}_{\text{int}}\) by:

\[
q_{\sigma}^{\text{up}} = \begin{cases} q_K & \text{if } u_\sigma \cdot n_{\sigma,K} > 0 \\
q_L & \text{if } u_\sigma \cdot n_{\sigma,K} \leq 0,
\end{cases}
\]  

and we denote

\[
U_{\text{up}}(q, u) = \sum_{\sigma \in \mathcal{E}(K) \cap \mathcal{E}_{\text{int}}} q_{\sigma}^{\text{up}} u_\sigma \cdot n_{\sigma,K} = \sum_{\sigma \in \mathcal{E}(K) \cap \mathcal{E}_{\text{int}}} (q_K[u_\sigma \cdot n_{\sigma,K}]^+ + q_L[u_\sigma \cdot n_{\sigma,K}]^-),
\]

where \(a^+ = \max(a,0), a^- = \min(a,0)\).

### 3.1. Numerical scheme

We consider a couple \((\varrho^n, u^n) = (\varrho^{n, (\Delta t, h)}, u^{n, (\Delta t, h)})\) of (numerical) solutions of the following algebraic system (numerical scheme):

\[
\varrho^n \in Q_h(\Omega_h), \quad \varrho^n > 0, \quad u^n \in V_{h,0}(\Omega_h; \mathbb{R}^3), \quad n = 0, 1, \ldots, N,
\]  

\[
\sum_{K \in T} |K| \frac{\varrho^n_K - \varrho^{n-1}_K}{\Delta t} \phi_K + \sum_{K \in T} \sum_{\sigma \in \mathcal{E}(K)} |\sigma| \varrho^n_{\sigma, \text{up}}(u^n_\sigma \cdot n_{\sigma,K}) \phi_K = 0 \quad \text{for any } \phi \in Q_h(\Omega_h) \text{ and } n = 1, \ldots, N, \quad (3.5)
\]

\[
\sum_{K \in T} |K| \frac{\varrho^n_K - \varrho^{n-1}_K}{\Delta t} u^n_K \cdot v_K + \sum_{K \in T} \sum_{\sigma \in \mathcal{E}(K)} |\sigma| \varrho^n_{\sigma, \text{up}} u^n_{\sigma, \text{up}}[u^n_\sigma \cdot n_{\sigma,K}] \cdot v_K
\]

\[
- \sum_{K \in T} p(\varrho^n_K) \sum_{\sigma \in \mathcal{E}(K)} |\sigma| v_\sigma \cdot n_{\sigma,K} + \mu \sum_{K \in T} \int_K \nabla u^n : \nabla v \, dx
\]

\[
+ \frac{\mu}{3} \sum_{K \in T} \int_K \text{div} u^n \text{div} v \, dx = 0, \quad \text{for any } v \in V_{h,0}(\Omega; \mathbb{R}^3) \text{ and } n = 1, \ldots, N.
\]  

The numerical solutions depend on the size \(h\) of the space discretization and on the time step \(\Delta t\). For the sake of clarity and in order to simplify notation we will always systematically write in all formulas \((\varrho^n, u^n)\) instead of \((\varrho^{n, (\Delta t, h)}, u^{n, (\Delta t, h)})\).

The numerical method (3.5)–(3.7) has been suggested in (31), Def. 3.1; it is strongly nonlinear and implicit. It is therefore not a trivial question whether this (finite dimensional) problem admits a solution. The problem of the well posedness of this numerical scheme is investigated in Karper (31), Prop. 3.3. Karper’s result states that:

For each fixed \(h > 0, \Delta t > 0\), problem (3.5)–(3.7) admits a solution \((\varrho^n_h, u^n_h)\):

\[
\varrho^n_h \in Q_h(\Omega_h), \quad u^n_h \in V_{h,0}(\Omega_h; \mathbb{R}^3), \quad n = 0, 1, \ldots, N,
\]

and \(\varrho^n_h > 0, n = 1, \ldots, N, \) provided \(\varrho^0_h > 0\).

The proof uses topological degree theory in the spirit suggested in [20]. All its details are available in Section 11 of [31]. Notice that the above result does not guarantee the uniqueness of numerical solutions.

**Remark 3.1.** Throughout the paper, \(q_{\sigma, \text{up}}\) is defined in (3.4), where \(u\) is the numerical solution constructed in (3.5)–(3.7).
3.2. Error estimates

The main result of this paper is announced in the following theorem:

**Theorem 3.2.** Let $\Omega \subset R^3$ be a bounded domain of class $C^3$ and let the pressure satisfy (1.4) with $\gamma \geq 3/2$. Let $\{\rho^n, u^n\}_{0 \leq n \leq N}$ be a family of numerical solutions resulting from the scheme (3.5)–(3.7). Moreover, suppose there are initial data $[r_0, V_0]$ belonging to the regularity class specified in Proposition 2.2 and giving rise to a weak solution $[r, V]$ to the initial-boundary value problem (1.1)–(1.6) in $(0, T) \times \Omega$ satisfying

$$0 \leq r(t, x) \leq T \text{ a.a. in } (0, T) \times \Omega.$$ 

Then $[r, V]$ is regular and there exists a positive number $\gamma$ such that

$$C = C \left( M_0, E_0, L, r, [p']_{C^{1}([-\infty, \infty]), \| (\partial_t r, \nabla r, V, \partial_t V, \nabla V, \nabla^2 V) \|_{L^\infty(Q_T; \mathbb{R}^{45})}, \| \partial_t^2 r \|_{L^1(0, T; L^{\gamma'}(\Omega))}, \| \partial_t \nabla r \|_{L^2(0, T; L^{6/5-\delta}(\Omega; \mathbb{R}^3))}, \| \partial_t^2 V, \partial_t \nabla V \|_{L^2(0, T; L^{6/5}(\Omega; \mathbb{R}^3))} \right),$$

such that

$$\sup_{1 \leq n \leq N} \int_{\Omega \cap \Omega_h} \left[ \frac{1}{2} \rho^n |\hat{u}^n - V(t_n, \cdot)|^2 + H(r^n - H'(r(t_n, \cdot))(\rho^n - r(t_n, \cdot)) - H(r(t_n)) \right] \, dx \quad (3.8)$$

$$+ \Delta t \sum_{1 \leq n \leq N} \int_{\Omega \cap \Omega_h} |\nabla_h u^n - \nabla x V(t_n, \cdot)|^2 \, dx$$

$$\leq C \left( \sqrt{\Delta t} + h^a + \int_{\Omega \cap \Omega_h} \left[ \frac{1}{2} \rho^0 |\hat{u}^0 - V_0|^2 + H(\rho^0) - H'(r_0)(\rho^0 - r_0) - H(r_0) \right] \, dx \right),$$

where

$$a = \frac{2\gamma - 3}{\gamma} \text{ if } \frac{3}{2} \leq \gamma \leq 2, \quad a = \frac{1}{2} \text{ otherwise.} \quad (3.9)$$

Note that for $\gamma = 3/2$ Theorem 3.2 gives only uniform bounds on the difference of exact and numerical solution, not the convergence.

**Remark 3.3.** The constitutive assumptions for the pressure (1.4) in Theorem 3.2 require, in particular, $p'(0) > 0$. This condition excludes the isentropic pressure laws

$$p(\rho) = \rho^\gamma, \quad \gamma > 1. \quad (3.10)$$

Nevertheless, Theorem 3.2 holds under the same assumptions also for the isentropic pressure laws (3.10). Here, we have adopted the more restrictive condition (1.4) (in particular $p'(0) > 0$) only for the sake of simplicity and clarity, in order to avoid some unnecessary technical difficulties. It allows to simplify proofs of some estimates: for example estimates (4.7), (4.10) are in this case immediate consequences of the energy inequality (4.2), while in the general case of pressure laws vanishing at 0, the derivation of the same estimates requires more effort (see [22], Cor. 4.1 and Lem. 4.2), where the proofs of these estimates are performed in the general case.

4. Uniform estimates

If we take $\phi = 1$ in formula (3.6) we get immediately the conservation of mass:

$$\forall n = 1, \ldots, N, \quad \int_{\Omega_h} \rho^n \, dx = \int_{\Omega_h} \rho^0 \, dx. \quad (4.1)$$

The next Lemma reports the standard energy estimates for the numerical scheme (3.5)–(3.7). The reader can consult Section 4.1 in Gallouet et al. ([22], Lem. 4.1) for its laborious but straightforward proof.
Let \((q^n, u^n)\) be a solution of the discrete problem (3.5)–(3.7) with the pressure \(p\) satisfying (1.4). Then there exist $\bar{\tau}_0 \in [\min(q^n_0, \epsilon), \max(q^n_0, \epsilon)]$, \(\sigma = K |L \in \mathcal{E}_{\text{int}}, n = 1, \ldots, N\), $\bar{\tau}^{n-1,n} \in [\min(q^{n-1}_0, \epsilon), \max(q^{n-1}_0, \epsilon)]$, \(\bar{\tau} \in T, n = 1, \ldots, N\), such that

\[
\sum_{K \in T} |K| \left( \frac{1}{2} \bar{\tau}^n_K |u^n_K|^2 + H(q^n_K) \right) - \sum_{K \in T} |K| \left( \frac{1}{2} \bar{\tau}^0_K |u^0_K|^2 + H(q^0_K) \right) + \Delta t \sum_{n=1}^m \sum_{K \in T} \left( \mu \int_K |\nabla_x u^n|^2 \, dx + \frac{\mu}{3} \int_K |\text{div} u^n|^2 \, dx \right)
\]

\[
+ [D_{\text{time}}^m,|\Delta u|] + [D_{\text{space}}^m,|\Delta \rho|] + [D_{\text{space}}^m,|\Delta \rho|] = 0, \tag{4.2}
\]

for all \(m = 1, \ldots, N\), where \(n\) is $c = c(M_0, E_0) > 0$ (independent of \(n, h\) and \(\Delta t\)) such that

\[
k \sum_{n=1}^N \int_K |\nabla_x u^n|^2 \, dx \leq c, \tag{4.4}
\]

\[
k \sum_{n=1}^N \|u^n\|^2_{L^6(\Omega_h; \mathbb{R}^3)} \leq c, \tag{4.5}
\]

\[
\sup_{n=0, \ldots, N} \|u^n\|^2_{L^1(\Omega_h)} \leq c. \tag{4.6}
\]

We have the following corollary of Lemma 4.1.

**Corollary 4.2.** Under assumptions of Lemma 4.1, we have:

1. There exists $c = c(M_0, E_0) > 0$ (independent of \(n, h\) and \(\Delta t\)) such that

\[
k \sum_{n=1}^N \int_K |\nabla_x u^n|^2 \, dx \leq c, \tag{4.4}
\]

\[
k \sum_{n=1}^N \|u^n\|^2_{L^6(\Omega_h; \mathbb{R}^3)} \leq c, \tag{4.5}
\]

\[
\sup_{n=0, \ldots, N} \|\hat{u}^n\|^2_{L^1(\Omega_h)} \leq c. \tag{4.6}
\]

2. $\sup_{n=0, \ldots, N} \|\hat{u}^n\|^2_{L^p(\Omega_h)} \leq c$, \(\sigma = K |L \in \mathcal{E}_{\text{int}}, n = 1, \ldots, N\),

3. If the pair \((r, U)\) belongs to the class (2.25) there is $c = c(M_0, E_0, L^\gamma, \mathcal{T}, \|U, \nabla U\|_{L^\infty(Q_T; \mathbb{R}^3)}) > 0$ such that for all $n = 1, \ldots, N$,

\[
\sup_{n=0, \ldots, N} \mathcal{E}(\hat{q}^n, \hat{u}^n|t_n), \hat{U}(t_n)) \leq c, \tag{4.8}
\]

where

\[
\mathcal{E}(\hat{q}, \hat{u}|z, v) = \int_{\Omega_h} (\hat{q}|u - v|^2 + E(\hat{q}|z)) \, dx, \quad E(\hat{q}|z) = H(\hat{q}) - H'(z)(\hat{q} - z) - H(z). \tag{4.9}
\]

(4.9)
There holds for all Lemma 5.1.

Let scheme (3.5)–(3.7) formulated in the following lemma.

The starting point of our error analysis is the discrete relative energy inequality for the numerical dissipation (4.3d). The interested reader can consult Section 4.2 in (Gallouet et al. [22], Cor. 4.1, Lem. 4.2) for the detailed proofs of these estimates.

5. Discrete relative energy inequality

The starting point of our error analysis is the discrete relative energy inequality for the numerical scheme (3.5)–(3.7) formulated in the following lemma.

Lemma 5.1. Let \((\varrho^n, \mathbf{u}^n)\) be a solution of the discrete problem (3.5)–(3.7) with the pressure \(p\) satisfying (1.4). Then there holds for all \(m = 1, \ldots, N\),

\[
\Delta t \sum_{n=1}^{m} \sum_{\sigma = K | L \in \mathcal{E}_{\text{int}}} |\sigma| (\varrho^n_K - \varrho^n_L)^2 \left[ \max \left\{ \frac{1}{\rho_{K,L}}, \frac{1}{\rho_{L,K}} \right\} ^{2-\gamma} + 1_{(\rho_{K,L} < 1)} \right] |\mathbf{u}^n_\sigma \cdot \mathbf{n}_{\sigma,K}| \leq c \quad \text{if } \gamma \in [1, 2),
\]

\[
\Delta t \sum_{n=1}^{m} \sum_{\sigma = K | L \in \mathcal{E}_{\text{int}}} |\sigma| (\varrho^n_K - \varrho^n_L)^2 |\mathbf{u}^n_\sigma \cdot \mathbf{n}_{\sigma,K}| \leq c \quad \text{if } \gamma \geq 2
\]

Items (1)–(3) of Corollary 4.2 are direct consequences of Lemma 4.1. Item (4) represents the convenient expression for the numerical dissipation (4.3d). The interested reader can consult Section 4.2 in (Gallouet et al. [22], Cor. 4.1, Lem. 4.2) for the detailed proofs of these estimates.

Proof. Lemma 5.1 is proved in Section 5 in (Gallouet et al. [22], Thm. 5.1). We provide here the proof for the sake of completeness.
First, noting that the numerical diffusion represented by terms (4.3a)–(4.3d) in the energy identity (4.2) is positive, we infer

$$I_1 + I_2 + I_3 \leq 0,$$

(5.3)

with

$$I_1 := \sum_{K \in T} \frac{1}{2} \frac{|K|}{\Delta t} (\theta_K^n \| u_K^n \|^2 - \theta_K^{n-1} \| u_K^{n-1} \|^2), \quad I_2 := \sum_{K \in T} \frac{|K|}{\Delta t} (H(\theta_K^n) - H(\theta_K^{n-1})),

$$I_3 := \sum_{K \in T} \left( \mu \int_K |\nabla u_K^n|^2 \, dx + \frac{\mu}{3} \int_K |\text{div} u_K^n|^2 \, dx \right).$$

Next, we consider the discrete continuity equation (3.6) with \( \phi = \frac{1}{2} |U^n|^2 \) as test function in order to obtain

$$I_4 := \sum_{K \in T} \frac{1}{2} \frac{|K|}{\Delta t} (\theta_K^n u_K^n - \theta_K^{n-1} u_K^{n-1}) \cdot U_K^n = J_2 + J_3 + J_4,$$

(5.4)

In the next step, taking \(-U^n\) as test function \( \mathbf{v} \) in the discrete momentum equation (3.7) one gets

$$I_5 = -\sum_{K \in T} \frac{|K|}{\Delta t} (\theta_K^n u_K^n - \theta_K^{n-1} u_K^{n-1}) \cdot U_K^n = J_2 + J_3 + J_4,$$

with

$$J_2 = \sum_{K \in T} \sum_{\sigma \in E(K)} \sum_{\sigma = K|L} |\sigma| \theta_{\sigma,\text{up}} \hat{u}_{\sigma,\text{up}} \cdot U_K^n [u_{\sigma} \cdot n_{\sigma,K}],

J_3 = \mu \sum_{K \in T} \int_K \nabla u_K^n : \nabla U_K^n \, dx + \frac{\mu}{3} \sum_{K \in T} \int_K \text{div} u_K^n \text{div} U_K^n \, dx

and

$$J_4 = -\sum_{K \in T} \sum_{\sigma \in E(K)} \sum_{\sigma = K|L} |\sigma| \theta_{\sigma} [U_{\sigma} \cdot n_{\sigma,K}].$$

We then consider the discrete continuity equation (3.6) with a test function \( \phi = H'(r_K^{n-1}) \) and obtain

$$-\sum_{K \in T} \frac{|K|}{\Delta t} (\theta_K^n - \theta_K^{n-1}) H'(r_K^{n-1}) = \sum_{K \in T} \sum_{\sigma \in E(K)} \sum_{\sigma = K|L} |\sigma| \theta_{\sigma,\text{up}} [u_{\sigma} \cdot n_{\sigma,K}] H'(r_K^{n-1}).$$

Observing that \( \theta_K^n H'(r_K^n) - \theta_K^{n-1} H'(r_K^{n-1}) = \theta_K^n (H'(r_K^n) - H'(r_K^{n-1})) + (\theta_K^n - \theta_K^{n-1}) H'(r_K^{n-1}) \), we rewrite the last identity in the form

$$I_6 := -\sum_{K \in T} \frac{|K|}{\Delta t} (\theta_K^n H'(r_K^n) - \theta_K^{n-1} H'(r_K^{n-1})) = J_5 + J_6$$

with

$$J_5 = -\sum_{K \in T} \frac{|K|}{\Delta t} \theta_K^n (H'(r_K^n) - H'(r_K^{n-1})) \quad \text{and} \quad J_6 = \sum_{K \in T} \sum_{\sigma \in E(K)} \sum_{\sigma = K|L} |\sigma| \theta_{\sigma,\text{up}} [u_{\sigma} \cdot n_{\sigma,K}] H'(r_K^{n-1}).$$

(5.5)
Finally, thanks to the convexity of the function $H$, we have

$$I_7 := \sum_{K \in T} \frac{|K|}{\Delta t} \left[ (r^n_K H'(r^n_K) - H(r^n_K)) - (r^{n-1}_K H'(r^{n-1}_K) - H(r^{n-1}_K)) \right]$$

$$= \sum_{K \in T} \frac{|K|}{\Delta t} r^n_K (H'(r^n_K) - H'(r^{n-1}_K)) - \sum_{K \in T} \frac{|K|}{\Delta t} (H(r^n_K) - (r^n_K - r^{n-1}_K)H'(r^{n-1}_K) - H(r^{n-1}_K))$$

$$\leq \sum_{K \in T} \frac{|K|}{\Delta t} r^n_K (H'(r^n_K) - H'(r^{n-1}_K)) := J_7. \quad (5.6)$$

Now, we gather the expressions (5.3)–(5.6); this is performed in several steps.

**Step 1:** Term $I_1 + I_4 + I_5$. We obtain by direct calculation,

$$I_1 + I_4 + I_5 = \sum_{K \in T} \frac{1}{2} \frac{|K|}{\Delta t} \left( \varrho^n_K |u^n_K - U^n_K|^2 - \varrho^{n-1}_K |u^{n-1}_K - U^{n-1}_K|^2 \right)$$

$$- \sum_{K \in T} |K| \varrho^{n-1}_K \frac{U^n_K - U^{n-1}_K}{\Delta t} \cdot \left( \frac{U^{n-1}_K + U^n_K}{2} - u^{n-1}_K \right). \quad (5.7)$$

**Step 2:** Term $J_1 + J_2$. Employing the definition (3.4) of the upwinding, one gets

$$J_1 + J_2 = - \sum_{K \in T} \sum_{\sigma = K} \sum_{L \in \mathcal{E}(K)} |\sigma| \varrho^{n,up}_\sigma \left( \frac{U^n_K + U^n_L}{2} - u^{n,up}_\sigma \right) : U^n_K [u^n_\sigma \cdot n_{\sigma,K}]. \quad (5.8)$$

**Step 3:** Term $I_3 - J_3$. This term can be written in the form

$$I_3 - J_3 = \sum_{K \in T} \left( \mu \int_K |\nabla_x (u^n - U^n)|^2 dx + \frac{\mu}{3} \int_K |\text{div}(u^n - U^n)|^2 dx \right)$$

$$- \sum_{K \in T} \mu \int_K \left( \nabla U^n : \nabla (U^n - u^n) + \frac{\mu}{3} \int_K \text{div} U^n \text{div}(U^n - u^n) \right). \quad (5.9)$$

**Step 4:** Term $I_2 + I_6 + I_7$. By virtue of (5.3), (5.5) and (5.6), we easily find that

$$I_2 + I_6 + I_7 = \sum_{K \in T} \frac{|K|}{\Delta t} \left( E(\varrho^n_K |r^n_K) - E(\varrho^{n-1}_K |r^{n-1}_K) \right), \quad (5.10)$$

where the function $E$ is defined in (4.9).

**Step 5:** Term $J_5 + J_6 + J_7$. Coming back to (5.5) and (5.6), we deduce that

$$J_5 + J_6 + J_7 = \sum_{K \in T} \frac{|K|}{\Delta t} (r^n_K - \varrho^n_K) (H'(r^n_K) - H'(r^{n-1}_K)) + \sum_{K \in T} \sum_{\sigma = K} |\sigma| \varrho^{n,up}_\sigma \left[ u^n_\sigma \cdot n_{\sigma,K} H'(r^{n-1}_K) \right]. \quad (5.11)$$

**Step 6:** **Conclusion**

According to (5.3)–(5.6), we have

$$\sum_{i=1}^7 I_i \leq \sum_{i=1}^7 J_i;$$
whence, writing this inequality by using expressions (5.7)–(5.11) calculated in steps 1–5, we get

\[
\sum_{K \in T} \frac{1}{2} \frac{|K|}{\Delta t} (\phi^n_K |u^n_K - U^n| - \phi^{n-1}_K |u^{n-1}_K - U^{n-1}|) + \sum_{K \in T} \frac{|K|}{\Delta t} (E(\phi^n_K |r^n_K) - E(\phi^{n-1}_K |r^{n-1}_K)) \\
+ \sum_{K \in T} \left( \mu \int_K |\nabla_x (u^n - U^n)|^2 \, dx + \frac{\mu}{3} \int_K |\text{div}(u^n - U^n)|^2 \, dx \right) \\
\leq \sum_{K \in T} \left( \mu \int_K |\nabla_x U^n_K : \nabla_x (U^n - u^n)| \, dx + \frac{\mu}{3} \int_K \text{div}U^n \text{div}(U^n - u^n) \, dx \right) \\
+ \sum_{K \in T} \left( |K| \phi^{n-1}_K \frac{U^n_K - U^{n-1}_K}{\Delta t} \cdot \left( \frac{U^n_K + U^{n-1}_K}{2} - u^{n-1}_K \right) \\
- \sum_{K \in T} \sum_{\sigma = K | L \in E(K)} |\sigma| \phi^{n,up}_\sigma \left( \frac{U^n_K + U^n_L}{2} - \tilde{u}^{n,up}_\sigma \right) \cdot U^n_K [u^{\sigma \cdot n}_{\sigma,K}] \\
- \sum_{K \in T} \sum_{\sigma = K | L \in E(K)} |\sigma| \phi^{n \cdot H'} \left( r^n_K - \phi^n_K \right) \left( H'(r^n_K) - H'(r^{n-1}_K) \right) \\
+ \sum_{K \in T} \sum_{\sigma = K | L \in E(K)} |\sigma| \phi^{n,up \cdot H'} \left( r^{n-1}_K \right) [u^{\sigma \cdot n}_{\sigma,K}] \right].
\]

We obtain formula (5.1) by summing (5.12) from \( n = 1 \) to \( n = m \) and multiplying the resulting inequality by \( \Delta t \). \( \Box \)

6. Approximate discrete relative energy inequality

In this section, we transform the right hand side of the relative energy inequality (5.1) to a form that is more convenient for the comparison with the strong solution. This transformation is given in the following lemma.

Lemma 6.1 (Approximate relative energy inequality). Let \((\phi^n, u^n)\) be a solution of the discrete problem (3.5)–(3.7), where the pressure satisfies (1.4) with \( \gamma \geq 3/2 \). Then there exists

\[
c = c \left( M_0, E_0, L, T, \|p^l\|_{C^1 \Omega}, \|\partial_t r, \nabla r, V, \partial_t V, \nabla V\|_{L^\infty(Q_T; \mathbb{R}^{18})}, \|\partial^2_t r\|_{L^1(0, T; L^1(\Omega))}, \|\partial_t \nabla r\|_{L^2(0, T; L^{6/5} - 3(\Omega; \mathbb{R}^3))} \right) > 0,
\]

such that for all \( m = 1, \ldots, N \), we have:

\[
\int_{\Omega_h} \left( \phi^m |\tilde{u}^m - \tilde{V}_{h,0}^m|^2 + E(\phi^m |\tilde{r}^m|^2) \right) \, dx - \int_{\Omega_h} \left( \phi^0 |\tilde{u}^0 - \tilde{V}_{h,0}^0|^2 + E(\phi^0 |\tilde{r}^0|^2) \right) \, dx \\
+ \Delta t \sum_{n=1}^m \sum_{K \in T} \left( \mu \int_K |\nabla_x (u^n - V^n_{h,0})|^2 \, dx + \frac{\mu}{3} \int_K |\text{div}(u^n - V^n_{h,0})|^2 \, dx \right) \leq \sum_{i=1}^6 S_i + R_i^{m, \Delta t} + G^m,
\]
for any couple \((r, \mathbf{V})\) belonging to the class \((2.25)\), where

\[
S_1 = \Delta t \sum_{n=1}^{m} \sum_{K \in \mathcal{T}} \left( \mu \int_K \nabla \cdot \mathbf{V}^n_{h,0} : \nabla \cdot (\mathbf{V}^n_{h,0} - \mathbf{u}^n) \, dx + \frac{\mu}{3} \int_K \text{div} \mathbf{V}^n_{h,0} \text{div}(\mathbf{V}^n_{h,0} - \mathbf{u}^n) \, dx \right),
\]

\[
S_2 = \Delta t \sum_{n=1}^{m} \sum_{K \in \mathcal{T}} |K| \frac{n-1}{n} \frac{\mathbf{V}^n_{h,0,K} - \mathbf{V}^{n-1}_{h,0,K}}{\Delta t} \cdot (\mathbf{V}^n_{h,0,K} - \mathbf{u}^n_K),
\]

\[
S_3 = \Delta t \sum_{n=1}^{m} \sum_{K \in \mathcal{T}} \sum_{\sigma \in \mathcal{E}(K)} |\sigma| \frac{n+1}{n} \left( \hat{\mathbf{V}}^{n,\text{up}}_{h,0,\sigma} - \hat{\mathbf{u}}^{n,\text{up}}_{\sigma} \right) \cdot (\mathbf{V}^n_{h,0,\sigma} - \mathbf{V}^n_{h,0,K}) \cdot \hat{\mathbf{V}}^{n,\text{up}}_{h,0,\sigma},
\]

\[
S_4 = -\Delta t \sum_{n=1}^{m} \int_{\Omega_h} p(\mathbf{V}^n) \text{div} \mathbf{V}^n \, dx,
\]

\[
S_5 = \Delta t \sum_{n=1}^{m} \int_{\Omega_h} (\hat{r}^n - \hat{\mathbf{V}}^n) \frac{p' \hat{r}^n}{\hat{r}^n} \left[ \partial_r \hat{r}^n \right] \, dx,
\]

\[
S_6 = -\Delta t \sum_{n=1}^{m} \int_{\Omega_h} \frac{\hat{r}^n p' \hat{r}^n}{\hat{r}^n} \mathbf{u}^n \cdot \nabla \hat{r}^n \, dx,
\]

and

\[
|G^n| \leq c \Delta t \sum_{n=1}^{m} \mathcal{E}(\mathbf{V}^n, \hat{\mathbf{u}}^n, \hat{\mathbf{V}}^n), \quad |R^n_{h,\Delta t}| \leq c(\sqrt{\Delta t} + h^n),
\]

with the power \(a\) defined in \((3.9)\) and with the functional \(\mathcal{E}\) introduced in \((4.9)\). (Recall that in agreement with the notation \((2.35)\), \((3.1)-(3.3)\), \(\mathbf{V}^n_{h,0} = \Pi_K^V \mathbf{V}^n(t_n), \mathbf{V}^n_{h,0,K} = \Pi_K^Q \Pi_K^V \mathbf{V}^{n}(t_n)|_K, \mathbf{V}^n_{h,0,\sigma} = \frac{1}{|\sigma|} \int_{\sigma} \mathbf{V}^n_{h,0}, \hat{r}^n = \Pi_h^Q [r(t_n)], \) where the projections \(\Pi_K^Q, \Pi_K^V\) are defined in \((2.31)\) and \((2.34)\).)

**Proof.** We take as test functions \(\mathbf{U}^n = \mathbf{V}^n_{h,0}\) and \(r^n = \hat{r}^n\) in the discrete relative energy inequality \((5.1)\). We keep the left hand side and the first term (term \(T_1\)) at the right hand side as they stay. The transformation of the remaining terms at the right hand side (terms \(T_2 - T_6\)) is performed in the following steps:

**Step 1: Term \(T_2\).** We have

\[
T_2 = T_{2,1} + R_{2,1} + R_{2,2}, \quad \text{with } T_{2,1} = \Delta t \sum_{n=1}^{m} \sum_{K \in \mathcal{T}} |K| \frac{n-1}{n} \frac{\mathbf{V}^n_{h,0,K} - \mathbf{V}^{n-1}_{h,0,K}}{\Delta t} \cdot (\mathbf{V}^n_{h,0,K} - \mathbf{u}^n_K),
\]

and

\[
R_{2,1} = \Delta t \sum_{n=1}^{m} \sum_{K \in \mathcal{T}} R^n_{2,1,K}, \quad R_{2,2} = \Delta t \sum_{n=1}^{m} R^n_{2,2},
\]

where

\[
R^n_{2,1,K} = -\frac{|K|}{2} \frac{n-1}{n} \frac{(\mathbf{V}^n_{h,0,K} - \mathbf{V}^{n-1}_{h,0,K})^2}{\Delta t} = -\frac{|K|}{2} \frac{n-1}{n} \frac{(\mathbf{V}^n - \mathbf{V}^{n-1})^2_{h,0,K}}{\Delta t},
\]

and

\[
R^n_{2,2} = -\sum_{K \in \mathcal{T}} |K| \frac{n-1}{n} \frac{\mathbf{V}^n_{h,0,K} - \mathbf{V}^{n-1}_{h,0,K}}{\Delta t} \cdot (\mathbf{u}^{n-1}_K - \mathbf{u}^n_K).
\]
We may write by virtue of the first order Taylor formula applied to function \(t \mapsto V(t, x)\),

\[
\left| \frac{V^n - V^{n-1}}{\Delta t} \right|_{h,0,K} = \left| \frac{1}{|K|} \int_K \left[ \frac{1}{\Delta t} \left[ \int_{t_{n-1}}^{t_n} \partial_t V(z, x) \, dz \right]_{h,0} \right] \, dx \right|
\]

\[= \left| \frac{1}{|K|} \int_K \left[ \frac{1}{\Delta t} \int_{t_{n-1}}^{t_n} \partial_t V(z) \, dz \right]_{h,0} \, dx \right| \leq \left\| \partial_t V \right\|_{L^\infty(0,T;L^\infty(\Omega;\mathbb{R}^3))} \leq \left\| \partial_t V \right\|_{L^\infty(0,T;L^\infty(\Omega;\mathbb{R}^3))},
\]

where we have used the property (2.39) of the projection \(\Pi^V_{h,0}\) on the space \(V_{h,0}(\Omega_h)\). Therefore, thanks to the mass conservation (4.1), we get

\[
|R_{2,1}^{n,K}| \leq \frac{M_0}{2} |K| \Delta t \left\| \partial_t V \right\|_{L^\infty(0,T;L^\infty(\Omega;\mathbb{R}^3))}^2.
\]

(6.5)

To treat term \(R_{2,2}^{n}\) we use the discrete Hölder inequality and identity (4.1) in order to get

\[
|R_{2,2}^{n}| \leq \Delta t \, c M_0 \left\| \partial_t V \right\|_{L^\infty(0,T;W^{1,\infty}(\Omega;\mathbb{R}^3))} + c M_0^{1/2} \left( \sum_{K \in \mathcal{T}} |K| \rho_0^{n-1} \left| u^{n-1}_K - u^n_K \right|^2 \right)^{1/2} \left\| \partial_t V \right\|_{L^\infty(0,T;L^\infty(\Omega;\mathbb{R}^3))};
\]

whence, by virtue of estimate (4.2) for the upwind dissipation term (4.3a), one obtains

\[
|R_{2,2}^{n}| \leq \sqrt{\Delta t} c(M_0, E_0, \left\| \partial_t V \right\|_{L^\infty(Q_T;\mathbb{R}^3)}).
\]

(6.6)

**Step 2: Term T3.** Employing the definition (3.4) of upwind quantities, we easily establish that

\[T_3 = T_{3,1} + R_{3,1},\]

with

\[T_{3,1} = \Delta t \sum_{n=1}^{m} \sum_{K \in \mathcal{T}} \sum_{\sigma \in \mathcal{E}(K)} |\sigma| \rho_0^{n,up} (\hat{u}^{n,up}_\sigma - \hat{V}^{n,up}_h,0,\sigma) \cdot V^n_{h,0,K} u^n_{\sigma,K}, \quad R_{3,1} = \Delta t \sum_{n=1}^{m} \sum_{\sigma \in \mathcal{E}_{int}} R_{3,1}^{n,\sigma},\]

and

\[R_{3,1}^{n,\sigma} = |\sigma| \rho_K^{n-1/2} \left| V^n_{h,0,K} - V^n_{h,0,L} \right| \left| u^n_{\sigma,K} \right|^2 + |\sigma| \rho_L^{n} \left| V^n_{h,0,L} - V^n_{h,0,K} \right| \left| u^n_{\sigma,L} \right|^2, \quad \forall \sigma = K|L| \in \mathcal{E}_{int}.\]

Writing

\[V^n_{h,0,K} - V^n_{h,0,L} = [V^n_{h,0} - V^n_{h}]_K + V^n_{h,K} - V^n_{h} + V^n_{h} - V^n_{h,0,L}, \quad \sigma = K|L| \in \mathcal{E}_{int},\]

and employing estimates (2.48) (if \(K \cap \partial \Omega_h = \emptyset\), (2.49) (if \(K \cap \partial \Omega_h \neq \emptyset\)) to evaluate the \(L^\infty\)-norm of the first term, (2.52) then (2.41)_{s=1} and (2.53) after (2.41)_{s=1} to evaluate the \(L^\infty\)-norm of the second and third terms, and performing the same tasks at the second line, we get

\[
\left\| V^n_{h,0,K} - V^n_{h,0,L} \right\|_{L^\infty(K \cup L;\mathbb{R}^3)} \leq c h \left\| \nabla V \right\|_{L^\infty(K \cup L;\mathbb{R}^3)};
\]

(6.7)

consequently

\[
|R_{3,1}^{n,\sigma}| \leq h^2 c \left\| \nabla V \right\|_{L^\infty((0,T) \times \partial\Omega;\mathbb{R}^3)} |\sigma| (\rho_K^{n} + \rho_L^{n}) \left| u^n_\sigma \right|^2, \quad \forall \sigma = K|L| \in \mathcal{E}_{int},
\]

whence

\[
|R_{3,1}| \leq h c \left\| \nabla V \right\|_{L^\infty((0,T) \times \partial\Omega;\mathbb{R}^3)} \left( \sum_{K \in \mathcal{T}} \sum_{\sigma = K|L| \in \mathcal{E}(K)} h |\sigma| (\rho_K^{n} + \rho_L^{n})^{6/5} \right)^{5/6}
\]

\[\times \left[ \Delta t \sum_{n=1}^{m} \left( \sum_{K \in \mathcal{T}} \sum_{\sigma \in \mathcal{E}(K)} h |\sigma| \left| u^n_\sigma \right|^6 \right)^{1/3} \right]^{1/2} \leq h c(M_0, E_0, \left\| \nabla V \right\|_{L^\infty(Q_T;\mathbb{R}^3)}),
\]

(6.8)
provided $\gamma \geq 6/5$, thanks to the discrete Hölder inequality, the equivalence relation (2.29), the equivalence of norms (2.42) and energy bounds listed in Corollary 4.2.

Clearly, for each face $\sigma = K \mid L \in E_{\text{int}}$, $u^n_{\sigma} \cdot n_{\sigma,K} + u^n_{\sigma} \cdot n_{\sigma,L} = 0$; whence, finally

$$T_{3,1} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \sum_{\sigma \in \mathcal{E}(K)} |\sigma|g^{n,\text{up}}_\sigma \left( \hat{u}^{n,\text{up}}_{\sigma} - \hat{V}_{h,0,\sigma}^{n,\text{up}} \right) \cdot \left( V_{h,0,K}^{n} - V_{h,0,\sigma}^{n} \right) u^n_{\sigma} \cdot n_{\sigma,K}. \quad (6.9)$$

Before the next transformation of term $T_{3,1}$, we realize that

$$V_{h,0,K}^{n} - V_{h,0,\sigma}^{n} = \left[ V_{h,0}^{n} - V_{h}^{n} \right]_{K} + V_{h}^{n} - V_{h,0,\sigma}^{n} + \left[ V_{h}^{n} - V_{h,0,\sigma}^{n} \right]_{\sigma};$$

whence by virtue of (2.48) and (2.49), (2.52) and (2.53) and (2.41)$_{a=1}$, similarly as in (6.7),

$$\|V_{h,0,K}^{n} - V_{h,0,\sigma}^{n}\|_{L^\infty(K; \mathbb{R}^d)} \leq \epsilon h \|\nabla_x V\|_{L^\infty(0,T; L^\infty(\Omega; \mathbb{R}^d))}, \quad \sigma \subset K. \quad (6.10)$$

Let us now decompose the term $T_{3,1}$ as

$$T_{3,1} = T_{3,2} + R_{3,2}, \quad \text{with } R_{3,2} = \Delta t \sum_{n=1}^{m} R_{3,2}^{n};$$

$$T_{3,2} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \sum_{\sigma \in \mathcal{E}(K)} |\sigma|g^{n,\text{up}}_\sigma \left( \hat{V}_{h,0,\sigma}^{n,\text{up}} - \hat{\bar{u}}^{n,\text{up}}_{\sigma} \right) \cdot \left( V_{h,0,\sigma}^{n} - V_{h,0,\sigma}^{n} \right) \hat{\bar{u}}^{n,\text{up}}_{\sigma} \cdot n_{\sigma,K},$$

$$R_{3,2}^{n} = \sum_{K \in T} \sum_{\sigma \in \mathcal{E}(K)} |\sigma|g^{n,\text{up}}_\sigma \left( \hat{V}_{h,0,\sigma}^{n,\text{up}} - \hat{\bar{u}}^{n,\text{up}}_{\sigma} \right) \cdot \left( V_{h,0,\sigma}^{n} - V_{h,0,\sigma}^{n} \right) \left( u_{\sigma}^{n} - \hat{\bar{u}}^{n,\text{up}}_{\sigma} \right) \cdot n_{\sigma,K}.$$
Finally, we rewrite term $T_{3,2}$ as

$$T_{3,2} = T_{3,3} + R_{3,3}, \quad \text{with } R_{3,3} = \Delta t \sum_{n=1}^{m} R_{3,3}^n,$$

where

$$T_{3,3} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \sum_{\sigma \in E(K)} |\sigma| \theta_{\sigma, n}^{up} \left( \hat{V}_{h,0,0,K}^{n,up} - \hat{u}_{\sigma, n}^{up} \right) \cdot (V_{h,0,0,K}^n - V_{h,0,K}^n) \hat{V}_{h,0,0,K}^{n,up} \cdot n_{\sigma,K}, \quad \text{and}$$

$$R_{3,3}^n = \sum_{K \in T} \sum_{\sigma \in E(K)} |\sigma| \theta_{\sigma, n}^{up} \left( \hat{V}_{h,0,0,K}^{n,up} - \hat{u}_{\sigma, n}^{up} \right) \cdot (V_{h,0,0,K}^n - V_{h,0,K}^n) \left( \hat{u}_{\sigma, n}^{up} - \hat{V}_{h,0,0,K}^{n,up} \right) \cdot n_{\sigma,K};$$

whence

$$|R_{3,3}| \leq c \left( \| \nabla V \|_{L^\infty(Q_T; R^p)} \right) \Delta t \sum_{n=1}^{m} \mathcal{E}(g^n, \hat{u}^n | \hat{r}^n, \hat{V}_{h,0}^n). \quad (6.12)$$

**Step 3:** Term $T_4$. Integration by parts over each $K \in T$ gives

$$T_4 = -\Delta t \sum_{n=1}^{m} \sum_{K \in T} \int_K p(\theta_K^n) \text{div}_x V_h^n \text{d}x.$$

We may write

$$\| \text{div}_x (V_h^n - V_h^m) \|_{L^\infty(K)} \leq c h \| \nabla_x V \|_{L^\infty(0,T; L^\infty(\Omega; R^p))}, \quad (6.14)$$

where we have used (2.48)–(2.49). Therefore, employing identity (2.44) we obtain

$$T_4 = T_{4,1} + R_{4,1}, \quad T_{4,1} = -\Delta t \sum_{n=1}^{m} \sum_{K \in T} \int_K p(\theta_K^n) \text{div}_x V^n \text{d}x,$$

$$R_{4,1} = -\Delta t \sum_{n=1}^{m} \sum_{K \in T} \int_K p(\theta_K^n) \text{div}_x (V_h^n - V_h^m) \text{d}x.$$

Due to (1.4) and (4.7), $p(\theta^n)$ is bounded uniformly in $L^\infty(L^1(\Omega))$; employing this fact and (6.14) we immediately get

$$|R_{4,1}| \leq h c(E_0, M_0, \| \nabla V \|_{L^\infty(0,T; L^\infty(\Omega; R^p))}). \quad (6.16)$$

**Step 4:** Term $T_5$. Using the Taylor formula, we get

$$H'(r_K^n) - H'(r_K^{n-1}) = H''(r_K^n)(r_K^n - r_K^{n-1}) - \frac{1}{2} H'''(\tilde{r}_K^n)(r_K^n - r_K^{n-1})^2,$$

where $\tilde{r}_K^n \in [\min(r_K^{n-1}, r_K^n), \max(r_K^{n-1}, r_K^n)]$. We infer

$$T_5 = T_{5,1} + R_{5,1}, \quad \text{with } T_{5,1} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} |K|(r_K^n - \theta_K^n) p'(r_K^n) \frac{r_K^n - r_K^{n-1} p'(r_K^n)}{\Delta t}, \quad R_{5,1} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} R_{5,1}^n,$$

$$R_{5,1}^n = \frac{1}{2} |K| H'''(\tilde{r}_K^n) \frac{(r_K^n - r_K^{n-1})^2}{\Delta t} (p(\theta_K^n) - r_K^n).$$

Consequently, by the first order Taylor formula applied to function $t \mapsto r(t, x)$ on the interval $(t_{n-1}, t_n)$ and thanks to the mass conservation (4.1)

$$|R_{5,1}| \leq \Delta t c(M_0, \tau, |p'|_{C^1(\tilde{r}^*)}, \| \partial_t r \|_{L^\infty(Q_T)}). \quad (6.17)$$
Let us now decompose $T_{5,1}$ as follows:

$$T_{5,1} = T_{5,2} + R_{5,2}, \text{ with } T_{5,2} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \int_{K} (r_{n}^{K} - q_{K}^{n}) \frac{p'(r_{n}^{K})}{r_{n}^{K}}[\partial_{t}r]^{n}dx, \text{ and } R_{5,2} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} R_{5,2}^{n,K},$$

$$R_{5,2}^{n,K} = \int_{K} (r_{n}^{K} - q_{K}^{n}) \frac{p'(r_{n}^{K})}{r_{n}^{K}} \left( \frac{r_{n}^{K} - r_{n-1}^{K}}{\Delta t} - [\partial_{t}r]^{n} \right) dx.$$  

(6.18)

In accordance with (3.2), here and in the sequel, $[\partial_{t}r]^{n}(x) = \partial_{t}r(t_{n}, x)$. We write using twice the Taylor formula in the integral form and the Fubini theorem,

$$|R_{5,2}^{n,K}| = \frac{1}{\Delta t} \left| p'(r_{n}^{K}) r_{n}^{K} (q_{K}^{n} - r_{n}^{K}) \int_{K} \int_{t_{n-1}}^{t_{n}} \int_{s}^{t_{n}} \partial_{t}^{2}r(z)dzdsdx \right|$$

$$\leq \frac{p'(r_{n}^{K})}{r_{n}^{K}} \int_{t_{n-1}}^{t_{n}} \int_{K} \left| q_{K}^{n} - r_{n}^{K} \right| \left| \partial_{t}^{2}r(z) \right| dzds$$

$$\leq \frac{p'(r_{n}^{K})}{r_{n}^{K}} \| q^{n} - r^{n} \|_{L^{2}(K)} \int_{t_{n-1}}^{t_{n}} \| \partial_{t}^{2}r(z) \|_{L^{2}(K)} dzds.$$

Therefore, by virtue of Corollary 4.2, we have estimate

$$|R_{5,2}| \leq \Delta t \ c(M_{0}, E_{0}, L; \tau, \|p'\|_{C^{1}(\overline{\Omega})}, \|\partial_{t}^{2}r\|_{L^{1}(0,T;L^{2}(\Omega))}).$$  

(6.19)

**Step 5: Term $T_{6}$**. We decompose this term as follows:

$$T_{6} = T_{6,1} + R_{6,1}, \text{ with } T_{6,1} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \sum_{\sigma \in \mathcal{E}(K)} R_{6,1}^{n,\sigma,K},$$

$$R_{6,1}^{n,\sigma,K} = |\sigma| \left( q_{\sigma}^{n,up} - q_{K}^{n} \right) \left( H'(r_{\sigma}^{n-1}) - H'(r_{\sigma}^{n-1}) \right) u_{\sigma}^{n} \cdot n_{\sigma,K},$$

for $\sigma = K|L \in \mathcal{E}_{int}.$

We will now estimate the term $R_{6,1}^{n,\sigma,K}$. We shall treat separately the cases $\gamma < 2$ and $\gamma \geq 2$. The ‘simple’ case $\gamma \geq 2$ is left to the reader. The more complicated case $\gamma < 2$ will be treated as follows: We first write

$$\left| R_{6,1}^{n,\sigma,K} \right| \leq \sqrt{h} \| \nabla H'(r) \|_{L^{\infty}(Q_{T};\mathbb{R}^{3})} |\sigma| \left| q_{\sigma}^{n,up} - q_{K}^{n} \right| \left[ \frac{1}{\max\{q_{K}, q_{L}\}}^{(2-\gamma)/2} + 1 \right] \sqrt{|u_{\sigma}^{n} \cdot n_{\sigma,K}|}$$

$$\times \left[ \frac{1}{\max\{q_{K}, q_{L}\}}^{(2-\gamma)/2} + 1 \right] \sqrt{h} \sqrt{|u_{\sigma}^{n} \cdot n_{\sigma,K}|},$$
where we have employed the first order Taylor formula applied to function $x \mapsto H'(r(t_{n-1}, x))$. Consequently, the application of the discrete Hölder and Young inequalities yield

$$|R_{6,1}| \leq \sqrt{h} c \|\nabla H'(r)\|_{L^\infty(Q_T; \mathbb{R}^3)}$$

$$\times \Delta t \sum_{n=1}^{m} \left( \sum_{K \in T} \sum_{\sigma \in E(K)} |\sigma| h \left[ \frac{1}{[\bar{\Omega}_K]} \max\{\theta_K, \theta_L\}^{2-\gamma} + 1\{\bar{\Omega}_K < 1\} \right] |u_{\sigma}^n \cdot n_{\sigma, K}| \right)^{1/2}$$

$$\times \left( \sum_{K \in T} \sum_{\sigma = \mathcal{K} | L \in E(K)} |\sigma| h (q_{n, \text{up}}^n - q_K^n)^2 \left[ \frac{1}{\max\{\theta_K, \theta_L\}}^{2-\gamma} + 1\{\bar{\Omega}_K < 1\} \right] |u_{\sigma}^n \cdot n_{\sigma, K}| \right)^{1/2}$$

$$\leq \sqrt{h} c \|\nabla H'(r)\|_{L^\infty(Q_T; \mathbb{R}^3)}$$

$$\times \Delta t \sum_{n=1}^{m} \left( \sum_{K \in T} \sum_{\sigma \in E(K)} |\sigma| h (q_{n, \text{up}}^n - q_K^n)^2 \left[ \frac{1}{\max\{\theta_K, \theta_L\}}^{2-\gamma} + 1\{\bar{\Omega}_K < 1\} \right] |u_{\sigma}^n \cdot n_{\sigma, K}| \right)^{1/2}$$

$$\leq \sqrt{h} c \|\nabla H'(r)\|_{L^\infty(Q_T; \mathbb{R}^3)}$$

$$\times \Delta t \sum_{n=1}^{m} \left( \sum_{K \in T} \sum_{\sigma \in E(K)} |\sigma| h (q_{n, \text{up}}^n - q_K^n)^2 \left[ \frac{1}{\max\{\theta_K, \theta_L\}}^{2-\gamma} + 1\{\bar{\Omega}_K < 1\} \right] |u_{\sigma}^n \cdot n_{\sigma, K}| \right)^{1/2}$$

$$\leq \sqrt{h} c(\mathcal{M}_0, E_0, L, \mathcal{T}, |p'|C([\omega, \mathcal{T}]), \|\nabla r\|_{L^\infty(Q_T; \mathbb{R}^3)}),$$

where, in order to get the last line, we have used the estimate (4.10) of the numerical dissipation to evaluate the second term, and finally equivalence of norms (2.42)$_{p=6}$ together with (4.5) and (4.7), under assumption $\gamma \geq 12/11$, to evaluate the first term.

Let us now decompose the term $T_{6,1}$ as

$$T_{6,1} = T_{6,2} + R_{6,2}, \text{ with } T_{6,2} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \sum_{\sigma \in E(K)} |\sigma| q_K^n H''(r_{K}^{n-1})(r_{K}^{n-1} - r_{\sigma}^{n-1})|u_{\sigma}^n \cdot n_{\sigma, K}|,$$

$$R_{6,2} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \sum_{\sigma \in E(K)} R_{6,2}^{n, \sigma, K}, \text{ and }$$

$$R_{6,2}^{n, \sigma, K} = |\sigma| q_K^n (H'(r_{K}^{n-1}) - H'(r_{\sigma}^{n-1}) - H''(r_{K}^{n-1})(r_{K}^{n-1} - r_{\sigma}^{n-1})) |u_{\sigma}^n \cdot n_{\sigma, K}|.$$

Therefore, by virtue of the second order Taylor formula applied to function $H'$, the Hölder inequality, (2.42), and (4.5), (4.7) in Corollary 4.2, we have, provided $\gamma \geq 6/5$,

$$|R_{6,2}| \leq h c \left( |H''|C([\omega, \mathcal{T}]) + |H'''|C([\omega, \mathcal{T}]) \right) \|\nabla r\|_{L^\infty(Q_T; \mathbb{R}^3)} \Delta t \sum_{n=1}^{m} \|\hat{q}^n\|_{L^\gamma(\Omega_0)} \|u^n\|_{L^6(\Omega_0; \mathbb{R}^3)}$$

$$\leq h c(\mathcal{M}_0, E_0, L, \mathcal{T}, |p'|C([\omega, \mathcal{T}]), \|\nabla r\|_{L^\infty(Q_T; \mathbb{R}^3)}), \quad (6.20)$$
Let us now deal with the term $T_{6,2}$. Noting that $\int_K \nabla r^{n-1} \, dx = \sum_{\sigma \in \mathcal{E}(K)} |\sigma| (r_{n-1}^\sigma - r_{-1}^\sigma) n_{\sigma,K}$, we may write $T_{6,2} = T_{6,3} + R_{6,3}$, with

$$T_{6,3} = -\Delta t \sum_{n=1}^m \sum_{K \in \mathcal{T}} \int_K \theta_K^n H''(r_K^{n-1}) u^n \cdot \nabla r^{n-1} \, dx,$$

$$R_{6,3} = \Delta t \sum_{n=1}^m \sum_{K \in \mathcal{T}} \int_K \theta_K^n H''(r_K^{n-1})(u^n - u_K^n) \cdot \nabla r^{n-1} \, dx$$

$$+ \Delta t \sum_{n=1}^m \sum_{K \in \mathcal{T}} \sum_{\sigma \in \mathcal{E}(K)} |\sigma| \theta_K^n H''(r_K^{n-1})(r_{n-1}^\sigma - r_{-1}^\sigma)(u_{n}^\sigma - u_{-1}^\sigma) \cdot n_{\sigma,K}.$$

Consequently, by virtue of Hölder’s inequality, interpolation inequality (2.56) (to estimate $\|u^n - u_K^n\|_{L^{\gamma_0}(K;\mathbb{R}^3)}$ by $h^{(5\gamma_0-6)/(2\gamma_0)} \|\nabla_x u^n\|_{L^2(K;\mathbb{R}^3)}$, $\gamma_0 = \min\{\gamma, 2\}$) in the first term, and by the Taylor formula applied to function $x \mapsto r(t_{n-1}, x)$, then Hölder’s inequality and (2.56)–(2.57) (to estimate $\|u^n - u_K^n\|_{L^{\gamma_0}(K;\mathbb{R}^3)}$ by $h^{(5\gamma_0-6)/(2\gamma_0)} \|\nabla_x u^n\|_{L^2(K;\mathbb{R}^3)}$), we get

$$|R_{6,3}| \leq h^b \|M_0, E_0, \mathfrak{T}, x, |p'|_{C^1(\Gamma)}\| \|\nabla r\|_{L^\infty(Q_T;\mathbb{R}^3)}, \quad b = \frac{5\gamma_0 - 6}{2\gamma_0},$$

(6.21)

provided $\gamma \geq 6/5$, where we have used at the end the discrete imbedding and Hölder inequalities (2.58) and (2.59) and finally estimates (4.4) and (4.7).

Finally we write $T_{6,3} = T_{6,4} + R_{6,4}$, with

$$T_{6,4} = -\Delta t \sum_{n=1}^m \sum_{K \in \mathcal{T}} \int_K \theta_K^n \frac{p'(r_K^n)}{r_K^n} u^n \cdot \nabla r^n \, dx,$$

$$R_{6,4} = \Delta t \sum_{n=1}^m \sum_{K \in \mathcal{T}} \int_K \theta_K^n (H''(r_K^n) \nabla r^n - H''(r_K^{n-1}) \nabla r^{n-1}) \cdot u^n \, dx,$$

(6.22)

where by the same token as in (6.19),

$$|R_{6,4}| \leq \Delta t \ c(M_0, E_0, \mathfrak{T}, |p'|_{C^1(\Gamma)}, \|\nabla r, \partial_t r\|_{L^\infty(Q_T;\mathbb{R}^3)}, \|\partial_t \nabla r\|_{L^2(0,T;L^{6/(5\gamma_0-6)}(\Omega;\mathbb{R}^3))},$$

(6.23)

provided $\gamma \geq 6/5$.

We are now in position to conclude the proof of Lemma 6.1: we obtain the inequality (6.1) by gathering the principal terms (6.4), (6.12), (6.15), (6.18), (6.22) and the residual terms estimated in (6.5), (6.6), (6.8), (6.11), (6.13), (6.17), (6.19), (6.20), (6.21), (6.23) at the right hand side $\sum_{i=1}^6 T_i$ of the discrete relative energy inequality (5.1). \hfill \Box

7. A DISCRETE IDENTITY SATISFIED BY THE STRONG SOLUTION

This section is devoted to the proof of a discrete identity satisfied by any strong solution of problem (1.1)–(1.6) in the class (2.9)–(2.10) extended eventually to $\mathbb{R}^3$ according to Lemma 2.3. This identity is stated in Lemma 7.1 below. It will be used in combination with the approximate relative energy inequality stated in Lemma 6.1 to deduce the convenient form of the relative energy inequality verified by any function being a strong solution to the compressible Navier–Stokes system. This last step is performed in the next section.
Lemma 7.1 (A discrete identity for strong solutions). Let \((\rho^n, u^n)\) be a solution of the discrete problem (3.5)–(3.7) with the pressure satisfying (1.4), where \(\gamma \geq 3/2\). There exists

\[
c = c \left( M_0, E_0, \mathbf{u}_0, \mathbf{V}_0, |p'|_{C^1([0,T])}, \left\| (\partial_t r, \nabla r, \mathbf{V}, \partial_t \mathbf{V}, \nabla \mathbf{V}, \nabla^2 \mathbf{V}) \right\|_{L^\infty(Q_T; \mathbb{R}^{45})}, \right.
\]

\[
\left. \| \partial_r^2 r \|_{L^1(0,T; L^\infty(\Omega))}, \| \partial_t \nabla r \|_{L^2(0,T; L^{6/5} \rightarrow \gamma(\Omega; \mathbb{R}^3))}, \| \partial_r^2 \mathbf{V}, \partial_t \nabla \mathbf{V} \|_{L^2(0,T; L^{6/5} (\Omega; \mathbb{R}^{12}))} \right) > 0,
\]

such that for all \(m = 1, \ldots, N\), we have:

\[
\sum_{i=1}^6 S_i + R_{h,\Delta t}^m = 0, \quad (7.1)
\]

where

\[
S_1 = \Delta t \sum_{n=1}^m \sum_{K \in T} \left( \mu \int_K \nabla_r V_{h,0}^n : \nabla_r (V_{h,0}^n - u^n) \, dx + \frac{\mu}{3} \int_K \text{div} V_{h,0}^n \text{div} (V_{h,0}^n - u^n) \, dx \right),
\]

\[
S_2 = \Delta t \sum_{n=1}^m \sum_{K \in T} |K| r_{h,K}^{-1} \frac{V_{h,0,K} - V_{h,0,K}^{-1}}{\Delta t} \cdot (V_{h,0,K}^n - u^n_K),
\]

\[
S_3 = \Delta t \sum_{n=1}^m \sum_{K \in T} \sum_{\sigma \in E(K)} \left| \sigma \right| r_{h,0,\sigma}^{n,up} \left( V_{h,0,\sigma}^{n,up} - \hat{u}_{\sigma}^{n,up} \right) \cdot \left( V_{h,0,\sigma}^n - V_{h,0,K}^n \right) \hat{v}_{h,0,\sigma}^{n,up} \cdot \mathbf{n}_{\sigma,K},
\]

\[
S_4 = -\Delta t \sum_{n=1}^m \int_{\Omega_h} p(\hat{r}^n) \text{div} V^n \, dx,
\]

\[
S_5 = 0,
\]

\[
S_6 = -\Delta t \sum_{n=1}^m \int_{\Omega_h} p'(\hat{r}^n) u^n \cdot \nabla r^n \, dx,
\]

and

\[
|R_{h,\Delta t}^m| \leq c \left( h^{5/6} + \Delta t \right),
\]

for any couple \((r, V)\) belonging to (2.25) and satisfying the continuity equation (1.1) on \((0, T) \times \mathbb{R}^3\) and momentum equation (1.2) with boundary conditions (1.5) on \((0, T) \times \partial \Omega\) in the classical sense. (Recall that in agreement with notation (2.35), (3.1)–(3.3), \(V_{h,0}^{n,0} = \Pi^V_{h,0}[V(t_n)]\), \(V_{h,0}^{n,K} = \Pi^V_{h,K}[V(t_n)]\), \(V_{h,0,\sigma}^{n} = \Pi_{h,\sigma}[V(t_n)]\), \(\hat{r}^{n} = \Pi_{h}^Q[r(t_n)]\), where projections \(\Pi^Q, \Pi^V\) are defined in (2.31) and (2.34)).

Before starting the proof we recall an auxiliary algebraic inequality whose straightforward proof is left to the reader, and introduce some notations.

Lemma 7.2. Let \(p\) satisfies assumptions (1.4). Let \(0 < a < b < \infty\). Then there exists \(c = c(a, b) > 0\) such that for all \(\varrho \in [0, \infty)\) and \(r \in [a, b]\) there holds

\[
E(\varrho | r) \geq c(a, b) \left( 1_{R_+ \backslash [a/2, 2b]}(\varrho) + \varrho \gamma 1_{R_+ \backslash [a/2, 2b]}(\varrho) + (\varrho - r)^2 1_{[a/2, 2b]}(\varrho) \right),
\]

where \(E(\varrho | r)\) is defined in (4.9).

If we consider Lemma 7.2 with \(\varrho = \varrho^n(x)\), \(r = \hat{r}^n(x)\), \(a = a, b = b\) (where \(r\) is a function belonging to class (2.25) and \(\mathbf{V}\) is its lower and upper bounds, respectively), we obtain

\[
E(\varrho^n(x)| \hat{r}^n(x)) \geq c(\mathbf{V}, \mathbf{\tau}) \left( 1_{R_+ \backslash [2, 2\mathbf{\tau}]}(\varrho^n(x)) + (\varrho^n)^\gamma(x) 1_{R_+ \backslash [2, 2\mathbf{\tau}]}(\varrho^n(x)) + (\varrho^n(x) - \hat{r}^n(x))^2 1_{[2, 2\mathbf{\tau}]}(\varrho^n(x)) \right). \quad (7.2)
\]
Now, for fixed numbers \( r \) and \( \tau \) and fixed functions \( \hat{g}^n, n = 0, \ldots, N \), we introduce the residual and essential subsets of \( \Omega \) (relative to \( \hat{g}^n \)) as follows:

\[
N^n_{\text{ess}} = \{ x \in \Omega \mid \frac{1}{2} 2r \leq \hat{g}^n(x) \leq 2\tau \}, \quad N^n_{\text{res}} = \Omega \setminus N^n_{\text{ess}},
\]

and we set

\[
[g]_{\text{ess}}(x) = \hat{g}(x)1_{N^n_{\text{ess}}(x)}, \quad [g]_{\text{res}}(x) = \hat{g}(x)1_{N^n_{\text{res}}(x)}, \quad x \in \Omega, \quad g \in L^1(\Omega).
\]

Integrating inequality (7.2) we deduce

\[
\alpha(\Omega, \tau) \sum_{K \in T} \int_K \left( \left[ 1 \right]_{\text{res}} + \left[ (\hat{g}^n)^\gamma \right]_{\text{res}} + \left[ \hat{g}^n - \hat{r}^n \right]_{\text{ess}}^2 \right) dx \leq E(\hat{g}^n, u^n|\hat{r}^n, V^n),
\]

for any pair \((r, V)\) belonging to the class \((2.25)\) and any \( \hat{g}^n \in Q_h(\Omega) \), \( \hat{g}^n \geq 0 \).

We are now ready to proceed to the proof of Lemma 7.1.

**Proof.** Since \((r, V)\) satisfies (1.1) on \((0, T) \times \Omega\) and belongs to the class \((2.25)\), equation (1.2) can be rewritten in the form

\[
r\partial_t V + r V \cdot \nabla V + \nabla p(r) - \mu \Delta V - \mu/3 \nabla \text{div} V = 0 \quad \text{in} \quad (0, T) \times \Omega.
\]

From this fact, we deduce the identity

\[
\sum_{i=1}^{5} T_i = \mathcal{R}_0,
\]

where

\[
\mathcal{R}_0 = -\Delta t \sum_{n=1}^{m} \int_{\Omega_h \setminus \Omega} \left( r^n [\partial_t V]^n + r V^n \cdot \nabla V^n + \nabla p(r^n) - \mu \Delta V^n - \frac{\mu}{3} \nabla \text{div} V^n \right) \cdot (V^n_{h,0} - u^n) dx,
\]

\[
T_1 = -\Delta t \sum_{n=1}^{m} \int_{\Omega_h} \left( \mu \Delta V^n \right) \cdot (V^n_{h,0} - u^n) dx, \quad T_2 = \Delta t \sum_{n=1}^{m} \int_{\Omega_h} r^n [\partial_t V]^n \cdot (V^n_{h,0} - u^n) dx,
\]

\[
T_3 = \Delta t \sum_{n=1}^{m} \int_{\Omega_h} r^n V^n \cdot \nabla V^n \cdot (V^n_{h,0} - u^n) dx, \quad T_4 = \Delta t \sum_{n=1}^{m} \int_{\Omega_h} \nabla p(r^n) \cdot V^n_{h,0} dx,
\]

\[
T_5 = 0, \quad T_6 = -\Delta t \sum_{n=1}^{m} \int_{\Omega_h} \nabla p(r^n) \cdot u^n dx.
\]

In the steps below, we deal with each of the terms \( \mathcal{R}_0 \) and \( T_i \).

**Step 0: Term \( \mathcal{R}_0 \).** By the Hölder inequality

\[
|\mathcal{R}_0| \leq |\Omega_h \setminus \Omega|^{5/6} c(\tau, p'|C[\mathcal{L}]) \| (\partial_t r, \nabla r, \nabla V, \nabla^{2} V) \|_{L^\infty(Q_T; \mathbb{R}^m)} \Delta t \sum_{n=1}^{m} \left( \| u^n \|_{L^6(\Omega_h)} + \| V^n_{h,0} \|_{L^6(\Omega_h)} \right)
\]

\[
\leq h^{5/3} c(M_0, E_0, \tau, p'|C[\mathcal{L}]) \| (\partial_t r, \nabla r, \nabla V, \nabla^{2} V) \|_{L^\infty(Q_T; \mathbb{R}^m)},
\]

where we have used (4.5), (2.48), (2.49) and (2.39).
Step 1: Term $T_1$. Integrating by parts, we get:

$$T_1 = T_{1,1} + R_{1,1},$$

where

$$T_{1,1} = \Delta t \sum_{n=1}^m \sum_{K \in T} \int_K \left( \mu \nabla V^n_{h,0} : \nabla (V^n_{h,0} - u^n) + \frac{\mu}{3} \text{div} V^n_{h,0} \text{div}(V^n_{h,0} - u^n) \right) \, dx,$$

and

$$R_{1,1} = I_1 + I_2,$$

with

$$I_1 = \Delta t \sum_{n=1}^m \sum_{K \in T} \int_K \left( \mu \nabla (V^n - V^n_{h,0}) : \nabla (V^n_{h,0} - u^n) + \frac{\mu}{3} \text{div}(V^n - V^n_{h,0}) \text{div}(V^n_{h,0} - u^n) \right) \, dx,$$

and

$$I_2 = -\Delta t \sum_{n=1}^m \sum_{K \in T} \sum_{\sigma \in \partial K} \int_{\sigma} \left( \mu n_{\sigma,K} \cdot \nabla V^n \cdot (V^n_{h,0} - u^n) + \frac{\mu}{3} \text{div} V^n (V^n_{h,0} - u^n) \cdot n_{\sigma,K} \right) \, dS,$$

where in the last line $n_\sigma$ is the unit normal to the face $\sigma$ and $[\cdot]_{\sigma,n_\sigma}$ is the jump over $\sigma$ (with respect to $n_\sigma$) defined in Lemma 2.10.

To estimate $I_1$, we use the Cauchy–Schwarz inequality, decompose $V^n - V^n_{h,0} = V^n - V^n_h + V^n_h - V^n_{h,0}$ and employ estimates (2.41)$_{s=2}$, (2.48)–(2.49) to evaluate the norms involving $\nabla(V^n - V^n_{h,0})$, and decompose $V^n_{h,0} - V^n_h + V^n_h$ use (2.48)–(2.49), (2.40)$_{s=1}$, (4.4), the Minkowski inequality to estimate the norms involving $\nabla(V^n_{h,0} - u^n)$. We get

$$|I_1| \leq h \, c(M_0, E_0, \|\nabla V, \nabla^2 V\|_{L^\infty(0,T;L^\infty(\Omega;\mathbb{R}^3))}).$$

Since the integral over any face $\sigma \in \partial T$ of the jump of a function from $V^n_{h,0}(\Omega_h)$ is zero, we may write

$$I_2 = \Delta t \sum_{n=1}^m \sum_{\sigma \in \partial T} \int_{\sigma} \left( \mu n_{\sigma} \cdot (\nabla V^n - (\nabla V^n)_\sigma) \cdot [u^n - V^n_{h,0}]_{\sigma,n_\sigma} \right) \, dS + \frac{\mu}{3} \text{div} V^n (u^n - V^n_{h,0}) \cdot n_{\sigma} \, dS,$$

whence by using the first order Taylor formula applied to functions $x \mapsto \nabla V^n(x)$ to evaluate the differences $\nabla V^n - (\nabla V^n)_\sigma$, div $V^n - [\text{div} V^n]_\sigma$, and Hölder’s inequality,

$$|I_2| \leq \Delta t \, h \, c \, \|\nabla^2 V\|_{L^\infty(Q_T;\mathbb{R}^3)} \sum_{n=1}^m \sum_{\sigma \in \partial T} \sqrt{|\sigma|} \sqrt{h} \left( \frac{1}{\sqrt{h}} \left\| [u^n - V^n_{h,0}]_{\sigma,n_\sigma} \right\|_{L^2(\sigma;\mathbb{R}^3)} \right) \leq \Delta t \, h \, c \, \|\nabla^2 V\|_{L^\infty(Q_T;\mathbb{R}^3)} \sum_{n=1}^m \sum_{\sigma \in \partial T} \left( |\sigma| h + \frac{1}{h} \left\| [u^n - V^n_{h,0}]_{\sigma,n_\sigma} \right\|_{L^2(\sigma;\mathbb{R}^3)}^2 \right).$$

Therefore,

$$|R_{1,1}| \leq h \, c(M_0, E_0, \|V, \nabla V, \nabla^2 V\|_{L^\infty(Q_T;\mathbb{R}^{39})}),$$

where we have employed Lemma 2.10, (4.4) and (2.48)–(2.49), (2.40).
**Step 2: Term \( T_2 \)**. Let us now decompose the term \( T_2 \) as

\[
T_2 = T_{2,1} + R_{2,1},
\]

with \( T_{2,1} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \int_{K} r^{n-1} \frac{V^n - V^{n-1}}{\Delta t} \cdot (V_{h,0}^{n} - u^n) \, dx \), \( R_{2,1} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} R_{2,1}^{n,K} \), and \( R_{2,1}^{n,K} = \int_{K} (r^n - r^{n-1}) [\partial_t V^n] \cdot (V_{h,0}^{n} - u^n) \, dx + \int_{K} r^{n-1} \left( [\partial_t V^n] - \frac{V^n - V^{n-1}}{\Delta t} \right) \cdot (V_{h,0}^{n} - u^n) \, dx \).

The remainder \( R_{2,1}^{n,K} \) can be rewritten as follows

\[
|R_{2,1}^{n,K}| = \Delta t \left[ \|r\|_{L^\infty(Q_T)} + \|\partial_t r\|_{L^\infty(Q_T)} \right] \left( \|\partial_t V^n\|_{L^\infty(Q_T;\mathbb{R}^3)} \|K^{5/6}\|_{L^6(K)} + \|V_{h,0}^n\|_{L^6(K)} \right)
\]

\[
+ \|\partial_t^2 V^n\|_{L^{6/5}(Q_T;\mathbb{R}^3)} \left( \|u^n\|_{L^6(K)} + \|V_{h,0}^n\|_{L^6(K)} \right)
\]

Consequently, by the same token as in (6.19) or (6.23),

\[
|R_{2,1}| \leq \Delta t c \left( M_0, E_0, \tau, \|\partial_t r, V, \partial_t V, \nabla V\|_{L^\infty(Q_T;\mathbb{R}^3)}, \|\partial_t^2 V\|_{L^{2}(0,T;L^{6/5}(\Omega;\mathbb{R}^3))} \right), \tag{7.9}
\]

where we have used the discrete Hölder and Young inequalities, the estimates (2.39), (2.48) and (2.49) and the energy bound (4.4) from Corollary 4.2.

**Step 2a: Term \( T_{2,1} \)**. We decompose the term \( T_{2,1} \) as

\[
T_{2,1} = T_{2,2} + R_{2,2},
\]

with \( T_{2,2} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \int_{K} r^{n-1} \frac{V^n - V^{n-1}}{\Delta t} \cdot (V_{h,0}^{n} - u^n) \, dx \), \( R_{2,2} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} R_{2,2}^{n,K} \), and \( R_{2,2}^{n,K} = \int_{K} (r^n - r^{n-1}) \frac{V^n - V^{n-1}}{\Delta t} \cdot (V_{h,0}^{n} - u^n) \, dx \);

therefore,

\[
|R_{2,2}^{n,K}| = \Delta t \left( \|r\|_{L^\infty(Q_T;\mathbb{R}^3)} \|\partial_t V^n\|_{L^\infty(Q_T;\mathbb{R}^3)} \|u^n - V_{h,0}^n\|_{L^6(\Omega;\mathbb{R}^3)} \right),
\]

Consequently, by virtue of formula (4.5) for \( u^n \) and estimates (2.39), (2.48) and (2.49),

\[
|R_{2,2}| \leq \Delta t c(M_0, E_0, \|\nabla r, V, \partial_t V, \nabla V\|_{L^\infty(Q_T;\mathbb{R}^3)}), \tag{7.10}
\]
Step 2b: Term $T_{2.2}$. We decompose the term $T_{2.2}$ as

$$T_{2.2} = T_{2.3} + R_{2.3},$$

with

$$T_{2.3} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \int_{K} r_{K}^{n-1} \frac{V_{h,0,K}^{n} - V_{h,K}^{n-1}}{\Delta t} \cdot (V_{h,0}^{n} - u^{n}) \, dx,$$

and

$$R_{2.3} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} r_{K}^{n} \nabla_{h,K} \cdot (V_{h,0}^{n} - u^{n}) \, dx.$$

We calculate carefully

$$|I_{3}^{K}| = \frac{1}{\Delta t} r_{K}^{n-1} \int_{K} \left\{ \int_{t_{n-1}}^{t_{n}} \left[ \frac{\partial_{t} V(z)}{h} - [\partial_{i} V(z)]_{h,0} \right] \cdot (V_{h,0}^{n} - u^{n}) \, dz \right\} \, dx,$$

and

$$\leq \frac{1}{\Delta t} r_{K}^{n-1} \int_{t_{n-1}}^{t_{n}} \left\| \frac{\partial_{t} V(z)}{h} - [\partial_{i} V(z)]_{h,0} \right\|_{L^{6/5}(K;\mathbb{R}^{3})} \left\| V_{h,0}^{n} - u^{n} \right\|_{L^{6}(K;\mathbb{R}^{3})} \, dz.$$

Summing over polyhedra $K \in T$ we get simply by using the discrete Sobolev inequality

$$\sum_{K \in T} |I_{3}^{K}| \leq \frac{1}{\Delta t} r_{K}^{n-1} \int_{t_{n-1}}^{t_{n}} \left\{ \left( \sum_{K \in T} \left\| V_{h,0}^{n} - u^{n} \right\|_{L^{6}(K;\mathbb{R}^{3})}^{6} \right)^{1/6} \left( \sum_{K \in T} \left\| [\partial_{t} V(z)]_{h} - [\partial_{i} V(z)]_{h,0} \right\|_{L^{6/5}(K;\mathbb{R}^{3})}^{6/5} \right)^{5/6} \right\} \, dz,$$

where we have used estimate (2.51) to obtain the last line.

As far as the term $I_{2}^{K}$ is concerned, we write

$$|I_{2}^{K}| = \frac{1}{\Delta t} r_{K}^{n-1} \int_{K} \left[ \int_{t_{n-1}}^{t_{n}} \partial_{t} V(z) \, dz \right]_{h} - \left[ \int_{t_{n-1}}^{t_{n}} \partial_{i} V(z) \, dz \right]_{h,K} \cdot (u^{n} - V_{h,0}^{n}) \, dx,$$

and

$$\leq \frac{h}{\Delta t} r_{K}^{n-1} \int_{t_{n-1}}^{t_{n}} \left\| \nabla_{x} \partial_{t} V(z) \right\|_{L^{6/5}(K;\mathbb{R}^{3})} \left\| u^{n} - V_{h,0}^{n} \right\|_{L^{6}(K;\mathbb{R}^{3})} \, dz,$$

where we have used the Fubini theorem, Hölder’s inequality and (2.52), (2.41)_{s=1}. Further, employing the Sobolev inequality on the Crouzeix–Raviart space $V_{h,0}(\Omega_{h})$ (2.43), the Hölder inequality and estimate (2.41)_{s=1}, we get

$$\sum_{K \in T} |I_{2}^{K}| \leq \frac{h}{\Delta t} r_{K}^{n-1} \left\| u^{n} - V_{h,0}^{n} \right\|_{L^{6}(\Omega_{h};\mathbb{R}^{3})} \int_{t_{n-1}}^{t_{n}} \left\| \nabla_{x} \partial_{t} V(z) \right\|_{L^{6/5}(\Omega_{h};\mathbb{R}^{3})} \, dz.$$

We reserve the similar treatment to the term $I_{1}^{K}$. Resuming these calculations and summing over $n$ from 1 to $m$ we get by using Corollary 4.2 and estimates (2.48)–(2.49), (2.39),

$$|R_{2.3}| \leq h^{5/6} c(M_{0}, E_{0}, \left\| (r, V, \nabla V, \partial_{t} V) \right\|_{L^{\infty}(Q_{T};\mathbb{R}^{16})}, \left\| \partial_{t} V \right\|_{L^{2}(0,T;L^{6/5}(\Omega;\mathbb{R}^{3}))}).$$
Step 2c: Term $T_{2,3}$. We rewrite this term in the form

$$T_{2,3} = T_{2,4} + R_{2,4}, \quad R_{2,4} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} R^{n,K}_{2,4},$$

with $T_{2,4} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \int_{K} r_{K}^{n-1} V^{n}_{h,0,K} - V^{n-1}_{h,0,K} \cdot \frac{u^{n}_{K} - V^{n}_{h,0,K}}{\Delta t} dx,$

and $R^{n,K}_{2,4} = \int_{K} r_{K}^{n-1} V^{n}_{h,0,K} - V^{n-1}_{h,0,K} \cdot \left( (u^{n} - u^{n}_{K}) - (V^{n}_{h,0} - V^{n}_{h,0,K}) \right) dx.$ (7.12)

First, we estimate the $L^\infty$ norm of $\frac{V^{n}_{h,0,K} - V^{n-1}_{h,0,K}}{\Delta t}$ as in (6.5). Next, we decompose

$$V^{n}_{h,0} - V^{n}_{h,0,K} = V^{n}_{h,0} - V^{n}_{h} + V^{n}_{h} - V^{n}_{h,K} + [V^{n}_{h} - V^{n}_{h,0,K}],$$

and use (2.52) to estimate $u^{n} - u^{n}_{K}$. (2.52) yields, (2.41) to estimate $V^{n}_{h} - V^{n}_{h,K}$ and (2.48)–(2.49) to evaluate $\| [V^{n}_{h} - V^{n}_{h,K}] \|_{L^\infty(K,\mathbb{R}^3)}$. Thanks to the Hölder inequality and (4.4) we finally deduce

$$\| R_{2,4} \| \leq h c \left( M_{0}, E_{0}, \pi, \| (V, \partial_{t} V, \nabla V) \|_{L^{\infty}(Q_{T,\mathbb{R}^{15}})} \right).$$

(7.13)

Step 3: Term $T_{3}$. Let us first decompose $T_{3}$ as

$$T_{3} = T_{3,1} + R_{3,1},$$

with $T_{3,1} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \int_{K} r_{K}^{n} V^{n}_{h,0,K} \cdot \nabla V^{n} \cdot (V^{n}_{h,0,K} - u^{n}_{K}) dx,$

and $R^{n,K}_{3,1} = \int_{K} (r^{n} - r^{n}_{K}) V^{n} \cdot \nabla V^{n} \cdot (V^{n}_{h,0,K} - u^{n}) dx + \int_{K} r^{n}_{K} (V^{n} - V^{n}_{h,0,K}) \cdot \nabla V^{n} \cdot (V^{n}_{h,0,K} - u^{n}) dx$

$$+ \int_{K} r^{n}_{K} V^{n}_{h,0,K} \cdot \nabla V^{n} \cdot (V^{n}_{h,0,K} - u^{n}) dx$$

We have

$$\| r^{n} - r^{n}_{K} \|_{L^{\infty}(K)} \lesssim h \| \nabla r^{n} \|_{L^{\infty}(K)},$$

by the Taylor formula,

$$\| V^{n} - V^{n}_{h,0,K} \|_{L^{\infty}(K,\mathbb{R}^3)} \lesssim h \| \nabla V^{n} \|_{L^{\infty}(K,\mathbb{R}^3)},$$

by virtue of (2.40) and (2.48) and (2.49),

$$\| V^{n}_{h,0,K} - V^{n}_{h,0,K} \|_{L^{\infty}(K,\mathbb{R}^3)} \leq \| V^{n}_{h,0} - V^{n}_{h} \|_{L^{\infty}(K,\mathbb{R}^3)} + \| V^{n}_{h} - V^{n}_{h,K} \|_{L^{\infty}(K,\mathbb{R}^3)}$$

$$+ \| V^{n}_{h} - V^{n}_{h,0,K} \|_{L^{\infty}(K,\mathbb{R}^3)} \lesssim h \| \nabla V^{n} \|_{L^{\infty}(K,\mathbb{R}^3)},$$

by virtue of (2.52), (2.40) and (2.41) and (2.48)–(2.49),

$$\| u^{n} - u^{n}_{K} \|_{L^{\infty}(K,\mathbb{R}^3)} \lesssim h \| \nabla u^{n} \|_{L^{\infty}(K,\mathbb{R}^3)}.$$
Consequently by employing several times the Hölder inequality (for integrals over $K$) and the discrete Hölder inequality (for the sums over $K \in T$), and using estimate (4.4), we arrive at

$$|\mathcal{R}_{3,1}| \leq h c(M_0, E_0, \tau, \|\nabla r, V, \nabla V\|_{L^\infty(Q_T; \mathbb{R}^3)}).$$

(7.14)

Now we shall deal wit term $\mathcal{T}_{3,1}$. Integrating by parts, we get:

$$ \int_K r_n^h V_{h,0,K} \cdot \nabla V^n \cdot (V^n_{h,0,K} - u^n_K) \, dx = \sum_{\sigma \in \mathcal{E}(K)} |\sigma| r^n_{h,K} [V^n_{h,0,K} \cdot n_{\sigma,K}] (V^n_{h,0,K} - u^n_K)$$

$$= \sum_{\sigma \in \mathcal{E}(K)} |\sigma| r^n_{h,K} [V^n_{h,0,K} \cdot n_{\sigma,K}] (V^n_{h,K} - V^n_{h,0,K}) \cdot (V^n_{h,0,K} - u^n_K),$$

thanks to the the fact that $\sum_{\sigma \in \mathcal{E}(K)} \int_{\sigma} V^n_{h,K} \cdot n_{\sigma,K} \, dS = 0$.

Next we write

$$\mathcal{T}_{3,1} = \mathcal{T}_{3,2} + \mathcal{R}_{3,2}, \quad \mathcal{R}_{3,2} = \Delta t \sum_{n=1}^{m} \mathcal{R}^n_{3,2},$$

$$\mathcal{T}_{3,2} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \sum_{\sigma \in \mathcal{E}(K)} |\sigma| (\hat{r}_{h,0,\sigma} - \hat{r}_{h,0,\sigma}^{n,up}) [V^n_{h,0,K} \cdot n_{\sigma,K}] (V^n_{h,K} - V^n_{h,0,K}) \cdot (V^n_{h,0,K} - u^n_K)$$

$$+ \sum_{K \in T} \sum_{\sigma \in \mathcal{E}(K)} |\sigma| (\hat{r}_{h,0,\sigma} - \hat{r}_{h,0,\sigma}^{n,up}) \left( (V^n_{h,0,K} - \hat{V}^{n,up}_{h,0,\sigma}) \cdot n_{\sigma,K} \right) (V^n_{h,K} - V^n_{h,0,K}) \cdot (V^n_{h,0,K} - u^n_K)$$

$$+ \sum_{K \in T} \sum_{\sigma \in \mathcal{E}(K)} |\sigma| (\hat{r}_{h,0,\sigma} - \hat{r}_{h,0,\sigma}^{n,up}) \hat{V}^{n,up}_{h,0,\sigma} \cdot n_{\sigma,K} (V^n_{h,K} - V^n_{h,0,K}) \cdot (V^n_{h,0,K} - \hat{V}^{n,up}_{h,0,\sigma} - (u^n_K - \hat{u}^{n,up}_{h,0,\sigma})).$$

We may write

$$V^n_{h,0,K} = V^n_{h,0,K} - V^n_{h,K} + V^n_{h,K} - V^n_{h,0,\sigma} + [V^n_{h} - V^n_{h,0}]_{K},$$

and use several times the Taylor formula along with (2.40)$_{s=1}$, (2.52), (2.41)$_{s=1}$, (2.48)–(2.49) (in order to estimate $r^n_{h,K} - \hat{r}_{h,0,\sigma}^{n,up}$, $V^n_{h,0,K}$, $V^n_{h,K} - \hat{V}^{n,up}_{h,\sigma}$) to get the bound

$$|\mathcal{R}^n_{3,2}| \leq h c \|r\|_{W^{1,\infty}(\Omega)} \left( 1 + \|V\|_{W^{1,\infty}(Q_T; \mathbb{R}^3)} \right)^3 \sum_{K \in T} h |\sigma| |u^n_K|$$

$$+ c \|r\|_{W^{1,\infty}(\Omega)} \left( 1 + \|V\|_{W^{1,\infty}(Q_T; \mathbb{R}^3)} \right)^2 \sum_{K \in T} \sum_{\sigma \in \mathcal{E}(K)} h |\sigma| |u^n_K - u^n_{\sigma}|.$$
We have by the Hölder inequality
\[
\sum_{K \in T} h|\sigma||u^n_K| \leq c \left( \sum_{\sigma \in T} h|\sigma||u^n_K|^{6/5} \right)^{1/6} \leq c \left( \sum_{K \in T} \|u^n - u^n_K\|_{L^6(K;\mathbb{R}^3)}^{6/5} \right)^{1/6} + \left( \sum_{K \in T} \|u^n\|_{L^6(K;\mathbb{R}^3)}^{6/5} \right)^{1/6} \leq c \left( \sum_{K \in T} \|\nabla u_n\|^2_{L^2(K;\mathbb{R}^3)} \right)^{1/2},
\]
\[
\sum_{K \in T} \sum_{\sigma \in \mathcal{E}(K)} h|\sigma||u^n_K - u^n_\sigma| \leq c \left( \sum_{K \in T} \|u^n - u^n_K\|^2_{L^2(K;\mathbb{R}^3)} \right)^{1/2} + \left( \sum_{K \in T} \sum_{\sigma \in \mathcal{E}(K)} \|u^n - u^n_\sigma\|^2_{L^2(K;\mathbb{R}^3)} \right)^{1/2} \leq h c \left( \sum_{K \in T} \|\nabla u_n\|^2_{L^2(K;\mathbb{R}^3)} \right),
\]
where we have used (2.54)_{p=2}, (2.52)–(2.53)_{p=2}. Consequently, we may use (4.4) to conclude
\[
|\mathcal{R}_{3,2}| \leq h c \left( M_0, E_0, \nabla r, V, \nabla V \right)_{L^\infty(Q_T;\mathbb{R}^{15})}. \tag{7.16}
\]
Finally, we replace in \( T_{3,2} V^n - V^n_{h,0,K} \) by \( V^n_{h,0,\sigma} - V^n_{h,0,K} \). We get
\[
T_{3,2} = T_{3,3} + \mathcal{R}_{3,3}, \quad \mathcal{R}_{3,3} = \Delta t \sum_{n=1}^m \mathcal{R}_{3,3}^n,
\]
\[
\mathcal{T}_{3,3} = \Delta t \sum_{n=1}^m \sum_{K \in T} \sum_{\sigma \in \mathcal{E}(K)} |\sigma|\hat{r}^{n,up}_{\sigma} [\hat{V}^{n,up}_{h,0,\sigma} \cdot n_{\sigma,K}] [V^n_{h,0,\sigma} - V^n_{h,0,K}] \cdot (\hat{V}^{n,up}_{h,0,\sigma} - \hat{u}^{n,up}_{\sigma}), \tag{7.17}
\]
and
\[
\mathcal{R}_{3,3}^n = \sum_{K \in T} \sum_{\sigma \in \mathcal{E}(K)} |\sigma|\hat{r}^{n,up}_{\sigma} V^n_{h,0,K} \cdot n_{\sigma,K} [V^n - V^n_{h,0,\sigma} - V^n - V^n_{h,0,K}] \cdot (\hat{V}^{n,up}_{h,0,\sigma} - \hat{u}^{n,up}_{\sigma}),
\]
committing error
\[
|\mathcal{R}_{3,3}| \leq h c \left( M_0, E_0, \nabla r, V, \nabla V \right)_{L^\infty(Q_T;\mathbb{R}^{15})}, \tag{7.18}
\]
as in the previous step.

**Step 4: Terms \( T_4 \)** We write
\[
\mathcal{T}_4 = \mathcal{T}_{4,1} + \mathcal{R}_{4,1}, \quad \mathcal{T}_{4,1} = -\int_{\Omega_h} \nabla p(r^n) \cdot \mathbf{V}^n dx,
\]
\[
\mathcal{R}_{4,1} = \int_{\Omega_h} \nabla p(r^n) \cdot (\mathbf{V}^n - V^n_{h,0}) dx;
\]
whence
\[
|\mathcal{R}_{4,1}| \leq h c \left( \nabla r, \nabla r, \nabla r \right)_{L^\infty(Q_T;\mathbb{R}^{15})}, \tag{7.19}
\]
by virtue of (2.40)_{a=1}, (2.48)–(2.49).
Next, employing the integration by parts
\[ T_{4,2} = T_{4,2} + R_{4,2}, \quad T_{4,2} = \int_{\Omega_h} p(r^n) \, \text{div} \, V^n \, dx, \]
\[ R_{4,2} = - \sum_{K \in T} \sum_{\sigma \in E(K), \sigma \in \partial \Omega_h} \int_{\sigma} p(r^n) V^n \cdot n_{\sigma, K} \, dS = - \sum_{K \in T} \sum_{\sigma \in E(K), \sigma \in \partial \Omega_h} \int_{\sigma} p(r^n) \left( V^n - V^n_{h,0,\sigma} \right) \cdot n_{\sigma, K} \, dS. \]
Writing
\[ V^n - V^n_{h,0,\sigma} = V^n - V^n_{h} + V^n_{h} - V^n_{h,\sigma} + [V^n_{h} - V^n_{h,0}]_{\sigma}, \]
we deduce by using (2.40)\(_{s=1}\), (2.41)\(_{s=1}\), (2.53)\(_{p=\infty}\), (2.48), (2.49),
\[ \| V^n - V^n_{h,0,\sigma} \|_{L^{\infty}(K;\mathbb{R}^3)} \lesssim h \| \nabla V^n \|_{L^{\infty}(K;\mathbb{R}^3)}, \quad \sigma \in K. \]
Now, we employ the fact that
\[ \sum_{K \in T} \sum_{\sigma \in E(K), \sigma \in \partial \Omega_h} \int_{\sigma} dS \approx 1; \]
whence
\[ |R_{4,2}| \leq hc(\mathcal{T}, |p|_{C[\overline{\Omega}]}, \| \nabla V \|_{L^{\infty}(Q_T;\mathbb{R}^3)}) \tag{7.20} \]
Finally,
\[ T_{4,2} = T_{4,3} + R_{4,3}, \quad T_{4,3} = \int_{\Omega_h} p(r^n) \, \text{div} \, V^n \, dx, \quad R_{4,3} = \int_{\Omega_h} (p(r^n) - p(\hat{r}^n)) \, \text{div} \, V^n \, dx; \tag{7.21} \]
whence
\[ |R_{4,3}| \leq hc(|p'|_{C[\overline{\Omega}]}, \| \nabla r, \nabla V \|_{L^{\infty}(Q_T;\mathbb{R}^{32})}). \tag{7.22} \]

**Step 5:** Term \( T_6 \) We decompose \( T_6 \) as
\[ T_6 = T_{6,1} + R_{6,1}, \quad T_{6,1} = -\Delta t \sum_{n=1}^{m} \sum_{K \in T} \int_{K} p'(\hat{r}^n) u^n \cdot \nabla r^n \, dx, \tag{7.23} \]
\[ R_{6,1} = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \int_{K} \left( p'(\hat{r}^n) - p'(\hat{r}^n) \right) \cdot u^n \cdot \nabla r^n \, dx. \]
Consequently, by the Taylor formula, Hölder inequality and estimate (4.5),
\[ |R_{6,1}| \leq hc(M_0, E_{0,1}, \sum_{\tau} |p'|_{C[\overline{\Omega}]}, \| \nabla r \|_{L^{\infty}(Q_T;\mathbb{R}^3)}). \tag{7.24} \]

Gathering the formulae (7.7), (7.12), (7.17), (7.21), (7.23) and estimates for the residual terms (7.8), (7.9)–(7.13), (7.14)–(7.18), (7.19), (7.20), (7.22), (7.24) concludes the proof of Lemma 7.1. \( \square \)

**8. A Gronwall Inequality**

In this section we put together the relative energy inequality (6.1) and the identity (7.1) derived in the previous section. The final inequality resulting from this manipulation is formulated in the following lemma.
Lemma 8.1. Let \((\rho^n, u^n)\) be a solution of the discrete problem (3.5)–(3.7) with the pressure satisfying (1.4), where \(\gamma \geq 3/2\). Then there exists a positive number
\[
c = c \left( M_0, E_0, \varrho, \frac{1}{\gamma}, \| \partial r, \nabla r, V, \partial_t V, \nabla V, \nabla^2 V \|_{L^\infty(Q_T; \mathbb{R}^3)}, \right.
\]
\[
\| \partial^2 r \|_{L^1(0, T; L^{\gamma'}(\Omega))}, \| \partial_t \nabla r \|_{L^2(0, T; L^{6\gamma/5}(\Omega; \mathbb{R}^3))}, \| \partial_t^2 V, \partial_t \nabla V \|_{L^2(0, T; L^{6/5}(\Omega; \mathbb{R}^1))},
\]
such that for all \(m = 1, \ldots, N\), there holds:
\[
\mathcal{E}(\rho^m, u^m|\hat{r}^m, \hat{V}^m_{h,0}) + \Delta t \frac{1}{2} \sum_{n=1}^{m} \sum_{K \in T} |\nabla_x (u^n - V^n_k)|^2 dx
\]
\[
\leq c \left[ h^n + \sqrt{\Delta t} + \mathcal{E}(\rho^0, u^0|\hat{r}(0), \hat{V}_{h,0}(0)) \right] + c \Delta t \sum_{n=1}^{m} \mathcal{E}(\rho^n, u^n|\hat{r}^n, \hat{V}^n_{h,0}),
\]
with any couple \((r, V)\) belonging to (2.25) and satisfying the continuity equation (1.1) on \((0, T) \times \mathbb{R}^3\) and momentum equation (1.2) with boundary conditions (1.5) on \((0, T) \times \Omega\) in the classical sense, where \(a\) is defined in (3.9) and \(\mathcal{E}\) is given in (4.9).

Proof. We observe that
\[
S_6 - S_6 = \Delta t \sum_{n=1}^{m} \int_{\Omega_h} p'(\hat{r}^n) \frac{\hat{\rho}^n - \rho^n}{\hat{\rho}^n} V^n \cdot \nabla r^n dx + \Delta t \sum_{n=1}^{m} \int_{\Omega_h} p'(\hat{r}^n) \frac{\hat{\rho}^n - \rho^n}{\hat{\rho}^n} (u^n - V^n) \cdot \nabla r^n dx.
\]
Gathering the formulae (6.1) and (6.2), one gets
\[
\mathcal{E}(\rho^m, u^m|\hat{r}^m, \hat{V}^m_{h,0}) - \mathcal{E}(\rho^0, u^0|\hat{r}(0), \hat{V}_{h,0}(0)) + \mu \Delta t \sum_{n=1}^{m} \sum_{K \in T} |\nabla(u^n - V^n_{0,h})|^2_{L^2(K; \mathbb{R}^3)} \leq \sum_{i=1}^{4} \mathcal{P}_i + \mathcal{Q}, \quad (8.1)
\]
where
\[
\mathcal{P}_1 = \Delta t \sum_{n=1}^{m} \sum_{K \in T} |K|(\hat{\rho}^{n-1}_K - r^{n-1}_K) \frac{V^n_{h,0,K} - V^{n-1}_{h,0,K}}{\Delta t} \cdot (V^n_{h,0,K} - u^n_K),
\]
\[
\mathcal{P}_2 = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \sum_{\sigma = K \cup K' \in \mathcal{E}_K} |\sigma| (q^{n,up}_{\sigma} - p^{n,up}_{\sigma}) \left( \hat{V}^{n,up}_{h,0,\sigma} - \hat{u}^{n,up}_{\sigma} \right) \cdot \left( V^n_{h,0,\sigma} - V^n_{h,0,K} \right) \cdot V^n_{h,0,\sigma} \cdot n_{\sigma,K},
\]
\[
\mathcal{P}_3 = -\Delta t \sum_{n=1}^{m} \int_{\Omega_h} \rho(q^n) - p'(\hat{r}^n)(\rho^n - \hat{r}^n) \cdot \rho(q^n) \) div\(V^n, \)
\]
\[
\mathcal{P}_4 = \Delta t \sum_{n=1}^{m} \sum_{K \in T} \int_K p'(\hat{r}^n) \frac{\hat{\rho}^n - \rho^n}{\hat{\rho}^n} (u^n - V^n) \cdot \nabla r^n dx,
\]
\[
\mathcal{Q} = \mathcal{R}_h^m + R_{h,\Delta t}^m + G^m.
\]
Now, we estimate conveniently the terms \(\mathcal{P}_i, i = 1, \ldots, 4\) in four steps.
Step 1: Term $\mathcal{P}_1$. We estimate the $L^\infty$ norm of $\frac{V_{h.o.K}^n - V_{h.o.K}^{n-1}}{\Delta t}$ by $L^\infty$ norm of $\partial_t V$ in the same manner as in (6.5). According to Lemma 7.2, $|q - r|^1_{1+\ell/2,2,\pi}(q) \leq c(p)E^p(q|r)$, with any $p \geq 1$; in particular,

$$|q - r|^{6/5}_{1+\ell/2,2,\pi}(q) \leq cE(q|r)$$  \hspace{1cm} (8.2)

provided $\gamma \geq 6/5$.

We get by using the Hölder inequality,

$$
\sum_{K \in \mathcal{T}} |K|(q_{K}^{n-1} - q_{K}^{n-1}) \frac{V_{h.o.K}^n - V_{h.o.K}^{n-1}}{\Delta t} \cdot (\nabla V_{h.o.K}^n - \nabla u_n^K) |\leq c\|\partial_t V\|_{L^\infty(Q_T;R^3)} + \left( \sum_{K \in \mathcal{T}} |K|(q_{K}^{n-1} - q_{K}^{n-1})^{6/5} |1_{L^2(\pi)}(q_{K})|^{5/6} \right) \left( \sum_{K \in \mathcal{T}} |K|(q_{K}^{n-1} - q_{K}^{n-1})^{5/6} |1_{L^2(\pi)}(q_{K})|^{1/6} \right)
$$

where we have used (8.2) and estimate (4.8) to obtain the last line. Now, we write $V_{h.o.K}^n - u_n^K = (V_{h.o.K}^n - u_n^K) - (V_{h.o.K}^n - u_n^K)$ and use the Minkowski inequality together with formulas (2.54), (2.43) to get

$$
\sum_{K \in \mathcal{T}} \|V_{h.o.K}^n - u_n^K\|_{L^6(\pi)}^{6} \leq c \left( \sum_{K \in \mathcal{T}} \|V_{h.o.K}^n - u_n^K\|_{L^6(\pi)}^{6} \right)^{1/6}.
$$

Finally, employing Young’s inequality, and estimate (4.8), we arrive at

$$|\mathcal{P}_1| \leq c \left( \sum_{K \in \mathcal{T}} \|V_{h.o.K}^n - u_n^K\|_{L^6(\pi)}^{6} \right)^{1/6} \leq \left( \sum_{K \in \mathcal{T}} \|V_{h.o.K}^n - u_n^K\|_{L^6(\pi)}^{6} \right)^{1/2}.
$$

Step 2: Term $\mathcal{P}_2$. We rewrite $V_{h.o,K}^n - V_{h.o.K}^n = V_{h.o,K}^n - V_{h.o,K}^{n-1} + [V_{h.o,K}^{n-1} - V_{h.o,K}^{n}]_{1+\ell/2,2,\pi}(q) \leq c(\sum_{n=1}^{m} \|V_{h.o,K}^n - u_n^K\|_{L^2(\pi)}^{2})$, with any $\delta > 0$. Now we write $\mathcal{P}_2 = \Delta t \sum_{n=1}^{m} \mathcal{P}_2^n$ where Lemma 7.2 and the Hölder inequality yield, similarly as in the previous step,

$$|\mathcal{P}_2^n| \leq c \left( \sum_{K \in \mathcal{T}} \|\nabla V\|_{L^\infty(Q_T;R^3)} \right)
$$

where $\mathcal{P}_2^n = \Delta t \sum_{n=1}^{m} \mathcal{P}_2^n$ where Lemma 7.2 and the Hölder inequality yield, similarly as in the previous step,

$$
|\mathcal{P}_2^n| \leq c \left( \sum_{K \in \mathcal{T}} \|\nabla V\|_{L^\infty(Q_T;R^3)} \right) \left( \sum_{K \in \mathcal{T}} \sum_{\sigma \in \mathcal{E}(K)} |\sigma|h \left( E^{1/2}(q_{\sigma}^{n,up}|q_{\sigma}^{n,up}) + E^{2/3}(q_{\sigma}^{n,up}|q_{\sigma}^{n,up}) \right) \right)^{1/2}.
$$

Finally, employing Young’s inequality, and estimate (4.8), we arrive at

$$|\mathcal{P}_2^n| \leq c \left( \sum_{K \in \mathcal{T}} \|\nabla V\|_{L^\infty(Q_T;R^3)} \right) \left( \sum_{K \in \mathcal{T}} \sum_{\sigma \in \mathcal{E}(K)} |\sigma|h \left( E^{1/2}(q_{\sigma}^{n,up}|q_{\sigma}^{n,up}) \right) \right)^{1/2}.
$$
provided $\gamma \geq 3/2$. Next, we observe that the term of the face $\sigma = K|L$ to the sums $\sum_{K \in T} \sum_{r \in \mathcal{E}(K)} |\sigma| h(E(\rho^p_{\text{up}} | r^n_{\text{up}}) + \sum_{K \in T} \sum_{r \in \mathcal{E}(K)} |\sigma| h(V^{n,up}_{h,0,\sigma} - \hat{u}^n_{\text{up}})|^6$ is less or equal than $2|\sigma| h(E(\rho^p_K | \tilde{r}^n_K) + E(\rho^p_L | \tilde{r}^n_L))$, and that $2|\sigma| h(||V^n_{h,0,K} - u^n_K||^6 + ||V^n_{h,0,L} - u^n_L||^6)$, respectively. Consequently, we get by the same reasoning as in the previous step, under assumption $\gamma \geq 3/2$,

$$|\mathcal{P}_2| \leq c(\delta, M_0, E_0, L, \bar{\tau}, \|\nabla \mathbf{V} \|_{L^\infty(Q_T; \mathbb{R}^d)}) \Delta t \sum_{n=1}^m \mathcal{G}(\rho^n, \hat{u}^n | \tilde{r}^n, \hat{V}^n_{h,0}) + \delta \Delta t \sum_{n=1}^m \|\nabla (V^n_{h,0} - u^n)\|^2_{L^2(K; \mathbb{R}^3)}. \tag{8.4}$$

**Step 3:** Term $\mathcal{P}_3$. We realize that

$$p(\rho^n_{\text{K}}) - p'(r^n_{\text{K}})(\rho^n_{\text{K}} - r^n_{\text{K}}) - p(r^n_{\text{K}}) \leq c(\bar{\tau}) E(\rho_K | r_K),$$

by virtue of Lemma 7.2 in combination with assumption (1.4). Consequently,

$$|\mathcal{P}_3| \leq c \|\nabla \mathbf{V} \|_{L^\infty(Q_T)} \Delta t \sum_{n=1}^m \mathcal{G}(\rho^n, \hat{u}^n | \tilde{r}^n, \hat{V}^n_{h,0}) \tag{8.5}$$

**Step 4:** Term $\mathcal{P}_4$. We write $u^n - V^n$ as the sum $(u^n - V^n_{h,0}) + (V^n_{h,0} - V^n)$ accordingly splitting $\mathcal{P}_4$ into two terms

$$\Delta t \sum_{n=1}^m \sum_{K \in T} \int_K \frac{p'(\tilde{r}^n)}{\tilde{r}^n} (u^n - V^n_{h,0}) \cdot \nabla \tilde{r}^n \, dx \text{ and } \Delta t \sum_{n=1}^m \sum_{K \in T} \int_K \frac{p'(\tilde{r}^n)}{\tilde{r}^n} (V^n_{h,0} - V^n) \cdot \nabla \tilde{r}^n \, dx.$$

Reasoning similarly as in Step 2, we get

$$|\mathcal{P}_4| \leq h^2 c(\delta, M_0, E_0, L, \bar{\tau}, |p'|_{C(\bar{\tau}^2)}) \|\nabla \mathbf{V} \|_{L^\infty(Q_T)} \Delta t \sum_{n=1}^m \mathcal{G}(\rho^n, \hat{u}^n | \tilde{r}^n, \hat{V}^n_{h,0}) + \delta \Delta t \sum_{n=1}^m \|\nabla (V^n_{h,0} - u^n)\|^2_{L^2(K; \mathbb{R}^3)}. \tag{8.6}$$

Gathering the formulae (8.1) and (8.3)–(8.6) with $\delta$ sufficiently small (with respect to $\mu$), we conclude the proof of Lemma 8.1. \hfill \Box

9. **End of the proof of the error estimate (Thm. 3.2)**

Finally, Lemma 8.1 in combination with the bound (4.8) yields

$$\mathcal{G}(\rho^m, \hat{u}^m | \tilde{r}^m, \hat{V}^m_{h,0}) \leq c \left[ h^A + \sqrt{\Delta t} + \Delta t + \mathcal{E}(\rho^0, \hat{u}^0 | \tilde{r}(0), \hat{V}^n_{h,0}(0)) \right] + c \Delta t \sum_{n=1}^{m-1} \mathcal{G}(\rho^n, \hat{u}^n | \tilde{r}^n, \hat{V}^n_{h,0});$$

whence by the discrete standard version of the Gronwall lemma one gets at the first step

$$\mathcal{G}(\rho^m, \hat{u}^m | \tilde{r}^m, \hat{V}^m_{h,0}) \leq c \left[ h^A + \sqrt{\Delta t} + \mathcal{E}(\rho^0, \hat{u}^0 | \tilde{r}(0), \hat{V}^n_{h,0}(0)) \right].$$

Going with this information back to Lemma 8.1, one gets finally

$$\mathcal{G}(\rho^m, \hat{u}^m | \tilde{r}^m, \hat{V}^m_{h,0}) + \Delta t \sum_{n=1}^{m} \int_K |\nabla_x (u^n - V^n_{h,0})|^2 \, dx \leq c \left[ h^A + \sqrt{\Delta t} + \mathcal{E}(\rho^0, \hat{u}^0 | \tilde{r}(0), \hat{V}^n_{h,0}(0)) \right]. \tag{9.1}$$
Now, we write
\[
\varrho_K^n (u_K^n - V_{h,0,K})^2 = \varrho_K^n (u_K^n - V_h^n)^2 + 2 \varrho_K^n (V_h^n - V_{h,0,K})^2 + \varrho_K^n (V_h^n - V_{h,0,K})^2,
\]
where
\[
\|V_h^n - V_{h,0,K}\|_{L^\infty(K;\mathbb{R}^3)} \lesssim \|V_h^n - V_h^n\|_{L^\infty(K;\mathbb{R}^3)} + \|V_h^n - V_h^n\|_{L^\infty(K;\mathbb{R}^3)} + \|V_h^n - V_{h,0,K}\|_{L^\infty(K;\mathbb{R}^3)} \lesssim h \|\nabla V_h^n\|_{L^\infty(K;\mathbb{R}^3)}.
\]
In the above calculation we have employed formula (2.40) to estimate the first term, estimates (2.52)_{s=1}, (2.41)_{s=1} to estimate the second term, and formulas (2.48) and (2.49) for $K \cap \partial \Omega_h = \emptyset$ and $K \cap \partial \Omega_h \neq \emptyset$, respectively, to evaluate the last term. We conclude that
\[
\sum_{K \in T} \frac{1}{2} |K| \left( \varrho_K^n |u_K^n - V_{h,0,K}|^2 - \varrho_K^n |u_K^n - V_{h,0,K}|^2 \right) \geq \int_{\Omega \cap \Omega_h} \varrho_m^n (u_K^n - u_K^n)^2 dx - \int_{\Omega \cap \Omega_h} \varrho_0^n (u_K^n - u_K^n)^2 dx + L_1,
\]
where
\[
|L_1| \lesssim h M_0 \|\nabla x V_h\|_{L^\infty((0,T) \times \Omega; \mathbb{R}^3)}.
\]
Similarly, we find with help of (4.8),
\[
\|E(\varrho_K^n r^n) - E(\varrho_K^n r^n)\|_{L^\infty(K)} \leq h c(M_0, \mathbb{Z}, \Gamma, \|c_1 \mathbb{Z} \| \|\nabla r\|_{L^\infty(Q_T; \mathbb{R}^3)});
\]
whence
\[
\sum_{K \in T} |K| \left( |E(\varrho_K^n r^n) - E(\varrho_K^n r^n)| \right) \geq \int_{\Omega \cap \Omega_h} E(\varrho_m^n |r_m^n|) dx - \int_{\Omega \cap \Omega_h} E(\varrho_0^n |r_0^n|) dx + L_2,
\]
where
\[
|L_2| \leq h c(M_0, \mathbb{Z}, \Gamma, \|c_1 \mathbb{Z} \| \|\nabla r\|_{L^\infty(Q_T; \mathbb{R}^3)}).
\]
Finally, by virtue of (2.48)–(2.49) and (2.41)_{s=2}
\[
\|\nabla (V_{h,0} - V_h^n)\|_{L^2(K;\mathbb{R}^3)} \lesssim h \|\nabla V_h^n, \nabla^2 V_h^n\|_{L^\infty(K;\mathbb{R}^{12})};
\]
whence
\[
\Delta t \sum_{n=1}^m \sum_{K \in T} \left| \nabla_x (u_h^n - V_{h,0}) \right|^2 dx \geq \Delta t \sum_{n=1}^m \int_{\Omega \cap \Omega_h} |(\nabla_x u_h^n - \nabla_x V_h^n)|^2 dx + L_3,
\]
where
\[
|L_3| \leq h^2 c(\|\nabla V_h^n, \nabla^2 V_h^n\|_{L^\infty(K;\mathbb{R}^{12})}).
\]

Theorem 3.2 is a direct consequence of estimate (9.1) and identities (9.2)–(9.4). Theorem 3.2 is thus proved.

10. CONCLUDING REMARKS

In the convergence proofs one usually needs to complete the numerical scheme by stabilizing terms, so that the new numerical scheme reads
\[
\sum_{K \in T_h} |K| \frac{\varrho_K^n - \varrho_K^{n-1}}{\Delta t} \phi_K + \sum_{K \in T_h} \sum_{\sigma \in E(K)} |\sigma| \varrho_{\sigma, n}^{\text{up}} (u^n_{\sigma} \cdot n_{\sigma,K}) \phi_K + T_c(\phi) = 0,
\]
for any $\phi \in Q_h(\Omega_h)$ and $n = 1, \ldots, N$,
\[
\sum_{K \in T} \frac{K}{\Delta t} \left( g_K^n u_K^n - g_K^{n-1} u_K^{n-1} \right) \cdot v_K + \sum_{K \in T} \sum_{\sigma \in \mathcal{E}(K)} |\sigma| g_\sigma^{n,up} u_\sigma^{n,up} [u_\sigma^n \cdot n_{\sigma,K}] \cdot v_K
\]
\[
- \sum_{K \in T} p(g_K^n) \sum_{\sigma \in \mathcal{E}(K)} |\sigma| v_\sigma \cdot n_{\sigma,K} + \mu \sum_{K \in T} \int_K \nabla u^n : \nabla v \, dx
\]
\[
+ \frac{\mu}{3} \sum_{K \in T} \int_K \text{div} u^n \text{div} v \, dx + T_m(\phi) = 0, \quad \text{for any } v \in V_h(\Omega; R^3) \text{ and } n = 1, \ldots, N,
\]
where
\[
T_c(\phi) = h^{1-\epsilon} \sum_{\sigma \in \mathcal{E}_{\text{int}}} |\sigma| [g^n_{\sigma}]^2_{\sigma,n_{\sigma}}, \quad T_m(\phi) = \sum_{\sigma \in \mathcal{E}_{\text{int}}} |\sigma| [\hat{u}^n_{\sigma}]_{\sigma,n_{\sigma}}, \quad \epsilon \in [0, 1),
\]
(see [20, 30]). These terms are designed to provide the supplementary positive term
\[
h^{1-\epsilon} \sum_{\sigma \in \mathcal{E}_{\text{int}}} |\sigma| [g^n_{\sigma}]^2_{\sigma,n_{\sigma}},
\]
to the left hand side of the discrete energy identity (4.2). They contribute to the right hand side of the discrete relative energy inequality (5.1) by supplementary terms whose absolute value is bounded from above by
\[
h^{(1-\epsilon)/2} c \left( M_0, E_0, \sup_{n=0,\ldots,N} \| r^n, U^n, \nabla U^n \|_{L^\infty(\Omega_h; \mathbb{R}^3)}, \sup_{n=0,\ldots,N} \sup_{\sigma \in \mathcal{E}_{\text{int}}} \| r^n_{\sigma,n_{\sigma}} / h \right).
\]
Consequently, they give rise to the contributions at the right hand side of the approximate relative energy inequality (6.1) whose bound is
\[
h^{(1-\epsilon)/2} c \left( M_0, E_0, \| r, \nabla r, U, \nabla U \|_{L^\infty(Q_T; \mathbb{R}^3)} \right).
\]
Similar estimates are true, if we replace in the numerical scheme everywhere classical upwind formula (3.4) by the modified upwind suggested in [15]:
\[
U_{K}(q, u) = \sum_{\sigma \in \mathcal{E}(K)} q_{\sigma}^{K} u_{\sigma} \cdot n_{\sigma,K} = \sum_{\sigma \in \mathcal{E}(K)} \frac{q_{\sigma}}{\sigma = K|L} \left( q_{\sigma} [u_{\sigma} \cdot n_{\sigma,K}] + q_{L} [u_{\sigma} \cdot n_{\sigma,K}] \right),
\]
by the modified upwind (10.3)
\[
U_{K}(q, u) = \sum_{\sigma \in \mathcal{E}(K)} \frac{q_{\sigma}}{\sigma = K|L} \left( [u_{\sigma} \cdot n_{\sigma,K} + h^{1-\epsilon}]^+ + [u_{\sigma} \cdot n_{\sigma,K} - h^{1-\epsilon}]^- \right)
\]
\[
+ \frac{q_{L}}{2} \left( [u_{\sigma} \cdot n_{\sigma,K} + h^{1-\epsilon}]^- + [u_{\sigma} \cdot n_{\sigma,K} - h^{1-\epsilon}]^- \right),
\]
where $\sigma = K|L \in \mathcal{E}_{\text{int}}$. We will finish by formulating the error estimate for the numerical problem (3.5), (10.1), (10.2) or for (3.5), (3.6), (3.7) with modified upwind (10.3).

**Theorem 10.1.** Let $\Omega$, $p$, $[r_0, V^0]$, $[r, V]$ satisfy assumptions of Theorem 3.2. Let $(q^n, u^n)_{n=0,\ldots,N}$ be a family of numerical solutions to the scheme (3.5), (10.1), (10.2) or to the scheme (3.5), (3.6), (3.7) with modified upwind (10.3), where $\epsilon \in [0, 1)$. Then error estimate (3.8) holds true with the exponent
\[
a = \min \left\{ \frac{2\gamma - 3}{\gamma}, \frac{1 - \epsilon}{2} \right\} \text{ if } \frac{3}{2} \leq \gamma < 2, \quad a = \frac{1 - \epsilon}{2} \text{ if } \gamma \geq 2.
\]
Finally, a natural question arises as top what extent the obtained error estimates are optimal. In the light of the results obtained in [28, 29], it may seem we loose, in particular in terms of the spatial discretization parameter $h$ for $\gamma \to 3/2$. On the other hand, however, it is worth noting we do not make any extra assumption concerning boundedness of the numerical solutions in contrast with [28].
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