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► **To cite this version:**

Thierry Gallouët, Raphaelae Herbin, David Maltese, Antonin Novotny. Implicit MAC scheme for compressible Navier-Stokes equations: Unconditional error estimates. 2017. hal-01448698

**HAL Id: hal-01448698**

**<https://hal.science/hal-01448698>**

Preprint submitted on 28 Jan 2017

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# Implicit MAC scheme for compressible Navier-Stokes equations: Unconditional error estimates

Thierry Gallouët      Raphaële Herbin      David Maltese      Antonin Novotny\*

January 27, 2017

Aix-Marseille Université, CNRS, Centrale Marseille, I2M, UMR 7373, 13453 Marseille, France

and

IMATH, EA 2134, Université de Toulon BP 20132, 83957 La Garde, France

## Abstract

We prove existence of a solution to the implicit MAC scheme for the compressible Navier-Stokes equations. We derive error estimates for this scheme on two and three dimensional Cartesian grids. These estimates are unconditional: They are uniform with respect to the space and time discretization with coefficient independent on the numerical solution. Error estimates are obtained by using the discrete version of the *relative energy method* introduced on the continuous level in [16]. A systematic use of the theoretical "continuous" analysis of the equations in combination with the numerical tools is crucial for the result. This is the first proof ever of the unconditional error estimate of the MAC scheme for the compressible Navier-Stokes equations.

**Keywords:** Compressible fluids, Navier-Stokes equations, Cartesian grids, Marker and Cell scheme, Error estimates.

**AMS classification** 35Q30, 65N12, 76N10, 76N15, 76M12, 76M20

## 1 Introduction

The aim of this paper is to derive error estimates for approximate solutions of the compressible barotropic Navier-Stokes equations obtained by the Marker-and-cell scheme. These equations are posed on the time-space domain  $Q_T = (0, T) \times \Omega$ , where  $\Omega$  is a bounded domain of  $\mathbb{R}^d$ ,  $d = 2, 3$ , adapted to the MAC scheme (see section 3), and  $T > 0$ , and read:

$$\partial_t \varrho + \operatorname{div}(\varrho \mathbf{u}) = 0, \tag{1.1a}$$

$$\partial_t(\varrho \mathbf{u}) + \operatorname{div}(\varrho \mathbf{u} \otimes \mathbf{u}) + \nabla p(\varrho) = \mu \Delta \mathbf{u} + (\mu + \lambda) \nabla \operatorname{div} \mathbf{u}, \tag{1.1b}$$

supplemented with the initial conditions

$$\varrho(0, \mathbf{x}) = \varrho_0(\mathbf{x}), \quad \varrho \mathbf{u}(0, \mathbf{x}) = \varrho_0 \mathbf{u}_0, \tag{1.2}$$

where  $\varrho_0$  and  $\mathbf{u}_0$  are given functions from  $\Omega$  to  $\mathbb{R}_+^*$  and  $\mathbb{R}^d$  respectively, and boundary conditions

$$\mathbf{u}|_{(0,T) \times \partial\Omega} = 0. \tag{1.3}$$

In the above equations, the unknown functions are the scalar density field  $\varrho(t, \mathbf{x}) \geq 0$  and vector velocity field  $\mathbf{u} = (u_1, \dots, u_d)(t, \mathbf{x})$ , where  $t \in (0, T)$  denotes the time and  $\mathbf{x} \in \Omega$  is the space variable. The viscosity coefficients  $\mu$  and  $\lambda$ , assumed to be constant, are such that

$$\mu > 0, \quad \lambda + \mu \geq 0. \tag{1.4}$$

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\*This work was supported by the MODTERCOM project within the APEX programme of the Provence-Alpes-Côte d'Azur region

In the compressible barotropic Navier-Stokes equations, the pressure is a given function of the density. Here we assume that the pressure satisfies

$$p \in C([0, \infty)), p \in C^2(0, \infty), p(0) = 0, p'(\varrho) > 0 \text{ for all } \varrho > 0, \quad (1.5a)$$

$$\lim_{\varrho \rightarrow \infty} \frac{p'(\varrho)}{\varrho^{\gamma-1}} = p_\infty > 0, \quad \inf_{\varrho \in (0,1)} \frac{p'(\varrho)}{\varrho} = p_0 > 0 \quad (1.5b)$$

where  $\gamma \geq 1$ . We notice that assumptions (1.5) are compatible with the isentropic pressure law  $p(\varrho) = \varrho^\gamma$  provided  $1 \leq \gamma \leq 2$ .

The main underlying idea of this paper is to derive the error estimates for approximate solutions of problem (1.1)–(1.5) obtained by time and space discretization by using the discrete version of the *relative energy method* introduced for equations (1.1a), (1.1b) on the continuous level in [16, 18, 19].

The discrete relative energy method was suggested in [24] in the context of rather academic finite-volume:finite element scheme proposed in [35]. The method provides unconditional estimate of error between any numerical solution of the scheme [35] and a classical solution of equations (1.1)–(1.5), without any additional assumption on the numerical solution. This is highly wanted result, first of its type in the mathematical literature. The natural question arises whether a similar method can lead to similar unconditional error estimates for the less academic and more practical numerical schemes.

The main goal of this paper is to get unconditional error estimates for the MAC scheme implicit in time.

In spite of the fact that we stuck to the [24] methodology, the proofs remain still difficult. Not speaking on technicalities linked to the approximations, interpolations and projections to the relevant function spaces related to the MAC discretization, the most involved part is the treatment of transport terms in the continuity and momentum equations which requires derivation of quite sophisticated formulas involving primal and dual fluxes. In this part, our approach is reminiscent to the recent work of Therme [30] devoted to the staggered space approximations to the Euler equations.

Since the very beginning of the introduction of the Marker-and-Cell (MAC) scheme [29], it is claimed that this discretization is suitable for both incompressible and compressible flow problems (see [27, 28] for the seminal papers, [2, 5, 7, 31, 32, 34, 40–42, 44, 45] for subsequent developments and [46] for a review). The use of the MAC scheme in the incompressible case is now standard, and the proof of convergence for the MAC scheme in primitive variables has been recently been completed [23].

The paper is organized as follows. After recalling the fundamental setting of the problem and the relative energy inequality in the continuous case in Section 2, we proceed in Section 3 to the discretization: we introduce the discrete meshes and functional spaces and the definition of the numerical scheme, and state a known existence result, along with the main result of the paper, that is the error estimate, which is stated in Theorem 3.3. The remaining sections are devoted to the proof of Theorem 3.3:

- In Section 4 we derive estimates provided by the scheme.
- In Section 5, we derive the discrete intrinsic version of the relative energy inequality for the solutions of the numerical scheme (see Theorem 5.1). We then transform this inequality to a more convenient form, see Lemma 5.1.
- Finally, in Section 6, we investigate the form of the discrete relative energy inequality with the test functions being strong solutions to the original problem. This investigation is formulated in Lemma 6.1 and finally leads to a Gronwall type estimate formulated in Lemma 7.1. The latter yields the error estimates and finishes the proof of the main result.

The Theorem 3.3 remains valid for other finite volume schemes with staggered space discretization as e.g. non conforming Rannacher-Turek finite elements or the lowest degree Crouzeix-Raviart finite elements on simplicial meshes. These results are formulated without proofs, that are similar and simpler than those for the MAC scheme, in Appendix B.

## 2 The continuous problem

The aim of this section is to recall some fundamental notions and results for the continuous problem. We begin by the definition of weak solutions to problem (1.1)–(1.5). Let us introduce the Helmholtz's

function defined by

$$\mathcal{H}(\varrho) = \varrho \int_1^\varrho \frac{p(t)}{t^2} dt, \quad \varrho \geq 0. \quad (2.1)$$

Note that  $\mathcal{H} \in C(\mathbb{R}_+)$ ,  $\mathcal{H}(0) = 0$  and that  $\mathcal{H}$  is a solution on  $\mathbb{R}_+^*$  of the ordinary differential equation

$$\varrho \mathcal{H}' - \mathcal{H} = p \quad (2.2)$$

with the constant of integration fixed such that  $\mathcal{H}(1) = 0$ . Note also that

$$\mathcal{H}''(\varrho) = \frac{p'(\varrho)}{\varrho}. \quad (2.3)$$

and there exists  $c > 0$  only depending on  $p_\infty$  and  $\gamma$  such that

$$\frac{1}{c}(\varrho^\gamma + 1) \leq \mathcal{H}(\varrho) \leq c(\varrho^\gamma + 1), \quad \text{for all } \varrho \geq 1. \quad (2.4)$$

**Definition 2.1** (Weak solutions). *Let  $\varrho_0 : \Omega \rightarrow (0, +\infty)$  and  $\mathbf{u}_0 : \Omega \rightarrow \mathbb{R}^d$  with finite energy  $\mathcal{E}_0 = \int_\Omega (\frac{1}{2}\varrho_0|\mathbf{u}_0|^2 + \mathcal{H}(\varrho_0)) d\mathbf{x}$  and finite mass  $0 < M_0 = \int_\Omega \varrho_0 d\mathbf{x}$ . We shall say that the pair  $(\varrho, \mathbf{u})$  is a weak solution to the problem (1.1)–(1.5) emanating from the initial data  $(\varrho_0, \mathbf{u}_0)$  if:*

1.  $\varrho \in L^\infty(0, T; L^\gamma(\Omega))$ ,  $\varrho \geq 0$  a.e. in  $(0, T) \times \Omega$ ,  $\mathbf{u} \in L^2(0, T; H_0^1(\Omega)^d)$  and  $\varrho|\mathbf{u}|^2 \in L^\infty(0, T; L^1(\Omega))$ .
2. The continuity equation (1.1a) is satisfied in the following weak sense

$$\int_0^T \int_\Omega \left( \varrho \partial_t \varphi + \varrho \mathbf{u} \cdot \nabla \varphi \right) d\mathbf{x} dt = - \int_\Omega \varrho_0 \varphi(0, \mathbf{x}) d\mathbf{x}, \quad (2.5)$$

for any  $\varphi \in C_c^\infty([0, T] \times \overline{\Omega})$  such that  $\varphi(T, \cdot) = 0$ .

3. The momentum equation (1.1b) is satisfied in the weak sense,

$$\begin{aligned} & \int_0^T \int_\Omega \left( \varrho \mathbf{u} \cdot \partial_t \boldsymbol{\psi} + \varrho \mathbf{u} \otimes \mathbf{u} : \nabla \boldsymbol{\psi} + p(\varrho) \operatorname{div} \boldsymbol{\psi} \right) d\mathbf{x} dt \\ & - \int_0^T \int_\Omega \left( \mu \nabla \mathbf{u} : \nabla \boldsymbol{\psi} d\mathbf{x} dt + (\mu + \lambda) \operatorname{div} \mathbf{u} \operatorname{div} \boldsymbol{\psi} \right) d\mathbf{x} dt = - \int_\Omega \varrho_0 \mathbf{u}_0 \cdot \boldsymbol{\psi}(0, \mathbf{x}) d\mathbf{x}, \end{aligned} \quad (2.6)$$

for any  $\boldsymbol{\psi} \in C_c^\infty([0, T] \times \Omega)^d$  such that  $\boldsymbol{\psi}(T, \cdot) = \mathbf{0}$ .

4. The following energy inequality is satisfied a.e in  $(0, T)$

$$\int_\Omega \left( \frac{1}{2} \varrho |\mathbf{u}|^2 + \mathcal{H}(\varrho) \right) (\tau) d\mathbf{x} + \int_0^\tau \int_\Omega \left( \mu |\nabla \mathbf{u}|^2 + (\mu + \lambda) |\operatorname{div} \mathbf{u}|^2 \right) d\mathbf{x} dt \leq \mathcal{E}_0. \quad (2.7)$$

Note that the existence of weak solutions emanating from the finite energy initial data is well-known on bounded Lipschitz domains under assumptions (1.4) and (1.5) provided  $\gamma > d/(d-1)$ , see Lions [36] for "large" values of  $\gamma$ , Feireisl and coauthors [17] for  $\gamma > d/(d-1)$ . More details about this problem are available in monographs [36], [14], [38].

**Remark 1.** *The density  $\varrho$  satisfy the conservation of mass that is*

$$\int_\Omega \varrho(t) d\mathbf{x} = M_0 \quad \text{a.e in } (0, T). \quad (2.8)$$

Let us now introduce the notion of relative energy. We first introduce the function

$$\begin{aligned} E : [0, \infty) \times (0, \infty) &\rightarrow \mathbb{R}, \\ (\varrho, r) &\mapsto E(\varrho|r) = \mathcal{H}(\varrho) - \mathcal{H}'(r)(\varrho - r) - \mathcal{H}(r), \end{aligned} \quad (2.9)$$

where  $\mathcal{H}$  is defined by (2.1). Since  $p$  satisfies the thermodynamic stability condition that is

$$p' > 0 \text{ on } \mathbb{R}_+^*,$$

the function  $\mathcal{H}$  is strictly convex on  $[0, \infty)$  and we have

$$E(\varrho|r) \geq 0 \quad \text{and} \quad E(\varrho|r) = 0 \Leftrightarrow \varrho = r.$$

More precisely,  $E$  satisfy the following algebraic inequality whose straightforward proof is left to the reader:

**Lemma 2.1.** *Let  $0 < a < b < \infty$ . Then there exists a number  $c = c(\gamma, p_\infty, a, b, \min_{[a,b]} p, \min_{[a/2,2b]} p') > 0$  such that for all  $\varrho \in [0, \infty)$  and  $r \in [a, b]$*

$$\begin{aligned} E(\varrho|r) &\geq c(a, b) \left( \varrho^\gamma \mathbf{1}_{\mathbb{R}_+ \setminus [a/2, 2b]}(\varrho) + \mathbf{1}_{\mathbb{R}_+ \setminus [a/2, 2b]}(\varrho) + (\varrho - r)^2 \mathbf{1}_{[a/2, 2b]}(\varrho) \right) \\ &\geq c(a, b, \gamma) \left( |\varrho - r|^\gamma \mathbf{1}_{\mathbb{R}_+ \setminus [a/2, 2b]}(\varrho) + (\varrho - r)^2 \mathbf{1}_{[a/2, 2b]}(\varrho) \right). \end{aligned} \quad (2.10)$$

In order to measure a “distance” between a weak solution  $(\varrho, \mathbf{u})$  of the compressible Navier-Stokes system and any other state  $(r, \mathbf{U})$  of the fluid, we introduce the relative energy functional, defined by

$$\mathcal{E}(\varrho, \mathbf{u} | r, \mathbf{U}) = \int_{\Omega} \left( \frac{1}{2} \varrho |\mathbf{u} - \mathbf{U}|^2 + E(\varrho | r) \right) d\mathbf{x}. \quad (2.11)$$

It was proved recently in [16] that, provided assumption (1.5) holds, any weak solution satisfies the following so-called relative energy inequality

$$\begin{aligned} \mathcal{E}(\varrho, \mathbf{u} | r, \mathbf{U})(\tau) - \mathcal{E}(\varrho, \mathbf{u} | r, \mathbf{U})(0) &+ \int_0^\tau \int_{\Omega} \left( \mu |\nabla(\mathbf{u} - \mathbf{U})|^2 + (\mu + \lambda) |\operatorname{div}(\mathbf{u} - \mathbf{U})|^2 \right) d\mathbf{x} dt \\ &\leq \int_0^\tau \int_{\Omega} \left( \mu \nabla \mathbf{U} : \nabla(\mathbf{U} - \mathbf{u}) + (\mu + \lambda) \operatorname{div} \mathbf{U} \operatorname{div}(\mathbf{U} - \mathbf{u}) \right) d\mathbf{x} dt \\ &+ \int_0^\tau \int_{\Omega} \varrho \partial_t \mathbf{U} \cdot (\mathbf{U} - \mathbf{u}) d\mathbf{x} dt + \int_0^\tau \int_{\Omega} \varrho \mathbf{u} \cdot \nabla \mathbf{U} \cdot (\mathbf{U} - \mathbf{u}) d\mathbf{x} dt \\ &+ \int_0^\tau \int_{\Omega} \frac{r - \varrho}{r} p'(r) \partial_t r d\mathbf{x} dt - \int_0^\tau \int_{\Omega} \frac{\varrho}{r} p'(r) \nabla r \cdot \mathbf{u} d\mathbf{x} dt \\ &- \int_0^\tau \int_{\Omega} p(\varrho) \operatorname{div} \mathbf{U} d\mathbf{x} dt. \end{aligned} \quad (2.12)$$

for a.a.  $\tau \in (0, T)$ , and for any pair of test functions

$$r \in C^1([0, T] \times \overline{\Omega}), \quad r > 0, \quad \mathbf{U} \in C^1([0, T] \times \overline{\Omega})^3, \quad \mathbf{U}|_{\partial\Omega} = \mathbf{0}.$$

Moreover if  $(r, \mathbf{U})$  is a sufficiently strong solution to problem (1.1)–(1.5) emanating from initial data  $(r_0, \mathbf{U}_0)$ , the right member becomes quadratic in difference  $(\varrho - r, \mathbf{u} - \mathbf{U})$  and inequality (2.12) reduces

$$\begin{aligned} \mathcal{E}(\varrho, \mathbf{u} | r, \mathbf{U})(\tau) + \int_0^\tau \int_{\Omega} \left( \mu |\nabla(\mathbf{u} - \mathbf{U})|^2 + (\mu + \lambda) |\operatorname{div}(\mathbf{u} - \mathbf{U})|^2 \right) d\mathbf{x} dt \\ \leq \mathcal{E}(\varrho_0, \mathbf{u}_0 | r(0), \mathbf{U}(0)) + \int_0^\tau \mathcal{R}(\varrho, \mathbf{u} | r, \mathbf{U}) dt \end{aligned} \quad (2.13)$$

where

$$\begin{aligned} \mathcal{R}(\varrho, \mathbf{u} | r, \mathbf{U}) &= \int_{\Omega} (\varrho - r) (\partial_t \mathbf{U} + \mathbf{U} \cdot \nabla \mathbf{U}) \cdot (\mathbf{U} - \mathbf{u}) d\mathbf{x} + \int_{\Omega} \varrho (\mathbf{u} - \mathbf{U}) \cdot \nabla \mathbf{U} \cdot (\mathbf{U} - \mathbf{u}) d\mathbf{x} \\ &+ \int_{\Omega} \frac{\nabla p(r)}{r} (r - \varrho) \cdot (\mathbf{u} - \mathbf{U}) d\mathbf{x} - \int_{\Omega} (p(\varrho) - p'(r)(\varrho - r) - p(r)) \operatorname{div} \mathbf{U} d\mathbf{x}. \end{aligned} \quad (2.14)$$

In order to obtain a stability result of strong solutions in the class of weak solutions, the goal is to find an estimate of the left hand side of from below by (2.13) by

$$c \int_0^\tau \|\mathbf{u} - \mathbf{U}\|_{W^{1,2}(\Omega)^3}^2 \, d\mathbf{x} - \bar{c}' \int_0^\tau \mathcal{E}(\varrho, \mathbf{u} | r, \mathbf{U})(t) \, dt + \mathcal{E}(\varrho, \mathbf{u} | r, \mathbf{U})(\tau) \quad (2.15)$$

and thanks to lemma 2.1 the right hand side from above by

$$\mathcal{E}(\varrho_0, \mathbf{u}_0 | r(0), \mathbf{U}(0)) + \delta \int_0^\tau \|\mathbf{u} - \mathbf{U}\|_{W^{1,2}(\Omega)^3}^2 \, d\mathbf{x} + c'(\delta) \int_0^\tau a(t) \mathcal{E}(\varrho, \mathbf{u} | r, \mathbf{U})(t) \, dt \quad (2.16)$$

with any  $\delta > 0$ , where  $c > 0$  is independant of  $\delta$ ,  $\bar{c}' \geq 0$ ,  $c' = c'(\delta) > 0$  and  $a \in L^1(0, T)$ . This process leads to the estimate

$$\mathcal{E}(\varrho, \mathbf{u} | r, \mathbf{U})(\tau) \leq \mathcal{E}(\varrho_0, \mathbf{u}_0 | r(0), \mathbf{U}(0)) + c \int_0^\tau a(t) \mathcal{E}(\varrho, \mathbf{u} | r, \mathbf{U})(t) \, dt. \quad (2.17)$$

It remains to conclude by using Gronwall Lemma.

The stability of strong solutions in the class of weak solutions is stated in the following proposition (see [16] for a proof).

**Proposition 2.1** (Estimate on the relative energy). *Let  $\Omega$  be a bounded Lipschitz domain. Assume that the viscosity coefficients satisfy assumptions (1.4) and that the pressure  $p$  satisfy*

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

where  $\gamma > \frac{6}{5}$ . Let  $(\varrho, \mathbf{u})$  is a weak solution to problem (1.1)–(1.5) emanating from initial data  $(\varrho_0 > 0, \mathbf{u}_0)$ , with finite energy  $\mathcal{E}_0$  and finite mass  $M_0 = \int_\Omega \varrho_0 \, dx > 0$ . Let  $(r, \mathbf{U})$  that belongs to the class

$$0 < \underline{r} \leq r \leq \bar{r}, \quad r \in L^\infty((0, T) \times \Omega), \quad (2.18a)$$

$$\mathbf{U} \in L^2(0, T; H_0^1(\Omega)^3), \quad (2.18b)$$

$$\nabla r, \nabla^2 \mathbf{U} \in L^2(0, T; L^q(\Omega)), \quad q > \max(3, \frac{6\gamma}{5\gamma - 6}), \quad (2.18c)$$

be a strong solution of the same equations with initial data  $(r(0), \mathbf{U}(0)) = (r_0, \mathbf{U}_0)$ . Then there exists

$$c = c(T, \Omega, M_0, \mathcal{E}_0, \underline{r}, \bar{r}, \gamma, \|\operatorname{div} \mathbf{U}\|_{L^1(0, T; L^\infty(\Omega))}, \|(\nabla r, \nabla^2 \mathbf{U})\|_{L^2(0, T; L^q(\Omega)^{12})}) > 0$$

such that for almost all  $t \in (0, T)$ ,

$$\mathcal{E}(\varrho, \mathbf{u} | r, \mathbf{U})(t) \leq c \mathcal{E}(\varrho_0, \mathbf{u}_0 | r_0, \mathbf{U}_0). \quad (2.19)$$

The goal of the present paper is to obtain estimate of type (2.19) for  $(\varrho, \mathbf{u})$  being a numerical solution of Problem (1.1)–(1.5) obtained by the MAC discretization.

## 3 The numerical scheme

### 3.1 Space discretization

We assume that the closure of the domain  $\Omega$  is a union of closed rectangles ( $d = 2$ ) or closed orthogonal parallelepipeds ( $d = 3$ ) with mutually disjoint interiors, and, without loss of generality, we assume that the edges (or faces) of these rectangles (or parallelepipeds) are orthogonal to the canonical basis vectors, denoted by  $(\mathbf{e}^{(1)}, \dots, \mathbf{e}^{(d)})$ ,

**Definition 3.1** (MAC grid). *A discretization of  $\Omega$  with MAC grid, denoted by  $\mathcal{D}$ , is given by  $\mathcal{D} = (\mathcal{M}, \mathcal{E})$ , where:*

- The density and pressure (or primal) grid denoted by  $\mathcal{M}$ , consists of a union of possibly non uniform (closed) rectangles ( $d=2$ ) or (closed) parallelepipeds ( $d=3$ ), the edges (or faces) of these rectangles (or parallelepipeds) are orthogonal to the canonical basis vectors; a generic cell of this grid is denoted by  $K$  ( a closed set), and its mass center  $\mathbf{x}_K$ . It is a conforming grid, meaning that

$$\overline{\Omega} = \cup_{K \in \mathcal{M}} K, \text{ where } \text{int}(K) \cap \text{int}(L) = \emptyset \text{ whenever } (K, L) \in \mathcal{M}^2, K \neq L, \quad (3.1)$$

and if  $K \cap L \neq \emptyset$  then  $K \cap L$  is a common face or edge or vertex of  $K$  and  $L$ . A generic face (or edge in the two-dimensional case) of such a cell is denoted by  $\sigma \in \mathcal{E}(K)$  (a closed set), and its mass center  $\mathbf{x}_\sigma$ , where  $\mathcal{E}(K)$  denotes the set of all faces of  $K$ . We denote by  $\mathbf{n}_{\sigma,K}$  the unit normal vector to  $\sigma$  outward  $K$ . The set of all faces of the mesh is denoted by  $\mathcal{E}$ ; we have  $\mathcal{E} = \mathcal{E}_{\text{int}} \cup \mathcal{E}_{\text{ext}}$ , where  $\mathcal{E}_{\text{int}}$  (resp.  $\mathcal{E}_{\text{ext}}$ ) are the edges of  $\mathcal{E}$  that lie in the interior (resp. on the boundary) of the domain. The set of faces that are orthogonal to the  $i^{\text{th}}$  unit vector  $\mathbf{e}^{(i)}$  of the canonical basis of  $\mathbb{R}^d$  is denoted by  $\mathcal{E}^{(i)}$ , for  $i = 1, \dots, d$ . We then have  $\mathcal{E}^{(i)} = \mathcal{E}_{\text{int}}^{(i)} \cup \mathcal{E}_{\text{ext}}^{(i)}$ , where  $\mathcal{E}_{\text{int}}^{(i)}$  (resp.  $\mathcal{E}_{\text{ext}}^{(i)}$ ) are the edges of  $\mathcal{E}^{(i)}$  that lie in the interior (resp. on the boundary) of the domain. Finally, for  $i = 1, \dots, d$  and  $K \in \mathcal{M}$ , we denote  $\mathcal{E}^{(i)}(K) = \mathcal{E}(K) \cap \mathcal{E}^{(i)}$  and  $\mathcal{E}_{\text{int}}^{(i)}(K) = \mathcal{E}(K) \cap \mathcal{E}_{\text{int}}^{(i)}$ .

- For each  $\sigma \in \mathcal{E}$ , we write that  $\sigma = K|L$  if  $\sigma = \partial K \cap \partial L$  and we write that  $\sigma = \overrightarrow{K|L}$  if, furthermore,  $\sigma \in \mathcal{E}^{(i)}$  and  $(\mathbf{x}_L - \mathbf{x}_K) \cdot \mathbf{e}^{(i)} > 0$  for some  $i \in [1, d] \equiv \{1, \dots, d\}$ . A primal cell  $K$  will be denoted  $K = [\overrightarrow{\sigma\sigma'}]$  if  $\sigma, \sigma' \in \mathcal{E}^{(i)} \cap \mathcal{E}(K)$  for some  $i = 1, \dots, d$  are such that  $(\mathbf{x}_{\sigma'} - \mathbf{x}_\sigma) \cdot \mathbf{e}^{(i)} > 0$ . For a face  $\sigma \in \mathcal{E}$ , the distance  $d_\sigma$  is defined by:

$$d_\sigma = \begin{cases} d(\mathbf{x}_K, \mathbf{x}_L) & \text{if } \sigma = K|L \in \mathcal{E}_{\text{int}}, \\ d(\mathbf{x}_K, \mathbf{x}_\sigma) & \text{if } \sigma \in \mathcal{E}_{\text{ext}} \cap \mathcal{E}(K) \end{cases} \quad (3.2)$$

where  $d(\cdot, \cdot)$  denotes the Euclidean distance in  $\mathbb{R}^d$ .

- A dual cell  $D_\sigma$  associated to a face  $\sigma \in \mathcal{E}$  is defined as follows:
  - \* if  $\sigma = K|L \in \mathcal{E}_{\text{int}}$  then  $D_\sigma = D_{\sigma,K} \cup D_{\sigma,L}$ , where  $D_{\sigma,K}$ - a closed set (resp.  $D_{\sigma,L}$  -a closed set) is the half-part of  $K$  (resp.  $L$ ) adjacent to  $\sigma$  (see Fig. 1 for the two-dimensional case) ;
  - \* if  $\sigma \in \mathcal{E}_{\text{ext}}$  is adjacent to the cell  $K$ , then  $D_\sigma = D_{\sigma,K}$ .

The dual grid  $\{D_\sigma\}_{\sigma \in \mathcal{E}^{(i)}}$  of  $\Omega$  (sometimes called the  $i$ -th velocity component grid) verifies for each fixed  $i \in \{1, \dots, d\}$

$$\overline{\Omega} = \cup_{\sigma \in \mathcal{E}^{(i)}} D_\sigma, \quad \text{int}(D_\sigma) \cap \text{int}(D_{\sigma'}) = \emptyset, \quad \sigma, \sigma' \in \mathcal{E}^{(i)}, \quad \sigma \neq \sigma'. \quad (3.3)$$

- A dual face separating two neighboring dual cells  $D_\sigma$  and  $D_{\sigma'}$  is denoted by  $\epsilon = \sigma|\sigma'$  or  $\epsilon = D_\sigma|D_{\sigma'}$  (a closed set) or  $\epsilon = \overrightarrow{\sigma|\sigma'}$  when specifying its orientation: more precisely we write that  $\epsilon = \overrightarrow{\sigma|\sigma'}$  if  $(\mathbf{x}_{\sigma'} - \mathbf{x}_\sigma) \cdot \mathbf{e}^{(j)} > 0$  for some  $j \in [1, d]$ . The set of all faces of  $D_\sigma$  is denoted  $\tilde{\mathcal{E}}(D_\sigma)$ ; it is decomposed to the set of external faces  $\tilde{\mathcal{E}}_{\text{ext}}(D_\sigma) = \{\epsilon \in \tilde{\mathcal{E}}(D_\sigma) | \epsilon \subset \partial\Omega\}$  and the set of internal faces  $\tilde{\mathcal{E}}_{\text{int}}(D_\sigma) = \{\epsilon \in \tilde{\mathcal{E}}(D_\sigma) | \text{int}_{d-1}\epsilon \subset \Omega\}$ , where  $\text{int}_{d-1}$  denote the interior in the topology of  $\mathbb{R}^{d-1}$ . The set of all dual faces of the dual grid  $\{D_\sigma\}_{\sigma \in \mathcal{E}^{(i)}}$  is decomposed into the internal and boundary edges:  $\tilde{\mathcal{E}}^{(i)} = \tilde{\mathcal{E}}_{\text{int}}^{(i)} \cup \tilde{\mathcal{E}}_{\text{ext}}^{(i)}$ , where  $\tilde{\mathcal{E}}_{\text{int}}^{(i)} = \{\epsilon = \sigma|\sigma' | \sigma, \sigma' \in \mathcal{E}^{(i)}\}$  and  $\tilde{\mathcal{E}}_{\text{ext}}^{(i)} = \{\epsilon = \partial D_\sigma \cap \partial\Omega | \sigma \in \mathcal{E}^{(i)}, \partial D_\sigma \cap \partial\Omega \neq \emptyset\}$ . We denote by  $\mathbf{n}_{\epsilon, D_\sigma}$  the unit normal vector to  $\epsilon \in D_\sigma$  outward  $D_\sigma$ .

We denote for further convenience  $\mathbf{n}_\epsilon$  and  $\mathbf{n}_\sigma$  a normal unit vector to face  $\epsilon$  and  $\sigma$ , respectively. We write  $\epsilon \perp \sigma$  resp.  $\sigma \perp \sigma'$  iff  $\mathbf{n}_\epsilon \cdot \mathbf{n}_\sigma = 0$  resp.  $\mathbf{n}_\sigma \cdot \mathbf{n}_{\sigma'} = 0$ . Similarly we write  $\epsilon \perp \mathbf{e}^{(j)}$  resp.  $\sigma \perp \mathbf{e}^{(j)}$  iff  $\mathbf{n}_\epsilon$  and  $\mathbf{e}^{(j)}$  resp.  $\mathbf{n}_\sigma$  and  $\mathbf{e}^{(j)}$  are parallel. We also denote by  $\mathbf{ab}$  the segment  $\{\mathbf{a} + t(\mathbf{b} - \mathbf{a}) | t \in [0, 1]\}$ , where  $(\mathbf{a}, \mathbf{b}) \in \mathbb{R}^{2d}$ , and by  $\mathbf{x}_\epsilon$  resp.  $\mathbf{x}_{\sigma \cap \epsilon}$  the mass centers of the face  $\epsilon$  resp. of the set  $\sigma \cap \epsilon$  (provided it is not empty).

- In order to define bi-dual grid, we introduce the set  $\tilde{\mathcal{E}}^{(i,j)} = \{\epsilon \in \tilde{\mathcal{E}}^{(i)} | \epsilon \perp \mathbf{e}^{(j)}\}$  of dual faces of the  $i$ -th component velocity grid that are orthogonal to  $\mathbf{e}^{(j)}$ . A bi-dual cell  $D_\epsilon$  associated to a face  $\epsilon \in \tilde{\mathcal{E}}$  is defined as follows:

- \* If  $\epsilon = \overrightarrow{\sigma|\sigma'} \in \tilde{\mathcal{E}}^{(i,j)} \cap \tilde{\mathcal{E}}_{\text{int}}^{(i)}$  then  $D_\epsilon = \epsilon \times \mathbf{x}_\sigma \mathbf{x}_{\sigma'}$  (see Figure 2). (We notice that, if  $\sigma, \sigma' \in \mathcal{E}^{(i)}$  with  $K = [\overrightarrow{\sigma\sigma'}] \in \mathcal{M}$  and  $\epsilon = \sigma|\sigma'$  then  $D_\epsilon = K$ .)
- \* If  $\epsilon \in \tilde{\mathcal{E}}^{(i,j)} \cap \tilde{\mathcal{E}}_{\text{ext}}^{(i)}$  with  $\epsilon \in \tilde{\mathcal{E}}(D_\sigma)$  and  $i \neq j$  then  $D_\epsilon = \epsilon \times \mathbf{x}_\sigma \mathbf{x}_{\sigma \cap \epsilon}$ .

In the list above we did not consider the situation  $\epsilon \in \tilde{\mathcal{E}}^{(i,i)} \cap \tilde{\mathcal{E}}_{\text{ext}}^{(i)}$  with  $\epsilon \in \tilde{\mathcal{E}}(D_\sigma)$ . In this case  $\epsilon = \sigma \subset \partial\Omega$ , and we set for completeness  $D_\epsilon = \emptyset$ .

It is to be noticed that, for each fixed couple  $(i, j) \in \{1, \dots, d\}^2$

$$\bigcup_{\epsilon \in \tilde{\mathcal{E}}^{(i,j)}} D_\epsilon = \overline{\Omega}, \quad \text{int}(D_\epsilon) \cap \text{int}(D_{\epsilon'}) = \emptyset, \quad \epsilon \neq \epsilon', \quad \epsilon, \epsilon' \in \tilde{\mathcal{E}}^{(i,j)}. \quad (3.4)$$

To any dual face  $\epsilon \in \tilde{\mathcal{E}}^{(i)}$ , we associate a distance  $d_\epsilon$

$$d_\epsilon = \begin{cases} d(\mathbf{x}_\sigma, \mathbf{x}_{\sigma'}) & \text{if } \epsilon \in \tilde{\mathcal{E}}^{(i,j)} \cap \tilde{\mathcal{E}}_{\text{int}}^{(i)}, \\ d(\mathbf{x}_\sigma, \mathbf{x}_{\sigma \cap \epsilon}) & \text{if } \epsilon \in \tilde{\mathcal{E}}^{(i,j)} \cap \tilde{\mathcal{E}}_{\text{ext}}^{(i)} \text{ with } \epsilon \in \tilde{\mathcal{E}}(D_\sigma) \text{ and } i \neq j, \\ d_\sigma & \text{if } \epsilon \in \tilde{\mathcal{E}}^{(i,i)} \cap \tilde{\mathcal{E}}_{\text{ext}}^{(i)} \text{ with } \epsilon \in \tilde{\mathcal{E}}(D_\sigma). \end{cases} \quad (3.5)$$

(We notice that the last line in the above definition is irrelevant and pure convention, since in that case  $D_\epsilon = \emptyset$ .)

- We also define the size of the mesh by

$$h_{\mathcal{M}} = \max\{h_K, K \in \mathcal{M}\} \quad (3.6)$$

where  $h_K$  stands for the diameter of  $K$ . Moreover if  $K = [\overrightarrow{\sigma\sigma'}]$  where  $\sigma, \sigma' \in \mathcal{E}^{(i)} \cap \mathcal{E}(K)$  for some  $i = 1, \dots, d$  we will denote

$$h_K^{(i)} = \frac{|K|}{|\sigma|} = \frac{|K|}{|\sigma'|}. \quad (3.7)$$

We measure the regularity of the mesh through the positive real number  $\eta_{\mathcal{M}}$  defined by

$$\eta_{\mathcal{M}} = \max\left\{\frac{|\sigma|}{|\sigma'|}, \sigma \in \mathcal{E}^{(i)}, \sigma' \in \mathcal{E}^{(j)}, (i, j) \in \{1, \dots, d\}^2, i \neq j\right\}. \quad (3.8)$$

Finally, we denote by  $h_\sigma$  the diameter of the face  $\sigma \in \mathcal{E}$ .

- Some geometric notions introduced in this definition are exposed in the figures 1 and 2:

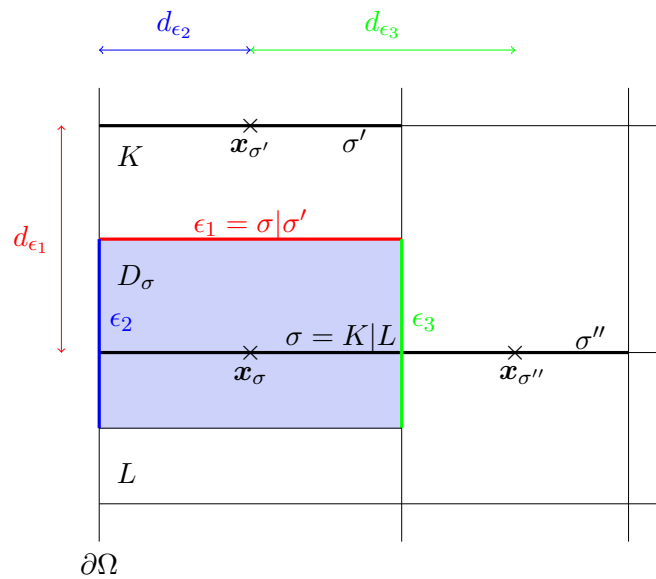


Figure 1: Notations for control volumes and dual cells



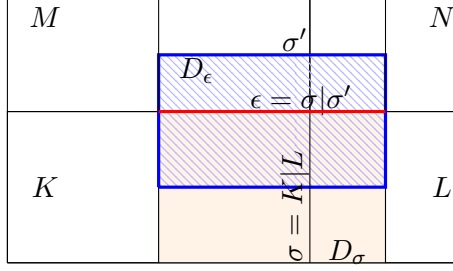


Figure 2: Notations for bi-dual cells

**Definition 3.2** (Discrete spaces). Let  $\mathcal{D} = (\mathcal{M}, \mathcal{E})$  be a MAC grid in the sense of Definition 3.1. The discrete density and pressure space  $L_{\mathcal{M}}$  is defined as the set of piecewise constant functions over each of the grid cells  $K$  of  $\mathcal{M}$ , and the discrete  $i$ -th velocity space  $H_{\mathcal{E}}^{(i)}$  as the set of piecewise constant functions over each of the grid cells  $D_{\sigma}$ ,  $\sigma \in \mathcal{E}^{(i)}$ . As in the continuous case, the Dirichlet boundary conditions (1.3) are (partly) incorporated in the definition of the velocity spaces, and, to this purpose, we introduce  $H_{\mathcal{E},0}^{(i)} \subset H_{\mathcal{E}}^{(i)}$ ,  $i = 1, \dots, d$ , defined as follows:

$$H_{\mathcal{E},0}^{(i)} = \left\{ v \in H_{\mathcal{E}}^{(i)}, v(\mathbf{x}) = 0 \forall \mathbf{x} \in D_{\sigma}, \sigma \in \tilde{\mathcal{E}}_{\text{ext}}^{(i)}, i = 1, \dots, d \right\}.$$

We then set  $\mathbf{H}_{\mathcal{E},0} = \prod_{i=1}^d H_{\mathcal{E},0}^{(i)}$ . Since we are dealing with piecewise constant functions, it is useful to introduce the characteristic functions  $\mathcal{X}_K, K \in \mathcal{M}$  and  $\mathcal{X}_{D_{\sigma}}, \sigma \in \mathcal{E}$  of the density (or pressure) and velocity cells, defined by

$$\mathcal{X}_K(\mathbf{x}) = \begin{cases} 1 & \text{if } \mathbf{x} \in K, \\ 0 & \text{if } \mathbf{x} \notin K, \end{cases} \quad \mathcal{X}_{D_{\sigma}}(\mathbf{x}) = \begin{cases} 1 & \text{if } \mathbf{x} \in D_{\sigma}, \\ 0 & \text{if } \mathbf{x} \notin D_{\sigma}. \end{cases}$$

We can then write a function  $\mathbf{v} \in \mathbf{H}_{\mathcal{E},0}$  as  $\mathbf{v} = (v_1, \dots, v_d)$  with  $v_i = \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} v_{\sigma} \mathcal{X}_{D_{\sigma}}$ ,  $i \in [1, d]$  and a

function  $q \in L_{\mathcal{M}}$  as  $q = \sum_{K \in \mathcal{M}} q_K \mathcal{X}_K$ .

### 3.2 Time discretization

Let us now turn to the time discretization of Problem 1.1. We consider a partition  $0 = t^0 < t^1 < \dots < t^N = T$  of the time interval  $(0, T)$ , and, for the sake of simplicity, a constant time step  $\delta t = t^n - t^{n-1}$ ; hence  $t^n = n\delta t$  for  $n \in \{0, \dots, N\}$ . We denote respectively by  $\{u_{\sigma}^n, \sigma \in \mathcal{E}_{\text{int}}^{(i)}, i \in \{1, \dots, d\}, n \in \{0, \dots, N\}\}$ , and  $\{\varrho_K^n, K \in \mathcal{M}, n \in \{1, \dots, N\}\}$  the sets of discrete  $i$ -th component of velocity and density unknowns. For  $\sigma \in \mathcal{E}_{\text{int}}^{(i)}$ ,  $i \in \{1, \dots, d\}$  the value  $u_{\sigma}^n$  is an expected approximation of the mean value over  $(t^{n-1}, t^n) \times D_{\sigma}$  of the  $i$ -th component of the velocity of a weak solution, while for  $K \in \mathcal{M}$  the value  $\varrho_K^n$  is an expected approximation of the mean value over  $(t^{n-1}, t^n) \times K$  of the density of a weak solution. To the discrete unknowns, we associate piecewise constant functions on time intervals and on primal or dual meshes, which are expected approximation of weak solutions, For the velocities, these constant functions are of the form:

$$u_i(t, \mathbf{x}) = \sum_{n=1}^N \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} u_{\sigma}^n \mathcal{X}_{D_{\sigma}}(\mathbf{x}) \mathcal{X}_{(t^{n-1}, t^n)}(t),$$

where  $\mathcal{X}_{(t^{n-1}, t^n)}$  is the characteristic function of the interval  $(t^{n-1}, t^n)$ . We denote by  $X_{i,\mathcal{E},\delta t}$  the set of such piecewise constant functions on time intervals and dual cells, and we set  $\mathbf{X}_{\mathcal{E},\delta t} = \prod_{i=1}^d X_{i,\mathcal{E},\delta t}$ . For the density, the constant function is of the form:

$$\varrho(t, \mathbf{x}) = \varrho_K^n \text{ for } \mathbf{x} \in K \text{ and } t \in (t^{n-1}, t^n),$$

and we denote by  $Y_{\mathcal{M},\delta t}$  the space of such piecewise constant functions.

For a given  $\mathbf{u} \in \mathbf{X}_{\mathcal{E},\delta t}$  associated to the set of discrete velocity unknowns  $\{u_\sigma^n, \sigma \in \mathcal{E}_{\text{int}}^{(i)}, i \in \{1, \dots, d\}, n \in \{1, \dots, N\}\}$ , and for  $n \in \{1, \dots, N\}$ , we denote by  $u_i^n \in H_{\mathcal{E},0}^{(i)}$  the piecewise constant function defined by  $u_i^n(\mathbf{x}) = u_\sigma^n$  for  $\mathbf{x} \in D_\sigma, \sigma \in \mathcal{E}_{\text{int}}^{(i)}$ , and set  $\mathbf{u}^n = (u_1^n, \dots, u_d^n)^t \in \mathbf{H}_{\mathcal{E},0}$ . We sometimes write  $u_{i,\sigma}^n$  instead of  $u_\sigma^n$  in order to avoid all confusion. Notice that  $u_{i,\sigma}^n$  may be non zero for  $\sigma \in \mathcal{E}_{\text{int}}^{(i)}$  while it is zero whenever  $\sigma \in \mathcal{E}_{\text{ext}}^{(i)}$ . In the same way, given  $\varrho \in Y_{\mathcal{M},\delta t}$  associated to the discrete density unknowns  $\{\varrho_K^n, K \in \mathcal{M}, n \in \{1, \dots, N\}\}$  we denote by  $\varrho^n \in L_{\mathcal{M}}$  the piecewise constant function defined by  $\varrho^n(\mathbf{x}) = \varrho_K^n$  for  $\mathbf{x} \in K, K \in \mathcal{M}$ .

Finally, the discrete initial condition  $(\varrho^0, \mathbf{u}^0) \in L_{\mathcal{M}} \times \mathbf{H}_{\mathcal{E},0}$  is such that  $\varrho^0 > 0$  and the discrete initial total mass and energy are respectively defined by

$$M_{0,\mathcal{M}} = \int_{\Omega} \varrho^0 \, d\mathbf{x}, \quad \mathcal{E}_{0,\mathcal{M}} = \int_{\Omega} \frac{1}{2} \varrho^0 |\mathbf{u}^0|^2 \, d\mathbf{x} + \int_{\Omega} \mathcal{H}(\varrho^0) \, d\mathbf{x}. \quad (3.9)$$

### 3.3 The numerical scheme

We consider an implicit-in-time scheme, which reads in its fully discrete form, for  $1 \leq n \leq N$  and  $1 \leq i \leq d$ :

$$\frac{1}{\delta t} (\varrho^n - \varrho^{n-1}) + \text{div}_{\mathcal{M}}^{\text{up}}(\varrho^n \mathbf{u}^n) = 0, \quad (3.10a)$$

$$\begin{aligned} \frac{1}{\delta t} (\widehat{\varrho^n}^{(i)} u_i^n - \widehat{\varrho^{n-1}}^{(i)} u_i^{n-1}) + \text{div}_{\mathcal{E}}^{(i)}(\varrho^n \mathbf{u}^n u_i^n) - \mu \Delta_{\mathcal{E}}^{(i)} u_i^n \\ - (\mu + \lambda) \delta_i \text{div}_{\mathcal{M}} \mathbf{u}^n + \delta_i p(\varrho^n) = 0, \end{aligned} \quad (3.10b)$$

where the terms introduced for each discrete equation are defined hereafter.

#### 3.3.1 Mass balance equation

Equation (3.10a) is a finite volume discretization of the mass balance (1.1a) over the primal mesh. The discrete "upwind" divergence is defined by

$$\text{div}_{\mathcal{M}}^{\text{up}} : \left\{ \begin{array}{l} L_{\mathcal{M}} \times \mathbf{H}_{\mathcal{E},0} \longrightarrow L_{\mathcal{M}} \\ (\varrho, \mathbf{u}) \longmapsto \text{div}_{\mathcal{M}}^{\text{up}}(\varrho \mathbf{u}) = \sum_{K \in \mathcal{M}} \frac{1}{|K|} \sum_{\sigma \in \mathcal{E}(K)} F_{\sigma,K}(\varrho, \mathbf{u}) \chi_K, \end{array} \right. \quad (3.11)$$

where  $F_{\sigma,K}(\varrho, \mathbf{u})$  stands for the mass flux across  $\sigma$  outward  $K$ , which, because of the Dirichlet boundary conditions, vanishes on external faces and is given on the internal faces by:

$$\forall \sigma = K|L \in \mathcal{E}_{\text{int}}, \quad F_{\sigma,K}(\varrho, \mathbf{u}) = |\sigma| \varrho_\sigma^{\text{up}} u_{\sigma,K}, \quad (3.12)$$

where  $u_{\sigma,K}$  is an approximation of the normal velocity to the face  $\sigma$  outward  $K$ , defined by:

$$u_{\sigma,K} = u_\sigma \mathbf{e}^{(i)} \cdot \mathbf{n}_{\sigma,K} \text{ for } \sigma \in \mathcal{E}^{(i)} \cap \mathcal{E}(K). \quad (3.13)$$

Thanks to the boundary conditions,  $u_{\sigma,K}$  vanishes for any external face  $\sigma$ . The density at the internal face  $\sigma = K|L$  is obtained by an upwind technique:

$$\varrho_\sigma^{\text{up}} = \begin{cases} \varrho_K & \text{if } u_{\sigma,K} \geq 0, \\ \varrho_L & \text{otherwise.} \end{cases} \quad (3.14)$$

Note that any solution  $(\varrho^n, \mathbf{u}^n) \in L_{\mathcal{M}} \times \mathbf{H}_{\mathcal{E},0}$  to (3.10a) satisfy  $\varrho_K^n > 0, \forall K \in \mathcal{M}$  provided  $\varrho_K^{n-1} > 0, \forall K \in \mathcal{M}$  and in particular  $p(\varrho^n)$  makes sense. The positivity of the density  $\varrho^n$  in (3.10a) is not enforced in the scheme but results from the above upwind choice. Indeed, for a given velocity field, the discrete mass balance (3.10a) is a linear system for  $\varrho^n$  the matrix of which is an invertible matrix with a non negative inverse [20, Lemma C.3].

Note also that, with this definition, we have the usual finite volume property of local conservativity of the flux through a primal face  $\sigma = K|L$  *i.e.*

$$F_{\sigma,K}(\varrho, \mathbf{u}) = -F_{\sigma,L}(\varrho, \mathbf{u}). \quad (3.15)$$

Consequently, summing (3.10a) over  $K \in \mathcal{M}$  immediately yields the total conservation of mass, which reads:

$$\forall n = 1, \dots, N, \quad \int_{\Omega} \varrho^n \, d\mathbf{x} = \int_{\Omega} \varrho^0 \, d\mathbf{x}, \quad (3.16)$$

which is nothing than a discrete version of (2.8).

### 3.3.2 The momentum equation

We now turn to the discrete momentum balances (3.10b), which are obtained by discretizing the momentum balance equation (1.1b) on the dual cells associated to the faces of the mesh.

**The discrete convective operator** - The discrete divergence of the convective term  $\varrho \mathbf{u} \otimes \mathbf{u}$  is defined by

$$\operatorname{div}_{\mathcal{E}}^{\text{up}} : \left\{ \begin{array}{l} L_{\mathcal{M}} \times \mathbf{H}_{\mathcal{E},0} \longrightarrow \mathbf{H}_{\mathcal{E},0} \\ (\varrho, \mathbf{u}) \longmapsto \operatorname{div}_{\mathcal{E}}^{\text{up}}(\varrho \mathbf{u} \otimes \mathbf{u}) = (\operatorname{div}_{\mathcal{E}}^{(1)}(\varrho \mathbf{u} u_1), \dots, \operatorname{div}_{\mathcal{E}}^{(d)}(\varrho \mathbf{u} u_d)), \end{array} \right. \quad (3.17)$$

where for any  $1 \leq i \leq d$ , the  $i^{\text{th}}$  component of the above operator reads:

$$\operatorname{div}_{\mathcal{E}}^{(i)} : \left\{ \begin{array}{l} L_{\mathcal{M}} \times \mathbf{H}_{\mathcal{E},0} \longrightarrow H_{\mathcal{E},0}^{(i)} \\ (\varrho, \mathbf{u}) \longmapsto \operatorname{div}_{\mathcal{E}}^{(i)}(\varrho \mathbf{u} u_i) = \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \frac{1}{|D_{\sigma}|} \sum_{\epsilon \in \tilde{\mathcal{E}}(D_{\sigma})} F_{\epsilon,\sigma}(\varrho, \mathbf{u}) u_{\epsilon} \mathcal{X}_{D_{\sigma}}, \end{array} \right. \quad (3.18)$$

where the quantity  $F_{\epsilon,\sigma} = F_{\epsilon,\sigma}(\varrho, \mathbf{u})$  stands for a mass flux through the dual faces of the mesh and  $u_{\epsilon}$  stands for an approximation of  $i^{\text{th}}$  component of the velocity over  $\epsilon$  are defined hereafter (see (3.19), (3.20), (3.26)).

Let  $\sigma \in \mathcal{E}^{(i)}$  (without loss of generality). The dual flux  $F_{\epsilon,\sigma}(\varrho, \mathbf{u})$  is defined as follows

- If  $\epsilon \in \tilde{\mathcal{E}}_{\text{ext}}$  then  $F_{\epsilon,\sigma}(\varrho, \mathbf{u}) = 0$ .

Otherwise:

- First case – The vector  $\mathbf{e}^{(i)}$  is normal to  $\epsilon$ , so  $\epsilon$  is included in a primal cell  $K$ , and we denote by  $\sigma'$  the second face of  $K$  which, in addition to  $\sigma$ , is normal to  $\mathbf{e}^{(i)}$ . We thus have  $\epsilon = D_{\sigma}|D_{\sigma'}$ . Then the mass flux through  $\epsilon$  is given by:

$$F_{\epsilon,\sigma}(\varrho, \mathbf{u}) = \frac{1}{2} [F_{\sigma,K}(\varrho, \mathbf{u}) \mathbf{n}_{\epsilon,D_{\sigma}} \cdot \mathbf{n}_{\sigma,K} + F_{\sigma',K}(\varrho, \mathbf{u}) \mathbf{n}_{\epsilon,D_{\sigma}} \cdot \mathbf{n}_{\sigma',K}]. \quad (3.19)$$

where  $\mathbf{n}_{\epsilon,D_{\sigma}}$  stands for the unit normal vector to  $\epsilon$  outward  $D_{\sigma}$ .

- Second case – The vector  $\mathbf{e}^{(i)}$  is tangent to  $\epsilon$ , and  $\epsilon$  is the union of the halves of two primal faces  $\tau$  and  $\tau'$  such that  $\tau \in \mathcal{E}(K)$  and  $\tau' \in \mathcal{E}(L)$ . The mass flux through  $\epsilon$  is then given by:

$$F_{\epsilon,\sigma}(\varrho, \mathbf{u}) = \frac{1}{2} [F_{\tau,K}(\varrho, \mathbf{u}) + F_{\tau',L}(\varrho, \mathbf{u})]. \quad (3.20)$$

- Third case – The vector  $\mathbf{e}^{(i)}$  is tangent to  $\epsilon$ , and  $\epsilon$  is the halve of a primal face  $\tau$  such that  $\tau \in \mathcal{E}(K)$ . In particular  $\sigma \in \mathcal{E}_{\text{ext}}^{(i)}$ . The mass flux through  $\epsilon$  is then given by:

$$F_{\epsilon,\sigma}(\varrho, \mathbf{u}) = \frac{1}{2} F_{\tau,K}(\varrho, \mathbf{u}). \quad (3.21)$$

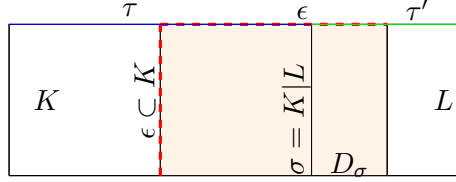


Figure 3: Notations for the dual fluxes of the first component of the velocity.

We notice that the sum over  $\epsilon \in \tilde{\mathcal{E}}(D_\sigma)$  in formula (3.18) can be replaced by the sum over  $\epsilon \in \tilde{\mathcal{E}}_{\text{int}}(D_\sigma)$ .

Note that, with this definition, we have the usual finite volume property of local conservativity of the flux through a dual face  $\epsilon = D_\sigma|D_{\sigma'}$  *i.e.*

$$F_{\epsilon,\sigma}(\varrho, \mathbf{u}) = -F_{\epsilon,\sigma'}(\varrho, \mathbf{u}). \quad (3.22)$$

In what follows we shall often use the abbreviated notation

$$F_{\sigma,K}(\varrho^n, \mathbf{u}^n) = F_{\sigma,K}^n, \quad F_{\epsilon,\sigma}(\varrho^n, \mathbf{u}^n) = F_{\epsilon,\sigma}^n. \quad (3.23)$$

The density on a dual cell is given by:

$$\begin{aligned} \text{for } \sigma \in \mathcal{E}_{\text{int}}, \sigma = K|L & \quad |D_\sigma| \varrho_{D_\sigma} = |D_{\sigma,K}| \varrho_K + |D_{\sigma,L}| \varrho_L, \\ \text{for } \sigma \in \mathcal{E}_{\text{ext}}, \sigma \in \mathcal{E}(K), & \quad \varrho_{D_\sigma} = \varrho_K. \end{aligned} \quad (3.24)$$

and we denote

$$\text{for } 1 \leq i \leq d, \quad \hat{\varrho}^{(i)} = \sum_{\sigma \in \mathcal{E}^{(i)}} \varrho_{D_\sigma} \mathcal{X}_{D_\sigma}.$$

These definitions of the dual mass fluxes and the dual densities ensures that a finite volume discretization of the mass balance equation over the diamond cells holds:

$$\forall 1 \leq i \leq d, \forall \sigma \in \mathcal{E}^{(i)}, \quad \frac{1}{\delta t} (\varrho_{D_\sigma}^n - \varrho_{D_\sigma}^{n-1}) + \frac{1}{|D_\sigma|} \sum_{\epsilon \in \tilde{\mathcal{E}}(D_\sigma)} F_{\epsilon,\sigma}^n = 0. \quad (3.25)$$

This is a necessary condition to be able to derive a discrete kinetic energy balance (see Theorem 4.1).

Since the flux across a dual face lying on the boundary is zero, the values  $u_\epsilon$  are only needed at the internal dual faces, and we make the centered choice for their discretization, *i.e.*, for  $\epsilon = D_\sigma|D_{\sigma'} \in \tilde{\mathcal{E}}_{\text{int}}^{(i)}$ ,

$$u_\epsilon \equiv u_{i,\epsilon} = \frac{u_\sigma + u_{\sigma'}}{2} \equiv \frac{u_{i,\sigma} + u_{i,\sigma'}}{2}. \quad (3.26)$$

**Discrete divergence and gradient** - The discrete divergence operator  $\text{div}_{\mathcal{M}}$  is defined by:

$$\text{div}_{\mathcal{M}} : \left\{ \begin{array}{l} \mathbf{H}_{\mathcal{E}} \longrightarrow L_{\mathcal{M}} \\ \mathbf{u} \longmapsto \text{div}_{\mathcal{M}} \mathbf{u} = \sum_{K \in \mathcal{M}} \frac{1}{|K|} \sum_{\sigma \in \mathcal{E}(K)} |\sigma| u_{\sigma,K} \mathcal{X}_K, \end{array} \right. \quad (3.27)$$

where  $u_{\sigma,K}$  is defined in (3.13).

The discrete divergence of  $\mathbf{u} = (u_1, \dots, u_d) \in \mathbf{H}_{\mathcal{E},0}$  may also be written as

$$\text{div}_{\mathcal{M}} \mathbf{u} = \sum_{i=1}^d \sum_{K \in \mathcal{M}} (\partial_i u_i)_K \mathcal{X}_K, \quad (3.28)$$

where the discrete derivative  $(\partial_i u_i)_K$  of  $u_i$  on  $K$  is defined by

$$(\partial_i u_i)_K = \frac{|\sigma|}{|K|} (u_{\sigma'} - u_\sigma) \text{ with } K = [\overrightarrow{\sigma\sigma'}], \sigma, \sigma' \in \mathcal{E}^{(i)}. \quad (3.29)$$

The gradient in the discrete momentum balance equation is defined as follows:

$$\nabla_{\mathcal{E}} : \begin{cases} L_{\mathcal{M}} \longrightarrow \mathbf{H}_{\mathcal{E},0} \\ p \longmapsto \nabla_{\mathcal{E}} p \\ \nabla_{\mathcal{E}} p(\mathbf{x}) = (\bar{\partial}_1 p(\mathbf{x}), \dots, \bar{\partial}_d p(\mathbf{x}))^t, \end{cases} \quad (3.30)$$

where  $\bar{\partial}_i p \in H_{\mathcal{E},0}^{(i)}$  is the discrete derivative of  $p$  in the  $i$ -th direction, defined by:

$$\bar{\partial}_i p(\mathbf{x}) = \frac{|\sigma|}{|D_{\sigma}|} (p_L - p_K) \quad \forall \mathbf{x} \in D_{\sigma}, \text{ for } \sigma = \overrightarrow{K|L} \in \mathcal{E}_{\text{int}}^{(i)}, \quad i = 1, \dots, d. \quad (3.31)$$

Note that in fact, the discrete gradient of a function of  $L_{\mathcal{M}}$  should only be defined on the internal faces, and does not need to be defined on the external faces; we set it here in  $\mathbf{H}_{\mathcal{E},0}$  (that is zero on the external faces) for the sake of simplicity.

The gradient in the discrete momentum balance equation is built as the dual operator of the discrete divergence which means:

**Lemma 3.1** (Discrete div –  $\nabla$  duality). *Let  $q \in L_{\mathcal{M}}$  and  $\mathbf{v} \in \mathbf{H}_{\mathcal{E},0}$  then we have:*

$$\int_{\Omega} q \operatorname{div}_{\mathcal{M}} \mathbf{v} \, d\mathbf{x} + \int_{\Omega} \nabla_{\mathcal{E}} q \cdot \mathbf{v} \, d\mathbf{x} = 0. \quad (3.32)$$

**Discrete Laplace operator** - For  $i = 1 \dots, d$ , we classically define the discrete Laplace operator on the  $i$ -th velocity grid by:

$$-\Delta_{\mathcal{E}}^{(i)} : \begin{cases} H_{\mathcal{E},0}^{(i)} \longrightarrow H_{\mathcal{E},0}^{(i)} \\ u_i \longmapsto -\Delta_{\mathcal{E}}^{(i)} u_i \end{cases} \\ -\Delta_{\mathcal{E}}^{(i)} u_i(\mathbf{x}) = \frac{1}{|D_{\sigma}|} \sum_{\epsilon \in \tilde{\mathcal{E}}(D_{\sigma})} \phi_{\epsilon,\sigma}(u_i), \quad \forall \mathbf{x} \in D_{\sigma}, \text{ for } \sigma \in \mathcal{E}_{\text{int}}^{(i)}, \quad (3.33)$$

where  $\tilde{\mathcal{E}}(D_{\sigma})$  denotes the set of faces of  $D_{\sigma}$ , and

$$\phi_{\epsilon,\sigma}(u_i) = \begin{cases} \frac{|\epsilon|}{d_{\epsilon}} (u_{\sigma} - u_{\sigma'}) & \text{if } \epsilon = \sigma|\sigma' \in \tilde{\mathcal{E}}_{\text{int}}^{(i)}, \\ \frac{|\epsilon|}{d_{\epsilon}} u_{\sigma} & \text{if } \epsilon \in \tilde{\mathcal{E}}_{\text{ext}}^{(i)} \cap \tilde{\mathcal{E}}(D_{\sigma}) \end{cases} \quad (3.34)$$

where  $d_{\epsilon}$  is defined by (3.5). Note that we have the usual finite volume property of local conservativity of the flux through an interface  $\epsilon = \sigma|\sigma'$ :

$$\phi_{\epsilon,\sigma}(u_i) = -\phi_{\epsilon,\sigma'}(u_i), \quad \forall \epsilon = \sigma|\sigma' \in \tilde{\mathcal{E}}_{\text{int}}^{(i)}. \quad (3.35)$$

Then the discrete Laplace operator of the full velocity vector is defined by

$$-\Delta_{\mathcal{E}} : \mathbf{H}_{\mathcal{E},0} \longrightarrow \mathbf{H}_{\mathcal{E},0} \\ \mathbf{u} \longmapsto -\Delta_{\mathcal{E}} \mathbf{u} = (-\Delta_{\mathcal{E}}^{(1)} u_1, \dots, -\Delta_{\mathcal{E}}^{(d)} u_d)^t. \quad (3.36)$$

Let us now recall the definition of the discrete  $H_0^1$  inner product [12]; it is obtained by multiplying the discrete Laplace operator scalarly by a test function  $\mathbf{v} \in \mathbf{H}_{\mathcal{E},0}$  and integrating over the computational domain. A simple reordering of the sums (which may be seen as a discrete integration by parts) yields, thanks to the conservativity of the diffusion flux (3.35):

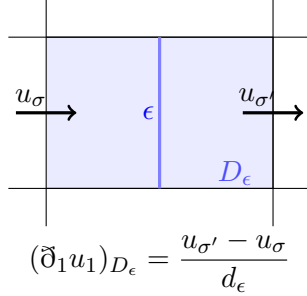
$$\forall (\mathbf{u}, \mathbf{v}) \in \mathbf{H}_{\mathcal{E},0}^2, \quad \int_{\Omega} -\Delta_{\mathcal{E}} \mathbf{u} \cdot \mathbf{v} \, d\mathbf{x} = [\mathbf{u}, \mathbf{v}]_{1,\mathcal{E},0} = \sum_{i=1}^d [u_i, v_i]_{1,\mathcal{E}^{(i)},0}, \\ \text{with } [u_i, v_i]_{1,\mathcal{E}^{(i)},0} = \sum_{\substack{\epsilon \in \tilde{\mathcal{E}}_{\text{int}}^{(i)} \\ \epsilon = \sigma|\sigma'}} \frac{|\epsilon|}{d_{\epsilon}} (u_{\sigma} - u_{\sigma'}) (v_{\sigma} - v_{\sigma'}) + \sum_{\substack{\epsilon \in \tilde{\mathcal{E}}_{\text{ext}}^{(i)} \\ \epsilon \in \tilde{\mathcal{E}}(D_{\sigma})}} \frac{|\epsilon|}{d_{\epsilon}} u_{\sigma} v_{\sigma} \quad (3.37)$$

The bilinear forms  $\left| \begin{array}{l} H_{\mathcal{E},0}^{(i)} \times H_{\mathcal{E},0}^{(i)} \rightarrow \mathbb{R} \\ (u, v) \mapsto [u_i, v_i]_{1,\mathcal{E}^{(i)},0} \end{array} \right.$  and  $\left| \begin{array}{l} \mathbf{H}_{\mathcal{E},0} \times \mathbf{H}_{\mathcal{E},0} \rightarrow \mathbb{R} \\ (\mathbf{u}, \mathbf{v}) \mapsto [\mathbf{u}, \mathbf{v}]_{1,\mathcal{E},0} \end{array} \right.$  are inner products on  $H_{\mathcal{E},0}^{(i)}$  and  $\mathbf{H}_{\mathcal{E},0}$  respectively, which induce the following discrete  $H_0^1$  norms:

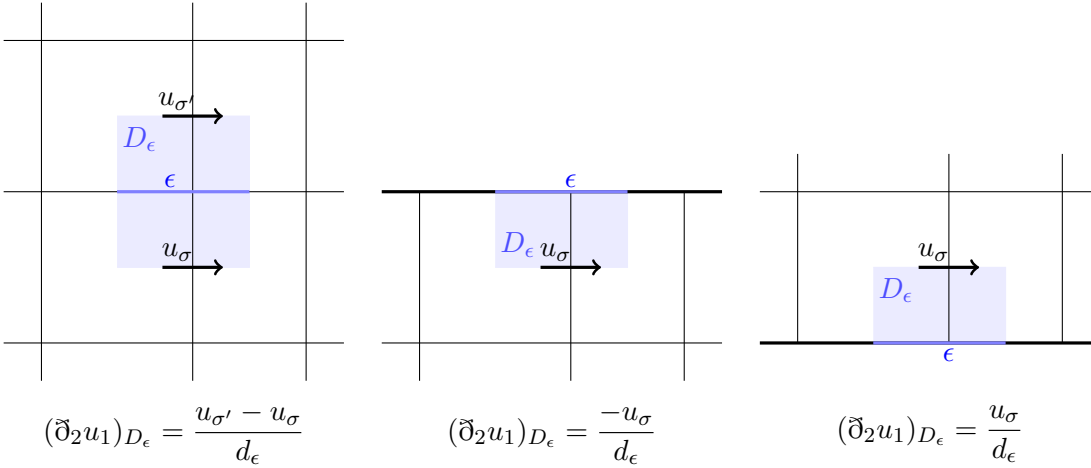
$$\|u_i\|_{1,\mathcal{E}^{(i)},0}^2 = [u_i, u_i]_{1,\mathcal{E}^{(i)},0} = \sum_{\substack{\epsilon \in \tilde{\mathcal{E}}_{\text{int}}^{(i)} \\ \epsilon = \sigma|\sigma'}} \frac{|\epsilon|}{d_\epsilon} (u_\sigma - u_{\sigma'})^2 + \sum_{\substack{\epsilon \in \tilde{\mathcal{E}}_{\text{ext}}^{(i)} \\ \epsilon \in \tilde{\mathcal{E}}(D_\sigma)}} \frac{|\epsilon|}{d_\epsilon} u_\sigma^2 \text{ for } i = 1, \dots, d, \quad (3.38a)$$

$$\|\mathbf{u}\|_{1,\mathcal{E},0}^2 = [\mathbf{u}, \mathbf{u}]_{1,\mathcal{E},0} = \sum_{i=1}^d \|u_i\|_{1,\mathcal{E}^{(i)},0}^2. \quad (3.38b)$$

Since we are working on Cartesian grids, this inner product may be formulated as the  $L^2$  inner product



$$(\delta_1 u_1)_{D_\epsilon} = \frac{u_{\sigma'} - u_\sigma}{d_\epsilon}$$



$$(\delta_2 u_1)_{D_\epsilon} = \frac{u_{\sigma'} - u_\sigma}{d_\epsilon} \quad (\delta_2 u_1)_{D_\epsilon} = \frac{-u_\sigma}{d_\epsilon} \quad (\delta_2 u_1)_{D_\epsilon} = \frac{u_\sigma}{d_\epsilon}$$

Figure 4: Notations for the definition of the partial space derivatives of the first component of the velocity, in two space dimensions.

of discrete gradients. Indeed, consider the following discrete gradient of each velocity component  $u_i$ .

$$\nabla_{\mathcal{E}^{(i)}} u_i = (\delta_1 u_i, \dots, \delta_d u_i) \text{ with } \delta_j u_i = \sum_{\substack{\epsilon \in \tilde{\mathcal{E}}^{(i)} \\ \epsilon \perp \mathbf{e}^{(j)}}} (\delta_j u_i)_{D_\epsilon} \mathcal{X}_{D_\epsilon}, \quad (3.39)$$

where the elements  $D_\epsilon$  of the bi-dual grid are defined in (3.4) (see also Figure 2) and

$$(\delta_j u_i)_{D_\epsilon} = \begin{cases} \frac{u_{\sigma'} - u_\sigma}{d_\epsilon} \text{ with } \epsilon = \overrightarrow{\sigma|\sigma'}, \\ -\frac{u_\sigma}{d_\epsilon} \mathbf{e}^{(j)} \cdot \mathbf{n}_{\epsilon, D_\sigma} \text{ with } \epsilon \in \tilde{\mathcal{E}}_{\text{ext}}^{(i)} \cap \tilde{\mathcal{E}}(D_\sigma), \end{cases} \quad (3.40)$$

where  $\mathbf{n}_{\epsilon, D_\sigma}$  stands for the unit normal vector to  $\epsilon$  outward  $D_\sigma$ , see Figure 4. This definition is compatible with the definition of the discrete derivative  $(\delta_i u_i)_K$  given by (3.29), since, if  $\epsilon \subset K$  then

$D_\epsilon = K$ . Note that the second line in (3.40) is zero provide  $i = j$ , or provided  $\sigma \in \mathcal{E}_{\text{ext}}^{(i)}$ ,  $\epsilon \perp \mathbf{e}^{(j)}$  with  $i \neq j$ . With this definition, it is easily seen that

$$\int_{\Omega} \nabla_{\mathcal{E}^{(i)}} u \cdot \nabla_{\mathcal{E}^{(i)}} v \, d\mathbf{x} = [u, v]_{1, \mathcal{E}^{(i)}, 0}, \forall u, v \in H_{\mathcal{E}, 0}^{(i)}, \forall i = 1, \dots, d. \quad (3.41)$$

where  $[u, v]_{1, \mathcal{E}^{(i)}, 0}$  is the discrete  $H_0^1$  inner product defined by (3.37). We may then define

$$\nabla_{\mathcal{E}} \mathbf{u} = (\nabla_{\mathcal{E}^{(1)}} u_1, \dots, \nabla_{\mathcal{E}^{(d)}} u_d),$$

so that

$$\int_{\Omega} \nabla_{\mathcal{E}} \mathbf{u} : \nabla_{\mathcal{E}} \mathbf{v} \, d\mathbf{x} = [\mathbf{u}, \mathbf{v}]_{1, \mathcal{E}, 0}.$$

We will need discrete Sobolev inequalities for the discrete approximations. The following Theorem is proved in [12].

**Theorem 3.1** (Discrete Sobolev inequalities). *Let  $\Omega$  be a bounded domain of  $\mathbb{R}^d$ ,  $d = 2$  or  $d = 3$ , adapted to the MAC-scheme (that is any finite union of rectangles in 2D or rectangular in 3D), and let  $\mathcal{D} = (\mathcal{M}, \mathcal{E})$  be a MAC grid of  $\Omega$ . Let  $q < +\infty$  if  $d = 2$  and  $q = 6$  if  $d = 3$ . Then there exists  $c = c(q, |\Omega|, \eta_{\mathcal{M}})$  depending on  $\eta_{\mathcal{M}}$  in a nondecreasing way such that, for all  $u \in \mathbf{H}_{\mathcal{E}, 0}$ ,*

$$\|\mathbf{u}\|_{L^q(\Omega)} \leq c \|\mathbf{u}\|_{1, \mathcal{E}, 0}.$$

### 3.4 Projection operators

In this section we introduce several projection operators. We first define the mean-value interpolator over  $L_{\mathcal{M}}$ :

$$\mathcal{P}_{\mathcal{M}} : \begin{cases} L_{\text{loc}}^1(\Omega) & \longrightarrow L_{\mathcal{M}} \\ \varphi & \mapsto \mathcal{P}_{\mathcal{M}} \varphi = \sum_{K \in \mathcal{M}} \varphi_K \mathcal{X}_K, \end{cases} \quad (3.42)$$

with

$$\varphi_K = \frac{1}{|K|} \int_K \varphi(\mathbf{x}) \, d\mathbf{x}, \quad \forall K \in \mathcal{M}. \quad (3.43)$$

This operator satisfies for any  $1 \leq p \leq \infty$  and for any  $r \in L^p(\Omega)$ ,

$$\|\mathcal{P}_{\mathcal{M}} r\|_{L^p(\Omega)} \leq \|r\|_{L^p(\Omega)}. \quad (3.44)$$

We also define over  $H_{\mathcal{E}, 0}^{(i)}$  the following interpolation operator  $\mathcal{P}_{\mathcal{E}}^{(i)}$ :

$$\mathcal{P}_{\mathcal{E}}^{(i)} : \begin{cases} H_0^1(\Omega) & \longrightarrow H_{\mathcal{E}, 0}^{(i)} \\ \varphi & \mapsto \mathcal{P}_{\mathcal{E}}^{(i)} \varphi = \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \varphi_{\sigma} \mathcal{X}_{D_{\sigma}}, \end{cases} \quad (3.45)$$

with

$$\varphi_{\sigma} = \frac{1}{|\sigma|} \int_{\sigma} \varphi(\mathbf{x}) \, d\gamma(\mathbf{x}), \quad \forall \sigma \in \mathcal{E}_{\text{int}}^{(i)}, \quad (3.46)$$

where  $d\gamma(\mathbf{x})$  is the  $d - 1$ -Lebesgue measure on  $\sigma$  and we denote

$$\mathcal{P}_{\mathcal{E}} = (\mathcal{P}_{\mathcal{E}}^{(1)}, \dots, \mathcal{P}_{\mathcal{E}}^{(d)}) \in \mathcal{L}(H_0^1(\Omega)^d, \mathbf{H}_{\mathcal{E}, 0}) \quad (3.47)$$

the vector valued extension. This operator preserves the divergence in the following sense:

$$\forall \mathbf{v} \in H_0^1(\Omega)^d, \forall q \in L_{\mathcal{M}}, \int_{\Omega} q \, \text{div}_{\mathcal{M}} \mathcal{P}_{\mathcal{E}} \mathbf{v} \, d\mathbf{x} = \int_{\Omega} q \, \text{div} \, \mathbf{v} \, d\mathbf{x}. \quad (3.48)$$

This operator satisfies for any  $1 \leq p \leq \infty$  and for any  $\mathbf{U} \in W_0^{1,p}(\Omega)^d$ ,

$$\|\mathcal{P}_{\mathcal{E}} \mathbf{U}\|_{L^p(\Omega)^d} \leq c \|\nabla \mathbf{U}\|_{L^p(\Omega)^{d \times d}}. \quad (3.49)$$

where the constant  $c$  depends on  $d$  and  $p$  and on  $|\Omega|$ .

In the following Lemma we recall some classical mean value inequalities. These inequalities are used to obtain estimates involving the projector operators  $\mathcal{P}_{\mathcal{M}}$  and  $\mathcal{P}_{\mathcal{E}}$  previously defined.

**Lemma 3.2.** [Mean value inequalities] Let  $D = \prod_{i=1}^d (a_i, b_i)$  be a bounded open square of  $\mathbb{R}^d$ ,  $d \geq 1$ . Let  $\sigma \subset \partial D$  be a face of  $D$ . Let  $1 \leq p \leq \infty$ . There exists  $c$  only depending on  $d$  and  $p$  such that  $\forall v \in W^{1,p}(D)$ ,

$$\|v - v_\sigma\|_{L^p(D)} \leq c \operatorname{diam}(D) \|\nabla v\|_{L^p(D)^d}, \quad (3.50)$$

$$\|v - v_D\|_{L^p(D)} \leq c \operatorname{diam}(D) \|\nabla v\|_{L^p(D)^d}, \quad (3.51)$$

where  $v_D = \frac{1}{|D|} \int_D v \, d\mathbf{x}$  and  $v_\sigma = \frac{1}{|\sigma|} \int_\sigma v \, d\gamma(\mathbf{x})$  ( $d\gamma(\mathbf{x})$  is the  $d-1$ -Lebesgue measure on  $\sigma$ ). Moreover if  $v \in C^2(\bar{D})$  then

$$|v_D - v(\mathbf{x}_D)| \leq \|\nabla^2 v\|_{L^\infty(D)^{d \times d}} \operatorname{diam}(D)^2, \quad (3.52)$$

where  $\mathbf{x}_D$  stands for the center of mass of  $D$  and

$$\left| v\left(\frac{\mathbf{x} + \mathbf{y}}{2}\right) - \frac{1}{2}(v(\mathbf{x}) + v(\mathbf{y})) \right| \leq \frac{1}{8} \|\nabla^2 v\|_{L^\infty(\Omega)^{d \times d}} |\mathbf{x} - \mathbf{y}|^2, \forall \mathbf{x}, \mathbf{y} \in \bar{D}. \quad (3.53)$$

Let  $\mathcal{D} = (\mathcal{M}, \mathcal{E})$  be a MAC grid of the computational domain  $\Omega$ , let  $1 \leq p \leq \infty$ . Then there exists  $c$  only depending on  $p$  and on  $d$  such that for any  $(r, \mathbf{U}) \in W^{1,p}(\Omega) \times W_0^{1,p}(\Omega)^d$ ,

$$\|r - \mathcal{P}_{\mathcal{M}} r\|_{L^p(\Omega)} \leq ch_{\mathcal{M}} \|\nabla v\|_{L^p(\Omega)^d}, \quad (3.54)$$

$$\|\mathbf{U} - \mathcal{P}_{\mathcal{E}} \mathbf{U}\|_{L^p(\Omega)^d} \leq ch_{\mathcal{M}} \|\nabla \mathbf{U}\|_{L^p(\Omega)^{d \times d}}, \quad (3.55)$$

There exists  $c$  only depending on  $d$  and  $p$  and  $|\Omega|$  and on  $\eta_{\mathcal{M}}$  in a nondecreasing way such that for any  $\mathbf{U} \in W_0^{1,p}(\Omega)^d$ ,

$$\|\nabla_{\mathcal{E}} \mathcal{P}_{\mathcal{E}} \mathbf{U}\|_{L^p(\Omega)^{d \times d}} \leq c \|\nabla \mathbf{U}\|_{L^p(\Omega)^{d \times d}}, \quad (3.56)$$

Moreover if  $\mathbf{U} \in C^2(\bar{\Omega})^d$ ,

$$\|\partial_j \mathcal{P}_{\mathcal{E}} U_i - \partial_j U_i\|_{L^\infty(\Omega)} \leq ch_{\mathcal{M}} \|\nabla^2 \mathbf{U}\|_{L^\infty(\Omega)^{d \times d}}. \quad (3.57)$$

*Proof.* Let us prove (3.51). Let us define the reference square  $\hat{D} = (0, 1)^d$  and let  $\varphi = (\varphi_i)_{1 \leq i \leq d}$  defined by

$$\varphi_i(x_i) = (1 - x_i)a_i + x_i b_i.$$

One has for any  $v \in W^{1,p}(D)$

$$\|v\|_{L^p(D)} = |D|^{\frac{1}{p}} \|v \circ \varphi\|_{L^p(\hat{D})} \quad \|\partial_i v\|_{L^p(D)} = \frac{|D|^{\frac{1}{p}}}{b_i - a_i} \|\partial_i (v \circ \varphi)\|_{L^p(\hat{D})}. \quad (3.58)$$

Since  $W^{1,p}(\hat{D})$  is compactly embedded in  $L^p(\hat{D})$  there exists  $c$  only depending on  $d$  and  $p$  such that for any  $v \in W^{1,p}(\hat{D})$

$$\|v - v_{\hat{D}}\|_{L^p(\hat{D})} \leq c \|\nabla v\|_{L^p(\hat{D})}.$$

If  $p = +\infty$  one has

$$\|v - v_D\|_{L^\infty(D)} = \|v - v \circ \varphi_{\hat{D}}\|_{L^\infty(D)} = \|v \circ \varphi - v \circ \varphi_{\hat{D}}\|_{L^\infty(\hat{D})} \leq c \|\nabla (v \circ \varphi)\|_{L^\infty(\hat{D})}.$$

Using (3.58) we infer that

$$\|\nabla (v \circ \varphi)\|_{L^\infty(\hat{D})} \leq c \operatorname{diam}(D) \|(\nabla v) \circ \varphi\|_{L^\infty(\hat{D})} \leq c \operatorname{diam}(D) \|\nabla v\|_{L^\infty(D)}$$

which gives (3.51). If  $1 \leq p < \infty$  one has for any  $v \in W^{1,p}(D)$

$$\|v - v_D\|_{L^p(D)}^p = \int_D |v - v_D|^p \, d\mathbf{x} = \int_D |v - v \circ \varphi_{\hat{D}}|^p \, d\mathbf{x} = |D| \int_{\hat{D}} |v \circ \varphi - v \circ \varphi_{\hat{D}}|^p \, d\mathbf{x} \leq c |D| \|\nabla (v \circ \varphi)\|_{L^p(\hat{D})}^p.$$

Using (3.58) we infer that

$$\|\nabla (v \circ \varphi)\|_{L^p(\hat{D})}^p \leq c \operatorname{diam}(D)^p \|(\nabla v) \circ \varphi\|_{L^p(\hat{D})}^p \leq c \operatorname{diam}(D)^p \frac{1}{|D|} \|\nabla v\|_{L^p(D)}^p$$



which also gives (3.51). The proof of (3.50) is similar. Let us prove (3.52). We have

$$v_D - v(\mathbf{x}_D) = \frac{1}{2|D|} \int_D (\nabla^2 v(c(\mathbf{x}))(\mathbf{x} - \mathbf{x}_D)) \cdot (\mathbf{x} - \mathbf{x}_D) \, d\mathbf{x}$$

where  $c(\mathbf{x}) \in \bar{D}$  wich gives

$$|v_D - v(\mathbf{x}_D)| \leq \|\nabla^2 v\|_{L^\infty(D)^{d \times d}} \frac{1}{|D|} \int_D |\mathbf{x} - \mathbf{x}_D|^2 \, d\mathbf{x}.$$

Consequently

$$|v_D - v(\mathbf{x}_D)| \leq \|\nabla^2 v\|_{L^\infty(D)^{d \times d}} \text{diam}(D)^2. \quad (3.59)$$

Let us prove (3.53). A Taylor expansion of the function  $t \rightarrow v(t\mathbf{x} + (1-t)\mathbf{y})$  gives

$$\begin{aligned} v(\mathbf{x}) &= v\left(\frac{\mathbf{x} + \mathbf{y}}{2}\right) + \nabla v\left(\frac{\mathbf{x} + \mathbf{y}}{2}\right) \cdot \frac{\mathbf{x} - \mathbf{y}}{2} + \frac{1}{8} (\nabla^2 v(\xi)(\mathbf{x} - \mathbf{y})) \cdot (\mathbf{x} - \mathbf{y}), \\ v(\mathbf{y}) &= v\left(\frac{\mathbf{x} + \mathbf{y}}{2}\right) + \nabla v\left(\frac{\mathbf{x} + \mathbf{y}}{2}\right) \cdot \frac{\mathbf{y} - \mathbf{x}}{2} + \frac{1}{8} (\nabla^2 v(\tilde{\xi})(\mathbf{x} - \mathbf{y})) \cdot (\mathbf{x} - \mathbf{y}). \end{aligned}$$

where  $\xi, \tilde{\xi} \in [\mathbf{x}, \mathbf{y}]$ . The expected result follows from the summation of the two previous identity. The proof of (3.54) and (3.55) are trivial consequences of (3.50) and (3.51). The proof of (3.56) can be found in [22]. Let us prove (3.57). By virtue of (3.4) one has

$$\|\tilde{\partial}_j \mathcal{P}_\mathcal{E} U_i - \partial_j U_i\|_{L^\infty(\Omega)} \leq \max_{\epsilon \in \tilde{\mathcal{E}}^{(i,j)}} \|\tilde{\partial}_j \mathcal{P}_\mathcal{E} U_i - \partial_j U_i\|_{L^\infty(D_\epsilon)}.$$

Moreover by virtue of (3.52) and (3.53) we can write for  $\epsilon = \overrightarrow{\sigma|\sigma'} \in \tilde{\mathcal{E}}_{\text{int}}^{(i)}$ ,  $\epsilon \perp \mathbf{e}^{(j)}$ ,  $\mathbf{x} \in D_\epsilon$ ,

$$\begin{aligned} \tilde{\partial}_j (\mathcal{P}_\mathcal{E}^{(i)} U_i)_{D_\epsilon} - \frac{\partial}{\partial x_j} U_i(\mathbf{x}) &= \frac{1}{d_\epsilon} ((\mathcal{P}_\mathcal{E}^{(i)} U_i)_{\sigma'} - (\mathcal{P}_\mathcal{E}^{(i)} U_i)_\sigma) - \frac{\partial}{\partial x_j} U_i(\mathbf{x}) \\ &= \frac{1}{d_\epsilon} (U_i(\mathbf{x}_{\sigma'}) - U_i(\mathbf{x}_\sigma)) - \frac{\partial}{\partial x_j} U_i(\mathbf{x}) + R_\epsilon \\ &= \frac{\partial}{\partial x_j} U_i^n(\mathbf{x}_{\sigma, \sigma'}) - \frac{\partial}{\partial x_j} U_i(\mathbf{x}) + R_\epsilon^n \end{aligned}$$

where  $\mathbf{x}_{\sigma, \sigma'} \in [\mathbf{x}_\sigma, \mathbf{x}_{\sigma'}]$  and where the remainder  $R_\epsilon^n$  satisfies

$$|R_\epsilon| \leq ch_{\mathcal{M}}$$

where  $c$  depends on  $\eta_{\mathcal{M}}$  and on  $\|\nabla^2 v\|_{L^\infty(\Omega)^{d \times d}}$ . Note that the case  $\epsilon \in \tilde{\mathcal{E}}_{\text{ext}}^{(i)}$  can be treated in the same way. Consequently we have inequality

$$\|\tilde{\partial}_j \mathcal{P}_\mathcal{E} U_i - \partial_j U_i\|_{L^\infty(D_\epsilon)} \leq ch_{\mathcal{M}}, \quad \forall (i, j) \in \{1, 2, 3\}^2, \forall \epsilon \in \tilde{\mathcal{E}}_{\text{int}}^{(i)}, \epsilon \perp \mathbf{e}^{(j)},$$

where the constant  $c$  depends on  $\|\nabla^2 \mathbf{U}\|_{L^\infty(\Omega)}$  and we obtain the expected result.  $\square$

In the following defintion, we introduce two velocity interpolators.

**Definition 3.3** (Velocity interpolators). *For a given MAC gris  $\mathcal{D} = (\mathcal{M}, \mathcal{E})$ , we define, for  $i, j = 1, \dots, d$ , the full grid velocity reconstruction operator with respect to  $(i, j)$  by*

$$\begin{aligned} \mathcal{R}_\mathcal{E}^{(i,j)} : H_{\mathcal{E},0}^{(i)} &\rightarrow H_{\mathcal{E},0}^{(j)} \\ v &\mapsto \mathcal{R}_\mathcal{E}^{(i,j)} v = \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(j)}} (R_\mathcal{E}^{(i,j)} v)_\sigma \mathcal{X}_{D_\sigma}, \end{aligned} \quad (3.60)$$

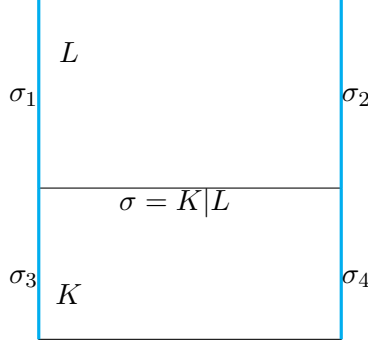


Figure 5: Set  $\mathcal{N}_\sigma = \{\sigma_1, \sigma_2, \sigma_3, \sigma_4\}$  with  $\sigma \in \mathcal{E}_{\text{int}}^{(j)}(K)$ ,  $j \neq i$  in two dimensions ( $i = 1, j = 2$ )

where

$$(\mathcal{R}_{\mathcal{E}}^{(i,j)}v)_\sigma = v_\sigma \text{ if } \sigma \in \mathcal{E}_{\text{int}}^{(i)}, \quad (\mathcal{R}_{\mathcal{E}}^{(i,j)}v)_\sigma = \frac{1}{\text{card}(\mathcal{N}_\sigma)} \sum_{\sigma' \in \mathcal{N}_\sigma} v_{\sigma'} \text{ otherwise,} \quad (3.61)$$

$$\text{where, for any } \sigma \in \mathcal{E}_{\text{int}} \setminus \mathcal{E}_{\text{int}}^{(i)}, \quad \mathcal{N}_\sigma = \{\sigma' \in \mathcal{E}^{(i)}, D_\sigma \cap \sigma' \neq \emptyset\}. \quad (3.62)$$

For any  $i = 1, \dots, d$ , we also define a projector from  $H_{\mathcal{E}}^{(i)}$  into  $L_{\mathcal{M}}$  by

$$\begin{aligned} \mathcal{R}_{\mathcal{M}}^{(i)} : H_{\mathcal{E}}^{(i)} &\rightarrow L_{\mathcal{M}} \\ v &\mapsto \mathcal{R}_{\mathcal{M}}^{(i)}v = \sum_{K \in \mathcal{M}} (\mathcal{R}_{\mathcal{M}}^{(i)}v)_K \mathcal{X}_K, \end{aligned} \quad (3.63)$$

where

$$(\mathcal{R}_{\mathcal{M}}^{(i)}v)_K = \frac{1}{2} \sum_{\sigma \in \mathcal{E}^{(i)}(K)} v_\sigma. \quad (3.64)$$

We then define

$$\begin{aligned} \mathcal{R}_{\mathcal{M}} : \mathbf{H}_{\mathcal{E}} &\rightarrow L_{\mathcal{M}}^d \\ \mathbf{v} = (v_1, \dots, v_d) &\mapsto \mathcal{R}_{\mathcal{M}}\mathbf{v} = (\mathcal{R}_{\mathcal{M}}^{(1)}v_1, \dots, \mathcal{R}_{\mathcal{M}}^{(d)}v_d). \end{aligned} \quad (3.65)$$

**Lemma 3.3.** *Then there exists  $c > 0$ , depending only on  $d, p$  and on  $\eta_{\mathcal{M}}$  in a nondecreasing way such that for any  $1 \leq p < \infty$ , for any  $i, j = 1, \dots, d$  and for any  $v \in H_{\mathcal{E},0}^{(i)}$ ,*

$$\|\mathcal{R}_{\mathcal{E}}^{(i,j)}v - v\|_{L^p(\Omega)} \leq ch_{\mathcal{M}} \|\nabla_{\mathcal{E}^{(i)}}v\|_{L^p(\Omega)}. \quad (3.66)$$

Then there exists  $c > 0$  such that for any  $i = 1, \dots, d$ , for any  $v \in H_{\mathcal{E},0}^{(i)}$  and for any  $1 \leq p \leq \infty$  one has

$$\|\mathcal{R}_{\mathcal{M}}^{(i)}v - v\|_{L^p(\Omega)} \leq ch_{\mathcal{M}} \|\bar{\partial}_i v\|_{L^p(\Omega)}. \quad (3.67)$$

*Proof.* Let us prove (3.67). From the definition of  $\mathcal{R}_{\mathcal{M}}^{(i)}$  (see (3.63)) we have for  $1 \leq p < \infty$

$$\begin{aligned} \|\mathcal{R}_{\mathcal{M}}^{(i)}v - v\|_{L^p(\Omega)}^p &= \sum_{K \in \mathcal{M}} \|\mathcal{R}_{\mathcal{M}}^{(i)}v - v\|_{L^p(K)}^p = \sum_{\substack{K = [\overrightarrow{\sigma\sigma'}] \\ \sigma, \sigma' \in \mathcal{E}^{(i)}}} \left( \|\mathcal{R}_{\mathcal{M}}^{(i)}v - v\|_{L^p(D_{\sigma,K})}^p + \|\mathcal{R}_{\mathcal{M}}^{(i)}v - v\|_{L^p(D_{\sigma',K})}^p \right) \\ &\leq \frac{1}{2^p} h_{\mathcal{M}}^p \sum_{K \in \mathcal{M}} \|\bar{\partial}_i v\|_{L^p(K)}^p \leq ch_{\mathcal{M}}^p \|\bar{\partial}_i v\|_{L^p(\Omega)}^p \end{aligned}$$

which gives the expected result. For  $p = +\infty$  we have

$$\begin{aligned} \|\mathcal{R}_{\mathcal{M}}^{(i)}v - v\|_{L^\infty(\Omega)} &\leq \max_{K \in \mathcal{M}} \|\mathcal{R}_{\mathcal{M}}^{(i)}v - v\|_{L^\infty(K)} = \max_{\substack{K = [\overrightarrow{\sigma\sigma'}] \\ \sigma, \sigma' \in \mathcal{E}^{(i)}}} \left( \|\mathcal{R}_{\mathcal{M}}^{(i)}v - v\|_{L^\infty(D_{\sigma,K})} + \|\mathcal{R}_{\mathcal{M}}^{(i)}v - v\|_{L^\infty(D_{\sigma',K})} \right) \\ &\leq \frac{1}{2} h_{\mathcal{M}} \sum_{K \in \mathcal{M}} \|\bar{\partial}_i v\|_{L^\infty(K)} \leq ch_{\mathcal{M}} \|\bar{\partial}_i v\|_{L^\infty(\Omega)} \end{aligned}$$

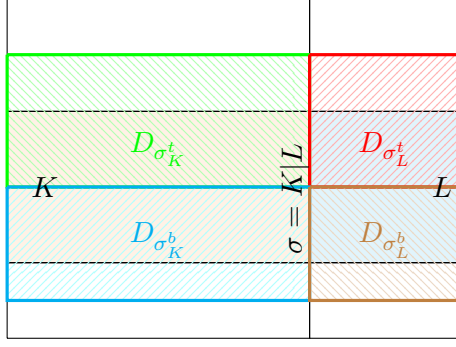


Figure 6: Full grid velocity interpolate.

which gives the expected result.

Let us now prove (3.66). For the sake of simplicity we assume that  $d = 2$ ,  $i = 1$  and  $j = 2$ . Other cases are similar. First we write

$$\mathcal{R}_{\mathcal{E}}^{(i,j)}v - v = \mathcal{R}_{\mathcal{E}}^{(i,j)}v - \mathcal{R}_{\mathcal{M}}^{(i)}v + \mathcal{R}_{\mathcal{M}}^{(i)}v - v$$

The second term in the right hand side of the previous equality is estimated using (3.67). Now using the decomposition of  $D_{\sigma}$  established in figure 7 we can write

$$\begin{aligned} \|\mathcal{R}_{\mathcal{E}}^{(i,j)}v - \mathcal{R}_{\mathcal{M}}^{(i)}v\|_{L^p(\Omega)}^p &= \sum_{\sigma \in \mathcal{E}^{(j)}} \|\mathcal{R}_{\mathcal{E}}^{(i,j)}v - \mathcal{R}_{\mathcal{M}}^{(i)}v\|_{L^p(D_{\sigma})}^p \\ &= \sum_{\sigma=K|L \in \mathcal{E}_{\text{int}}^{(j)}} \|\mathcal{R}_{\mathcal{E}}^{(i,j)}v - \mathcal{R}_{\mathcal{M}}^{(i)}v\|_{L^p(D_{\sigma,K})}^p + \|\mathcal{R}_{\mathcal{E}}^{(i,j)}v - \mathcal{R}_{\mathcal{M}}^{(i)}v\|_{L^p(D_{\sigma,L})}^p \\ &\quad + \sum_{\sigma \in \mathcal{E}_{\text{ext}}^{(j)}} \|\mathcal{R}_{\mathcal{E}}^{(i,j)}v - \mathcal{R}_{\mathcal{M}}^{(i)}v\|_{L^p(D_{\sigma})}^p \\ &\leq \sum_{\sigma=K|L \in \mathcal{E}_{\text{int}}^{(j)}} |D_{\sigma,K}| |(\mathcal{R}_{\mathcal{E}}^{(i,j)}v)_{\sigma} - (\mathcal{R}_{\mathcal{M}}^{(i)}v)_K|^p + |D_{\sigma,L}| |(\mathcal{R}_{\mathcal{E}}^{(i,j)}v)_{\sigma} - (\mathcal{R}_{\mathcal{M}}^{(i)}v)_L|^p \\ &\quad + \sum_{\sigma \in \mathcal{E}_{\text{ext}}^{(j)} \cap \mathcal{E}(K)} |D_{\sigma}| |(\mathcal{R}_{\mathcal{M}}^{(i)}v)_K|^p \\ &\leq ch_{\mathcal{M}}^p \sum_{\substack{\sigma \in \mathcal{E}_{\text{int}}^{(j)} \\ \sigma=K|L}} (\|\check{\partial}_j v\|_{L^p(D_{\sigma^l})}^p + \|\check{\partial}_j v\|_{L^p(D_{\sigma^r})}^p) + ch_{\mathcal{M}}^p \sum_{\epsilon \in \tilde{\mathcal{E}}_{\text{ext}}^{(i)} \cap \tilde{\mathcal{E}}^{(i,j)}} |D_{\epsilon}| |(\check{\partial}_j u_i)_{D_{\epsilon}}|^p \\ &\leq ch_{\mathcal{M}}^p \|\check{\partial}_j v\|_{L^p(\Omega)}^p. \end{aligned}$$

This finishes the proof of Lemma 3.3.

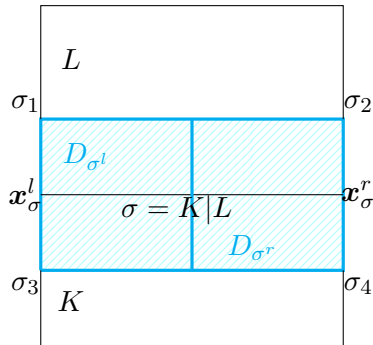


Figure 7: Decomposition of  $D_{\sigma}$

□

The following algebraic identity is used to transform some terms involving the dual fluxes into terms involving primal fluxes for which the expression is easier to manipulate.

**Lemma 3.4.** *Let  $\varrho \in L_{\mathcal{M}}$  and  $\mathbf{u} \in \mathbf{H}_{\mathcal{E},0}$ . Let  $i \in \{1, \dots, d\}$ . Let  $\varphi = \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \varphi_{\sigma} \chi_{D_{\sigma}} \in H_{\mathcal{E},0}^{(i)}$  be a discrete scalar function. Let the primal fluxes be given by (3.12) and let the dual fluxes  $F_{\epsilon,\sigma}$  be given by (3.19) or (3.20) (depending on the direction of  $\mathbf{n}_{\epsilon}$  with respect to  $\mathbf{e}^{(i)}$ ). Then we have:*

$$\sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \sum_{\epsilon \in \tilde{\mathcal{E}}(D_{\sigma})} F_{\epsilon,\sigma} u_{\epsilon} \varphi_{\sigma} = \sum_{K \in \mathcal{M}} (\mathcal{R}_{\mathcal{M}}^{(i)} \varphi)_K \sum_{j=1}^d \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(j)}(K)} F_{\sigma,K} (\mathcal{R}_{\mathcal{E}}^{(i,j)} u_i)_{\sigma} + R^i(u_i, \varphi)$$

where

$$\begin{aligned} R^i(u_i, \varphi) &= \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} (\varphi_{\sigma} - (\mathcal{R}_{\mathcal{M}}^{(i)} \varphi)_K) F_{\sigma,K} (u_{\sigma} - (\mathcal{R}_{\mathcal{M}}^{(i)} u_i)_K) \\ &+ \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} (\varphi_{\sigma} - (\mathcal{R}_{\mathcal{M}}^{(i)} \varphi)_K) \sum_{j=1, j \neq i}^d \sum_{\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)} \sum_{\sigma' \in \mathcal{N}_{\tau,\sigma}} \frac{F_{\tau,K}}{2} \left( \frac{u_{i,\sigma} + u_{i,\sigma'}}{2} - (\mathcal{R}_{\mathcal{M}}^{(i)} u_i)_K \right). \end{aligned}$$

In the last sum we have denoted

$$\mathcal{N}_{\tau,\sigma} = \{\sigma' \in \mathcal{E}^{(i)} \mid \text{int}_{d-1} \tau \cap \text{int}_{d-1}(D_{\sigma} | D_{\sigma'}) \neq \emptyset\},$$

where  $\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)$ ,  $\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)$ ,  $j \neq i$ ,  $\text{int}_{d-1}$  means interior in the topology of  $\mathbb{R}^{d-1}$ .

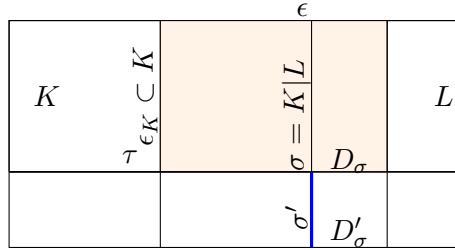


Figure 8: Set  $\mathcal{N}_{\tau,\sigma} = \{\sigma'\}$  with  $\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)$ ,  $\sigma \in \mathcal{E}^{(i)}(K)$ ,  $j \neq i$  in two dimensions ( $i = 1$ ,  $j = 2$ )

*Proof.* We split the sum at the left hand side of the identity in Lemma 3.4 to two sums, first one over faces  $\epsilon$  parallel to faces  $\sigma$  and second one over faces  $\epsilon$  orthogonal to sigma:

$$\begin{aligned} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \varphi_{\sigma} \left[ \sum_{\epsilon \in \tilde{\mathcal{E}}(D_{\sigma})} F_{\epsilon,\sigma} u_{i,\epsilon} \right] &= \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \varphi_{\sigma} \left[ \sum_{\epsilon \in \tilde{\mathcal{E}}_{\text{int}}(D_{\sigma})} F_{\epsilon,\sigma} u_{i,\epsilon} \right] \\ &= \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} \varphi_{\sigma} \left[ \sum_{\epsilon \in \tilde{\mathcal{E}}_{\text{int}}(D_{\sigma}), \epsilon \in K} F_{\epsilon,\sigma} u_{i,\epsilon} + \sum_{j=1, j \neq i}^d \sum_{\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)} \sum_{\sigma' \in \mathcal{N}_{\tau,\sigma}} \frac{F_{\tau,K}}{2} u_{i,\epsilon} \right] \end{aligned}$$

where we have used definition (3.20) of  $F_{\epsilon,\sigma}$  and denoted for fixed  $\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)$  and  $\tau \in \mathcal{E}_{\text{int}}(K) \setminus \mathcal{E}_{\text{int}}^{(i)}(K)$ .

$$\tilde{\mathcal{N}}_{\tau,\sigma} = \{\epsilon \in \tilde{\mathcal{E}}(D_{\sigma}) \mid \epsilon \perp \sigma, \emptyset \neq \epsilon \cap K \subset \tau\}.$$

For further calculation we notice that

$$\mathcal{N}_{\tau} = \cup_{\sigma \in \mathcal{E}^{(i)}(K)} \mathcal{N}_{\tau,\sigma} \cup \mathcal{E}^{(i)}(K), \quad \tilde{\mathcal{N}}_{\tau,\sigma} = \{D_{\sigma} | D_{\sigma'} \mid \sigma' \in \mathcal{N}_{\tau,\sigma}\}, \quad (3.68)$$

where  $\mathcal{N}_{\tau}$  is defined in (3.62).

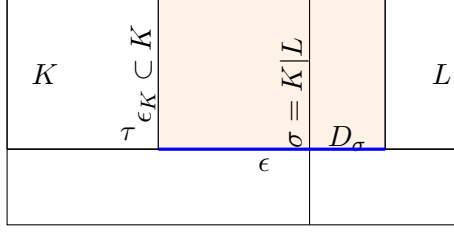


Figure 9: Set  $\tilde{\mathcal{N}}_{\tau,\sigma} = \{\epsilon\}$  with  $\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)$ ,  $\sigma \in \mathcal{E}^{(i)}(K)$ ,  $j \neq i$  in two dimensions ( $i = 1, j = 2$ )

Realizing that the set  $\{\epsilon \in \tilde{\mathcal{E}}(D_\sigma) | \epsilon \in K\}$  contains exactly one face denoted  $\epsilon_K$  (see Figure 8), we rewrite the above expression using definitions (3.26), (3.68) as follows

$$\begin{aligned}
\sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \varphi_\sigma \left[ \sum_{\epsilon \in \tilde{\mathcal{E}}(D_\sigma)} F_{\epsilon,\sigma} u_{i,\epsilon} \right] &= \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} \varphi_\sigma \left[ F_{\epsilon_K,\sigma} u_{i,\epsilon_K} + \sum_{j=1, j \neq i}^d \sum_{\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)} \sum_{\sigma' \in \mathcal{N}_{\tau,\sigma}} \frac{F_{\tau,K} u_{i,\sigma} + u_{i,\sigma'}}{2} \right] \\
&= \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} \varphi_\sigma \left[ F_{\epsilon_K,\sigma} u_{i,\epsilon_K} + F_{\sigma,K} u_{i,\sigma} + \sum_{j=1, j \neq i}^d \sum_{\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)} \sum_{\sigma' \in \mathcal{N}_{\tau,\sigma}} \frac{F_{\tau,K} u_{i,\sigma} + u_{i,\sigma'}}{2} \right] \\
&= \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} (\mathcal{R}_{\mathcal{M}}^{(i)}(\varphi))_K \left[ F_{\sigma,K} u_{i,\sigma} + \sum_{j=1, j \neq i}^d \sum_{\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)} \sum_{\sigma' \in \mathcal{N}_{\tau,\sigma}} \frac{F_{\tau,K} u_{i,\sigma} + u_{i,\sigma'}}{2} \right] \\
&+ \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} \left[ \varphi_\sigma - (\mathcal{R}_{\mathcal{M}}^{(i)}(\varphi))_K \right] \left[ F_{\epsilon_K,\sigma} u_{i,\epsilon_K} + F_{\sigma,K} u_{i,\sigma} + \sum_{j=1, j \neq i}^d \sum_{\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)} \sum_{\sigma' \in \mathcal{N}_{\tau,\sigma}} \frac{F_{\tau,K} u_{i,\sigma} + u_{i,\sigma'}}{2} \right].
\end{aligned}$$

In the above we have used the conservation (3.15) of primal fluxes (which gives in particular  $\sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} \varphi_\sigma F_{\sigma,K} = 0$ ) to pass from the first to the second expression, and the conservation of (3.22) of dual fluxes (in particular  $\sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} (\mathcal{R}_{\mathcal{M}}^{(i)}(\varphi))_K F_{\epsilon_K,\sigma} u_{i,\epsilon_K} = 0$ ). Consequently,

$$\sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} \varphi_\sigma \left[ \sum_{\epsilon \in \tilde{\mathcal{E}}(D_\sigma)} F_{\epsilon,\sigma} u_{i,\epsilon} \right] = \sum_{K \in \mathcal{M}} (\mathcal{R}_{\mathcal{M}}^{(i)}(\varphi))_K I_i^K + \sum_{K \in \mathcal{M}} J_i^K, \quad (3.69)$$

where

$$I_i^K := \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} F_{\sigma,K} u_{i,\sigma} + \sum_{j=1, j \neq i}^d \sum_{\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} \sum_{\sigma' \in \mathcal{N}_{\tau,\sigma}} \frac{F_{\tau,K} u_{i,\sigma} + u_{i,\sigma'}}{2}$$

and

$$J_i^K := \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} \left[ \varphi_\sigma - (\mathcal{R}_{\mathcal{M}}^{(i)}(\varphi))_K \right] \left[ F_{\epsilon_K,\sigma} u_{i,\epsilon_K} + F_{\sigma,K} u_{i,\sigma} + \sum_{j=1, j \neq i}^d \sum_{\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)} \sum_{\sigma' \in \mathcal{N}_{\tau,\sigma}} \frac{F_{\tau,K} u_{i,\sigma} + u_{i,\sigma'}}{2} \right].$$

Employing (3.68) together with (3.61) (see also Figures 5 and 8) we easily find that

$$I_i^K = \sum_{j=1}^d \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(j)}(K)} F_{\sigma,K} (\mathcal{R}_{\mathcal{E}}^{(i,j)}(u_i))_\sigma \quad (3.70)$$

In order to transform  $J_i^K$ , we first remark with help of (3.19) the identity

$$F_{\sigma,K} + F_{\epsilon_K,\sigma} + \sum_{j=1, j \neq i}^d \sum_{\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)} \sum_{\sigma' \in \mathcal{N}_{\tau,\sigma}} \frac{F_{\tau,K}}{2} = \frac{1}{2} \sum_{\sigma \in \mathcal{E}_{\text{int}}(K)} F_{\sigma,K}; \quad (3.71)$$

consequently,

$$\sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} (\varphi_\sigma - (\mathcal{R}_{\mathcal{M}}^{(i)} \varphi)_K) \left[ F_{\sigma,K} + F_{\epsilon_K, \sigma} + \sum_{j=1, j \neq i}^d \sum_{\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)} \sum_{\sigma' \in \mathcal{N}_{\tau, \sigma}} \frac{F_{\tau,K}}{2} \right] = \left[ \sum_{\sigma \in \mathcal{E}_{\text{int}}(K)} F_{\sigma,K} \right] \left[ \left( \sum_{\sigma \in \mathcal{E}^{(i)}(K)} \frac{\varphi_\sigma}{2} \right) - (\mathcal{R}_{\mathcal{M}}^{(i)} \varphi)_K \right] = 0,$$

where, we have used (3.64). Next we write

$$\begin{aligned} J_i^K &= \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} \left[ \varphi_\sigma - (\mathcal{R}_{\mathcal{M}}^{(i)}(\varphi))_K \right] \left[ F_{\sigma,K} \left( u_{i,\sigma} - (\mathcal{R}_{\mathcal{M}}^{(i)}(u_i))_K \right) + F_{\epsilon_K, \sigma} \left( u_{i,\epsilon_K} - (\mathcal{R}_{\mathcal{M}}^{(i)}(u_i))_K \right) \right. \\ &\quad \left. + \sum_{j=1, j \neq i}^d \sum_{\tau \in \mathcal{E}_{r_{\text{mint}}}^{(j)}(K)} \sum_{\sigma' \in \mathcal{N}_{\tau, \sigma}} \frac{F_{\tau,K}}{2} \left( \frac{u_{i,\sigma} + u_{i,\sigma'}}{2} - (\mathcal{R}_{\mathcal{M}}^{(i)}(u_i))_K \right) \right] \\ &\quad + \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} \left[ \varphi_\sigma - (\mathcal{R}_{\mathcal{M}}^{(i)}(\varphi))_K \right] \left[ F_{\epsilon_K, \sigma} + F_{\sigma,K} + \sum_{j=1, j \neq i}^d \sum_{\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)} \sum_{\sigma' \in \mathcal{N}_{\tau, \sigma}} \frac{F_{\tau,K}}{2} \right] (\mathcal{R}_{\mathcal{M}}^{(i)}(u_i))_K, \end{aligned}$$

where

$$u_{i,\epsilon_K} - (\mathcal{R}_{\mathcal{M}}^{(i)}(u_i))_K = 0$$

(due to (3.64) and (3.26)) and

$$\sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} \left[ \varphi_\sigma - (\mathcal{R}_{\mathcal{M}}^{(i)}(\varphi))_K \right] \left[ F_{\epsilon_K, \sigma} + F_{\sigma,K} + \sum_{j=1, j \neq i}^d \sum_{\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)} \sum_{\sigma' \in \mathcal{N}_{\tau, \sigma}} \frac{F_{\tau,K}}{2} \right] (\mathcal{R}_{\mathcal{M}}^{(i)}(u_i))_K = 0$$

due to (3.71). Consequently,

$$\begin{aligned} R^i(u_i, \varphi) &= \sum_{K \in \mathcal{M}} J_i^K = \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} (\varphi_\sigma - (\mathcal{R}_{\mathcal{M}}^{(i)} \varphi)_K) F_{\sigma,K} (u_\sigma - (\mathcal{R}_{\mathcal{M}}^{(i)} u_i)_K) \\ &\quad + \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} (\varphi_\sigma - (\mathcal{R}_{\mathcal{M}}^{(i)} \varphi)_K) \sum_{j=1, j \neq i}^d \sum_{\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)} \sum_{\sigma' \in \mathcal{N}_{\tau, \sigma}} \frac{F_{\tau,K}}{2} \left( \frac{u_{i,\sigma} + u_{i,\sigma'}}{2} - (\mathcal{R}_{\mathcal{M}}^{(i)}(u_i))_K \right) \end{aligned} \quad (3.72)$$

Putting together formulas (3.69), (3.70) and (3.72) concludes the proof of Lemma 3.4.  $\square$

### 3.5 Main result: error estimates

Now, we are ready to state the main result of this paper. For the sake of clarity, we shall state the theorem and perform the proofs only in the most interesting three dimensional case. The modifications to be done for the two dimensional case, which is in fact more simple, are mostly due to the different Sobolev embeddings and are left to the interested reader.

Let us introduce the following functional space:

$$\mathcal{F} = \left\{ (r, \mathbf{U}) \in C^1([0, T] \times \bar{\Omega})^4, 0 < \underline{r} = \inf_{(t,x) \in \bar{Q}_T} r(t, x), \nabla^2 \mathbf{U} \in C([0, T] \times \bar{\Omega})^3, \partial_t^2 r \in L^1(0, T; L^\gamma(\Omega)), \partial_t \nabla r \in L^2(0, T; L^{6\gamma/(5\gamma-6)}(\Omega)^3), (\partial_t^2 \mathbf{U}, \partial_t \nabla \mathbf{U}) \in L^2(0, T; L^{6/5}(\Omega)^{12}) \right\}, \quad (3.73)$$

endowed with the following norm

$$\begin{aligned} \|(r, \mathbf{U})\|_{\mathcal{F}} &= \|(r, \mathbf{U})\|_{C^1([0, T] \times \bar{\Omega})^4} + \|\nabla^2 \mathbf{U}\|_{C([0, T] \times \bar{\Omega})^3} + \|\partial_t^2 r\|_{L^1(0, T; L^\gamma(\Omega))} + \|\partial_t \nabla r\|_{L^2(0, T; L^{6\gamma/(5\gamma-6)}(\Omega)^3)} \\ &\quad + \|\partial_t^2 \mathbf{U}\|_{L^2(0, T; L^{6/5}(\Omega)^{12})} + \|\partial_t \nabla \mathbf{U}\|_{L^2(0, T; L^{6/5}(\Omega)^{12})}. \end{aligned} \quad (3.74)$$

Let  $(r, \mathbf{U}) \in \mathcal{F}$  such that  $\mathbf{U} = \mathbf{0}$  on  $\partial\Omega$ . Let us consider a MAC grid  $\mathcal{D} = (\mathcal{M}, \mathcal{E})$  of size  $h_{\mathcal{M}}$  and regularity  $\eta_{\mathcal{M}}$  of the computational domain  $\Omega$ , a partition  $0 = t^0 < t^1 < \dots < t^N = T$  of the time interval  $[0, T]$ , which, for the sake of simplicity, we suppose uniform (where  $\delta t$  stands for the constant time step) and  $(\varrho, \mathbf{u}) \in Y_{\mathcal{M}, \delta t} \times \mathbf{X}_{\mathcal{E}, \delta t}$  a solution of the discrete problem (3.10). Inspired by (2.11), we introduce the discrete relative energy functional

$$\begin{aligned} \mathcal{E}(\varrho^n, \mathbf{u}^n | r_{\mathcal{M}}^n, \mathbf{U}_{\mathcal{E}}^n) &= \int_{\Omega} \left( \frac{1}{2} \varrho^n |\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n|^2 + E(\varrho^n | r_{\mathcal{M}}^n) \right) d\mathbf{x} \\ &= \sum_{i=1}^3 \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \frac{1}{2} |D_{\sigma}| \varrho_{D_{\sigma}}^n |u_{\sigma}^n - U_{\sigma}^n|^2 + \sum_{K \in \mathcal{M}} |K| E(\varrho_K^n | r_K^n) \end{aligned} \quad (3.75)$$

where

$$r^n = r(t^n, \cdot), \quad \mathbf{U}^n = \mathbf{U}(t^n, \cdot), \quad r_{\mathcal{M}}^n = \mathcal{P}_{\mathcal{M}}(r^n), \quad \mathbf{U}_{\mathcal{E}}^n = \mathcal{P}_{\mathcal{E}}(\mathbf{U}^n), \quad (3.76)$$

where  $\mathcal{P}_{\mathcal{M}}$  and  $\mathcal{P}_{\mathcal{E}}$  are respectively defined in (3.42) and (3.47). Finally we denote

$$0 < \underline{r} = \min_{(0, T) \times \Omega} r, \quad \bar{r} = \max_{(0, T) \times \Omega} r, \quad [\partial_t r]^n = \partial_t r(t^n, \cdot). \quad (3.77)$$

Let us now state that the discrete problem (3.10) admits at least one solution. This existence result follows from standard arguments of the topological degree theory (see [9] for the theory, [11] for the first application to a nonlinear scheme). We refer to Appendix A for a proof.

**Theorem 3.2.** *Let  $(\varrho^0, \mathbf{u}^0) \in L_{\mathcal{M}} \times \mathbf{H}_{\mathcal{E}, 0}$  such that  $\varrho^0 > 0$  (that is  $\varrho_K^0 > 0$  for any  $K \in \mathcal{M}$ ). There exists a solution  $(\mathbf{u}, \varrho) \in \mathbf{H}_{\mathcal{E}, 0} \times L_{\mathcal{M}}$  of Problem (3.10). Moreover any solution is such that  $\varrho > 0$  a.e in  $\Omega$  (meaning that  $\varrho_K^n > 0$  for any  $n = 1, \dots, N$  and for any  $K \in \mathcal{M}$ ).*

The following Theorem is the main result of the paper. It can be seen as a discrete version of inequality (2.19).

**Theorem 3.3** (Error estimate). *Let  $\Omega \subset \mathbb{R}^3$  be a domain which is a union of orthogonal closed parallelepipeds with mutually disjoint interiors, and, without loss of generality, such that the faces of these parallelepipeds are orthogonal to the canonical basis vectors. Assume that the viscosity coefficients satisfy assumptions (1.4) and that the pressure  $p$  satisfy (1.5). Let  $\mathcal{D} = (\mathcal{M}, \mathcal{E})$  be a MAC grid of  $\Omega$  (see Definition 3.1 in Section 3), with step size  $h_{\mathcal{M}}$  (see (3.6)) and regularity  $\eta_{\mathcal{M}}$  where  $\eta_{\mathcal{M}}$  is defined in (3.8). Let us consider a partition  $0 = t^0 < t^1 < \dots < t^N = T$  of the time interval  $[0, T]$ , which, for the sake of simplicity, we suppose uniform, where  $\delta t$  stands for the constant time step. Let  $(\varrho, \mathbf{u}) \in Y_{\mathcal{M}, \delta t} \times \mathbf{X}_{\mathcal{E}, \delta t}$  be a solution of the discrete problem (3.10) emanating from  $(\varrho^0, \mathbf{u}^0) \in L_{\mathcal{M}} \times \mathbf{H}_{\mathcal{E}, 0}$  such that  $\varrho^0 > 0$  (the existence of which granted by Theorem 3.2), and  $(r, \mathbf{U}) \in \mathcal{F}$  be a (strong) solution of problem (1.1). Then there exists a constant  $c > 0$  only depending on  $T, |\Omega|, p_0, p_{\infty}, \mu, \lambda, \gamma, \underline{r}, \min_{[\underline{r}, \bar{r}]} p, \min_{[\underline{r}/2, 2\bar{r}]} p', \|p\|_{C^2([\underline{r}, \bar{r}])}$ , on  $\|(r, \mathbf{U})\|_{\mathcal{F}}$  in a non decreasing way, on  $\mathcal{E}_{0, \mathcal{M}}$  in a nondecreasing way and on  $\eta_{\mathcal{M}}$  in a nondecreasing way such that*

$$\max_{0 \leq n \leq N} \mathcal{E}(\varrho^n, \mathbf{u}^n | r_{\mathcal{M}}^n, \mathbf{U}_{\mathcal{E}}^n) \leq c \left( \mathcal{E}(\varrho^0, \mathbf{u}^0 | r_{\mathcal{M}}^0, \mathbf{U}_{\mathcal{E}}^0) + h_{\mathcal{M}}^A + \sqrt{\delta t} \right), \quad (3.78)$$

where

$$A = \min\left(\frac{2\gamma - 3}{\gamma}, \frac{1}{2}\right). \quad (3.79)$$

**Remark 2.**

1. As mentioned previously, Theorem 3.3 holds also in dimension 2 under the assumption that  $\gamma > 1$ . The value of  $A$  in the error estimate (3.78) can be chosen such that

$$\begin{cases} A < \min\left(\frac{2\gamma - 2}{\gamma}, 1\right) \text{ if } \gamma \in (1, 2], \\ A = 1 \text{ if } \gamma > 2. \end{cases} \quad (3.80)$$

2. Suppose that the discrete initial data  $(\varrho^0, \mathbf{u}^0)$  coincides with the projection  $(\mathcal{P}_{\mathcal{M}} r_0, \mathcal{P}_{\mathcal{E}} \mathbf{u}_0)$  of the initial data determining the strong solution. Then formula (3.78), combined with Lemma 2.1, provides in terms of classical Lebesgue spaces the following bounds:

$$\|\varrho^n - r^n\|_{L^2(\{\underline{r}/2 \leq \varrho^n \leq 2\bar{r}\})}^2 + \|\mathbf{u}^n - \mathbf{U}^n\|_{L^2(\{\underline{r}/2 \leq \varrho^n \leq 2\bar{r}\})}^2 \leq c \left( h_{\mathcal{M}}^A + \sqrt{\delta t} \right)$$

for the "essential part" of the solution (where the numerical density remains bounded from above and from below outside zero), and

$$|\{\varrho^n \leq \underline{r}/2\}| + |\{\varrho^n \geq 2\bar{r}\}| + \|\varrho^n\|_{L^\gamma(\Omega \cap \{\varrho^n \geq 2\bar{r}\})}^\gamma + \|\varrho^n |\mathbf{u}^n - \mathbf{U}^n|^2\|_{L^1(\{\varrho^n \geq 2\bar{r}\})} \leq c \left( h_{\mathcal{M}}^A + \sqrt{\delta t} \right)$$

for the "residual part" of the solution, where the numerical density can be "close" to zero or infinity. (In the above formula, for  $B \subset \Omega$ ,  $|B|$  denotes the Lebesgue measure of  $B$ .) In particular, we obtain

$$\|\varrho - r\|_{L^2(\{\underline{r}/2 \leq \varrho \leq 2\bar{r}\})}^2 + \|\mathbf{u} - \mathbf{U}\|_{L^2(\{\underline{r}/2 \leq \varrho \leq 2\bar{r}\})}^2 \leq c \left( h_{\mathcal{M}}^A + \sqrt{\delta t} \right)$$

Moreover, in the particular case of  $p(\varrho) = \varrho^2$  (that however represents a non physical situation)  $E(\varrho|r) = (\varrho - r)^2$  and the error estimate (3.78) gives

$$\|\varrho - r\|_{L^\infty(0,T;L^2(\Omega))}^2 + \|\varrho |\mathbf{u} - \mathbf{U}|^2\|_{L^\infty(0,T;L^1(\Omega))} \leq c \left( \sqrt{h_{\mathcal{M}}} + \sqrt{\delta t} \right)$$

3. If we assume that the discrete density  $\varrho$  is bounded from above uniformly with respect to  $(h_{\mathcal{M}}, \delta t)$ , the growth condition at infinity in (1.5) becomes irrelevant. In this case, following step by step proof of Theorem 3.3 we obtain error estimate (3.78) with  $A = \frac{1}{2}$  for any  $\gamma \geq 1$ . Compare with [15], where the similar problem is treated for a Finite volume/Finite element method. This is qualitatively better result than any other conditional error estimate in the mathematical literature dealing with finite volume or mixed finite volume/finite element methods for compressible fluids (see [4], [11], [33], [43], [47]), where the authors need to assume other bounds for the numerical solution, in addition to the upper bound for the density.
4. Theorem 3.3 can be viewed as a discrete version of Proposition 2.1. It is to be noticed that the assumptions on the constitutive law for pressure guaranteeing the error estimates for the scheme (3.10) are somewhat stronger ( $\gamma \geq 3/2$ ) than the assumptions needed for the stability in the continuous case ( $\gamma > \frac{6}{5}$ ). In particular the asymptotic behaviour of the pressure for small densities is not needed in the continuous case. The threshold value  $\gamma = 3/2$  is however in accordance with the existence theory of weak solutions. The assumptions on the regularity of the strong solution to be compared with the discrete solution in the scheme are slightly stronger than those needed to establish the stability estimates in the continuous case.
5. The assumption on the asymptotic behaviour of the pressure for small densities in (1.5) can be relaxed for  $\gamma \geq 2$ , see [24]. In particular Theorem 3.3 also holds for the isentropic pressure law  $p(\varrho) = \varrho^\gamma$  where  $\gamma \geq 2$ .

The rest of the paper is devoted to the proof of Theorem 3.3. We employ the methodology inspired by that one suggested in [16] in the continuous case. It can be summarized as follows

1. We establish the energy inequality for discrete solutions of the numerical scheme - see Theorem 4.1, formula (4.1). This correspond to energy inequality (2.7) in the continuous case.
2. Knowing (4.1) we establish the discrete relative energy inequality for the discrete solution of the numerical scheme with test functions taken in the discrete spaces introduced in Definition 3.2 - see formula (5.1) in Proposition 5.1. This is a numerical counterpart of relative energy inequality (2.12) in the continuous case.
3. We take in the discrete relative energy inequality as test functions We derive a consistency error for the strong solution above, see equality (6.1) in Lemma 6.1. Combining Lemma 5.1 and Lemma 6.1 we obtain inequality (7.1). This inequality is a numerical counterpart of relative energy inequality (2.13) in the continuous case.
4. We estimate conveniently the right hand side of inequality (7.1) in order to get the Gronwall type estimate, see Lemma 7.1. The rather Lemma implies the result.



## 4 Mesh independent estimates

### 4.1 Energy Inequality

Our analysis starts with an energy equality (which can be seen as a discrete differential version of (2.7)), which is crucial both in the convergence analysis and in the error analysis.

**Theorem 4.1** (Energy estimate). *Let  $(\varrho, \mathbf{u}) \in Y_{\mathcal{M},\delta t} \times \mathbf{X}_{\mathcal{E},\delta t}$  be a solution of (3.10). Then for any  $n = 1, \dots, N$ , there exists  $\varrho^{n-1,n} \in L_{\mathcal{M}}$  such that  $\min(\varrho^{n-1}, \varrho^n) \leq \varrho^{n-1,n} \leq \max(\varrho^{n-1}, \varrho^n)$  and  $\bar{\varrho}_\sigma^n \in [\min(\varrho_K^n, \varrho_L^n), \max(\varrho_K^n, \varrho_L^n)]$ ,  $\sigma = K|L \in \mathcal{E}_{\text{int}}$  such that*

$$\begin{aligned} & \frac{1}{\delta t} \int_{\Omega} \mathcal{H}(\varrho^n) - \mathcal{H}(\varrho^{n-1}) \, d\mathbf{x} + \frac{1}{2\delta t} \int_{\Omega} \varrho^n |\mathbf{u}^n|^2 - \varrho^{n-1} |\mathbf{u}^{n-1}|^2 \, d\mathbf{x} \\ & \quad + \mu \|\mathbf{u}^n\|_{1,\mathcal{E},0}^2 + (\mu + \lambda) \|\operatorname{div}_{\mathcal{M}} \mathbf{u}^n\|_{L^2(\Omega)}^2 + \frac{1}{2\delta t} \int_{\Omega} \varrho^{n-1} |\mathbf{u}^n - \mathbf{u}^{n-1}|^2 \, d\mathbf{x} \\ & \quad + \int_{\Omega} \frac{1}{2\delta t} \mathcal{H}''(\varrho^{n-1,n}) (\varrho^n - \varrho^{n-1})^2 \, d\mathbf{x} + \frac{1}{2} \sum_{\sigma \in \mathcal{E}_{\text{int}}, \sigma=K|L} |\sigma| \mathcal{H}''(\bar{\varrho}_\sigma^n) (\varrho_K^n - \varrho_L^n)^2 |\mathbf{u}_{\sigma,K}^n| = 0. \end{aligned} \quad (4.1)$$

*Proof.* Multiplying (3.10a) by  $\mathcal{H}'(\varrho^n)$  and using a Taylor expansion we obtain the existence of  $\varrho^{n-1,n} \in L_{\mathcal{M}}$  such that  $\min(\varrho^{n-1}, \varrho^n) \leq \varrho^{n-1,n} \leq \max(\varrho^{n-1}, \varrho^n)$  and

$$\int_{\Omega} \frac{\mathcal{H}(\varrho^n) - \mathcal{H}'(\varrho^{n-1})}{\delta t} \, d\mathbf{x} + \int_{\Omega} \frac{1}{2\delta t} \mathcal{H}''(\varrho^{n-1,n}) (\varrho^n - \varrho^{n-1})^2 \, d\mathbf{x} + \int_{\Omega} \operatorname{div}_{\mathcal{M}}^{\text{up}}(\varrho^n \mathbf{u}^n) \mathcal{H}'(\varrho^n) \, d\mathbf{x} = 0. \quad (4.2)$$

Using again a Taylor expansion (see for instance [21]) one has

$$\int_{\Omega} \operatorname{div}_{\mathcal{M}}^{\text{up}}(\varrho^n \mathbf{u}^n) \mathcal{H}'(\varrho^n) \, d\mathbf{x} = \int_{\Omega} p(\varrho^n) \operatorname{div}_{\mathcal{M}} \mathbf{u}^n \, d\mathbf{x} + \frac{1}{2} \sum_{\sigma \in \mathcal{E}_{\text{int}}, \sigma=K|L} |\sigma| \mathcal{H}''(\varrho_\sigma^n) (\varrho_K^n - \varrho_L^n)^2 |\mathbf{u}_{\sigma,K}^n| \quad (4.3)$$

where  $\varrho_\sigma^n \in [\min(\varrho_K^n, \varrho_L^n), \max(\varrho_K^n, \varrho_L^n)]$ . Consequently

$$\begin{aligned} & \int_{\Omega} \frac{\mathcal{H}(\varrho^n) - \mathcal{H}'(\varrho^{n-1})}{\delta t} \, d\mathbf{x} + \int_{\Omega} \frac{1}{2\delta t} \mathcal{H}''(\varrho^{n-1,n}) (\varrho^n - \varrho^{n-1})^2 \, d\mathbf{x} \\ & \quad + \int_{\Omega} p(\varrho^n) \operatorname{div}_{\mathcal{M}} \mathbf{u}^n \, d\mathbf{x} + \frac{1}{2} \sum_{\sigma \in \mathcal{E}_{\text{int}}, \sigma=K|L} |\sigma| \mathcal{H}''(\varrho_\sigma^n) (\varrho_K^n - \varrho_L^n)^2 |\mathbf{u}_{\sigma,K}^n| = 0. \end{aligned} \quad (4.4)$$

Multiplying (3.10b) by  $u_\sigma^n$ , summing over  $\sigma \in \mathcal{E}_{\text{int}}^{(i)}$  and  $i = 1, 2, 3$  and using (3.32) we infer that

$$\begin{aligned} & \int_{\Omega} \frac{\varrho^n \mathbf{u}^n - \varrho^{n-1} \mathbf{u}^{n-1}}{\delta t} \cdot \mathbf{u}^n \, d\mathbf{x} + \mu \|\mathbf{u}^n\|_{1,\mathcal{E},0}^2 + (\mu + \lambda) \|\operatorname{div}_{\mathcal{M}} \mathbf{u}^n\|_{L^2(\Omega)}^2 \\ & \quad + \sum_{i=1}^3 \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \sum_{\epsilon \in \tilde{\mathcal{E}}(D_\sigma)} F_{\epsilon,\sigma}^n u_\epsilon^n u_\sigma^n - \int_{\Omega} p(\varrho^n) \operatorname{div}_{\mathcal{M}} \mathbf{u}^n \, d\mathbf{x} = 0. \end{aligned} \quad (4.5)$$

By virtue of the centered choice for  $u_\epsilon^n$  (see (3.26)) we have

$$\sum_{i=1}^3 \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \sum_{\epsilon \in \tilde{\mathcal{E}}(D_\sigma)} F_{\epsilon,\sigma}^n u_\epsilon^n u_\sigma^n = \sum_{i=1}^3 \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \sum_{\epsilon \in \tilde{\mathcal{E}}(D_\sigma)} F_{\epsilon,\sigma}^n \frac{(u_\sigma^n)^2}{2}. \quad (4.6)$$

Multiplying (3.25) by  $\frac{(u_\sigma^n)^2}{2}$  and summing over  $\sigma \in \mathcal{E}_{\text{int}}^{(i)}$  and  $i = 1, 2, 3$  we infer that

$$\frac{1}{2\delta t} \int_{\Omega} (\varrho^n - \varrho^{n-1}) |\mathbf{u}^n|^2 \, d\mathbf{x} + \sum_{i=1}^3 \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \sum_{\epsilon \in \tilde{\mathcal{E}}(D_\sigma)} F_{\epsilon,\sigma}^n \frac{(u_\sigma^n)^2}{2} = 0 \quad (4.7)$$

Subtracting (4.7) to (4.5) gives

$$\frac{1}{2\delta t} \int_{\Omega} \varrho^n |\mathbf{u}^n|^2 - \varrho^{n-1} |\mathbf{u}^{n-1}|^2 \, d\mathbf{x} + \mu \|\mathbf{u}^n\|_{1,\mathcal{E},0}^2 + (\mu + \lambda) \|\operatorname{div}_{\mathcal{M}} \mathbf{u}^n\|_{L^2(\Omega)}^2 - \int_{\Omega} p(\varrho^n) \operatorname{div}_{\mathcal{M}} \mathbf{u}^n \, d\mathbf{x} = 0. \quad (4.8)$$

Consequently adding (4.4) to (4.8) and using (4.3) gives (4.1).  $\square$

**Remark 3.** *The above computation shows that this numerical scheme is unconditionally stable meaning that the discrete energy inequality holds without any extra assumptions on the discrete solution.*

The following estimates are obtained thanks to the identity (4.1) together (2.4) and Theorem 3.1. In particular the numerical diffusion (4.16) is due to the upwinding and assumptions (1.5), as is classical in the framework of hyperbolic conservation laws, see e.g. [12].

**Corollary 4.1.** *Let  $(\varrho, \mathbf{u}) \in Y_{\mathcal{M},\delta t} \times \mathbf{X}_{\mathcal{E},\delta t}$  be a solution of (3.10). Then we have*

1. *There exists  $c > 0$  only depending on  $\mathcal{E}_{0,\mathcal{M}}$  in a nondecreasing way (independent of  $h_{\mathcal{M}}$  and  $\delta t$ ) such that*

$$\|\mathbf{u}\|_{L^2(0,T;\mathbf{H}_{\mathcal{E},0}(\Omega))} \leq c, \quad (4.9)$$

$$\|\mathbf{u}\|_{L^2(0,T;L^6(\Omega)^3)} \leq c, \quad (4.10)$$

$$\|\varrho |\mathbf{u}|^2\|_{L^\infty(0,T;L^1(\Omega))} \leq c, \quad (4.11)$$

$$\|\varrho\|_{L^\infty(0,T;L^\gamma(\Omega))} \leq c, \quad (4.12)$$

$$\|\varrho \mathbf{u}\|_{L^2(0,T;L^{\frac{6\gamma}{\gamma+6}}(\Omega)^3)} \leq c. \quad (4.13)$$

2. *If  $(r, \mathbf{U}) \in L^\infty((0,T) \times \Omega) \times L^\infty((0,T) \times \Omega)^3$ , then*

$$\max_{1 \leq n \leq N} \mathcal{E}(\varrho^n, \mathbf{u}^n | r_{\mathcal{M}}^n, \mathbf{U}_{\mathcal{E}}^n) \leq c, \quad (4.14)$$

where  $c$  depends on  $\bar{r}$ ,  $\|\mathbf{U}\|_{L^\infty((0,T) \times \Omega)^3}$ ,  $\mathcal{E}_{0,\mathcal{M}}$  in a nondecreasing way.

3. *There exists  $c$  only depending on  $\mathcal{E}_{0,\mathcal{M}}$  in a nondecreasing way such that for any  $m = 1, \dots, N$*

$$\sum_{n=1}^m \sum_{i=1}^3 \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} |D_\sigma| \varrho_{D_\sigma}^{n-1} |u_\sigma^n - u_\sigma^{n-1}|^2 \leq c. \quad (4.15)$$

4. *The following dissipation estimate due to the upwinding of the density in (3.10a) and (1.5) holds*

$$\begin{aligned} \delta t \sum_{n=1}^N \sum_{\sigma=K|L \in \mathcal{E}_{\text{int}}} |\sigma| \frac{(\varrho_K^n - \varrho_L^n)^2}{[\max(\varrho_K^n, \varrho_L^n)]^{(2-\gamma)^+}} \mathbf{1}_{\{\bar{\varrho}_\sigma^n \geq 1\}} |u_{\sigma,K}^n| \\ + \delta t \sum_{n=1}^N \sum_{\sigma=K|L \in \mathcal{E}_{\text{int}}} |\sigma| (\varrho_K^n - \varrho_L^n)^2 \mathbf{1}_{\{\bar{\varrho}_\sigma^n < 1\}} |u_{\sigma,K}^n| \leq c. \end{aligned} \quad (4.16)$$

where  $c$  depends on  $\mathcal{E}_{0,\mathcal{M}}$  in a nondecreasing way and where the quantity  $\bar{\varrho}_\sigma^n$  is defined in Theorem 4.1.

## 5 Relative energy inequality for the discrete problem

### 5.1 Exact relative energy inequality for the discrete problem

The goal of this section is to prove the discrete (differential) version of the relative energy inequality (2.12).

**Proposition 5.1** (Exact discrete relative energy). *Any solution  $(\varrho, \mathbf{u}) \in Y_{\mathcal{M},\delta t} \times \mathbf{X}_{\mathcal{E},\delta t}$  of the discrete problem (3.10) satisfy*

$$\begin{aligned}
& \frac{1}{\delta t} \left( \mathcal{E}(\varrho^n, \mathbf{u}^n | r^n, \mathbf{U}^n) - \mathcal{E}(\varrho^{n-1}, \mathbf{u}^{n-1} | r^{n-1}, \mathbf{U}^{n-1}) \right) + \mu \|\mathbf{u}^n - \mathbf{U}^n\|_{1,\mathcal{E},0}^2 + (\mu + \lambda) \|\operatorname{div}_{\mathcal{M}}(\mathbf{u}^n - \mathbf{U}^n)\|_{L^2(\Omega)}^2 \\
& \leq \int_{\Omega} (r^n - \varrho^n) \frac{\mathcal{H}'(r^n) - \mathcal{H}'(r^{n-1})}{\delta t} \, d\mathbf{x} + \int_{\Omega} \operatorname{div}_{\mathcal{M}}^{\text{up}}(\varrho^n \mathbf{u}^n) \mathcal{H}'(r^{n-1}) \, d\mathbf{x} \\
& \quad + \mu [\mathbf{U}^n - \mathbf{u}^n, \mathbf{U}^n]_{1,\mathcal{E},0} + (\mu + \lambda) \int_{\Omega} \operatorname{div}_{\mathcal{M}}(\mathbf{U}^n - \mathbf{u}^n) \operatorname{div}_{\mathcal{M}} \mathbf{U}^n \, d\mathbf{x} \\
& \quad - \int_{\Omega} p(\varrho^n) \operatorname{div}_{\mathcal{M}} \mathbf{U}^n \, d\mathbf{x} + \int_{\Omega} \varrho^{n-1} \frac{\mathbf{U}^{n-1} - \mathbf{U}^n}{\delta t} \cdot \left( \mathbf{u}^{n-1} - \frac{1}{2}(\mathbf{U}^{n-1} + \mathbf{U}^n) \right) \, d\mathbf{x} \\
& \quad + \sum_{i=1}^3 \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \sum_{\epsilon \in \tilde{\mathcal{E}}(D_{\sigma})} F_{\epsilon,\sigma}^n U_{\sigma}^n (u_{\epsilon}^n - U_{\epsilon}^n) \quad (5.1)
\end{aligned}$$

for any  $0 < r \in Y_{\mathcal{M},\delta t}$ ,  $\mathbf{U} \in \mathbf{X}_{\mathcal{E},\delta t}$ .

We notice, comparing the terms in the “discrete” formula (5.1) with the terms in the “continuous” formula (2.12), that Theorem 5.1 represents a discrete counterpart of the “continuous” relative energy inequality (2.12). The rest of this section is devoted to its proof. To this end, we shall follow the proof of the “continuous” relative energy inequality (see [16] and [19]) and adapt it to the discrete case.

*Proof.* We proceed in several steps.

**Investigation of the momentum equation (3.10b)** : Multiplying (3.10b) by  $\mathbf{U}^n$  and integrating over  $\Omega$  we obtain

$$\begin{aligned}
& \int_{\Omega} \frac{1}{\delta t} (\varrho^n \mathbf{u}^n - \varrho^{n-1} \mathbf{u}^{n-1}) \cdot \mathbf{U}^n \, d\mathbf{x} + \sum_{i=1}^3 \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \sum_{\epsilon \in \tilde{\mathcal{E}}(D_{\sigma})} F_{\epsilon,\sigma}^n u_{\epsilon}^n U_{\sigma}^n \\
& \quad + \mu [\mathbf{u}^n, \mathbf{U}^n]_{1,\mathcal{E},0} + (\mu + \lambda) \int_{\Omega} \operatorname{div}_{\mathcal{M}} \mathbf{u}^n \operatorname{div}_{\mathcal{M}} \mathbf{U}^n \, d\mathbf{x} - \int_{\Omega} p^n \operatorname{div}_{\mathcal{M}} \mathbf{U}^n \, d\mathbf{x} = 0
\end{aligned}$$

We observe that

$$(\varrho^n \mathbf{u}^n - \varrho^{n-1} \mathbf{u}^{n-1}) \cdot \mathbf{U}^n = \varrho^n \mathbf{u}^n \cdot \mathbf{U}^n - \varrho^{n-1} \mathbf{u}^{n-1} \cdot \mathbf{U}^{n-1} + \varrho^{n-1} \mathbf{u}^{n-1} \cdot (\mathbf{U}^{n-1} - \mathbf{U}^n).$$

Consequently

$$\begin{aligned}
& -\frac{1}{\delta t} \int_{\Omega} \varrho^n \mathbf{u}^n \cdot \mathbf{U}^n - \varrho^{n-1} \mathbf{u}^{n-1} \cdot \mathbf{U}^{n-1} \, d\mathbf{x} = \frac{1}{\delta t} \int_{\Omega} \varrho^{n-1} \mathbf{u}^{n-1} \cdot (\mathbf{U}^{n-1} - \mathbf{U}^n) \, d\mathbf{x} + \sum_{i=1}^3 \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \sum_{\epsilon \in \tilde{\mathcal{E}}(D_{\sigma})} F_{\epsilon,\sigma}^n u_{\epsilon}^n U_{\sigma}^n \\
& \quad + \mu [\mathbf{u}^n, \mathbf{U}^n]_{1,\mathcal{E},0} + (\mu + \lambda) \int_{\Omega} \operatorname{div}_{\mathcal{M}} \mathbf{u}^n \operatorname{div}_{\mathcal{M}} \mathbf{U}^n \, d\mathbf{x} - \int_{\Omega} p^n \operatorname{div}_{\mathcal{M}} \mathbf{U}^n \, d\mathbf{x}. \quad (5.2)
\end{aligned}$$

**Investigation of the dual continuity equation (3.25)** : Multiplying (3.25) by  $\frac{1}{2} |\mathbf{U}_{\sigma}^n|^2$  we obtain

$$\frac{1}{2\delta t} \int_{\Omega} (\varrho^n - \varrho^{n-1}) |\mathbf{U}^n|^2 \, d\mathbf{x} + \frac{1}{2} \sum_{i=1}^3 \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \sum_{\epsilon \in \tilde{\mathcal{E}}(D_{\sigma})} F_{\epsilon,\sigma}^n |U_{\sigma}^n|^2 = 0. \quad (5.3)$$

Moreover due to (3.22)

$$\frac{1}{2} \sum_{i=1}^3 \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \sum_{\epsilon \in \tilde{\mathcal{E}}(D_\sigma)} F_{\epsilon, \sigma}^n U_\sigma^n U_{\sigma'}^n = 0. \quad (5.4)$$

We observe that

$$\int_{\Omega} (\varrho^n - \varrho^{n-1}) |\mathbf{U}^n|^2 \, d\mathbf{x} = \int_{\Omega} \varrho^n |\mathbf{U}^n|^2 - \varrho^{n-1} |\mathbf{U}^{n-1}|^2 \, d\mathbf{x} + \int_{\Omega} \varrho^{n-1} (\mathbf{U}^{n-1} + \mathbf{U}^n) \cdot (\mathbf{U}^{n-1} - \mathbf{U}^n) \, d\mathbf{x}$$

which gives

$$\begin{aligned} \int_{\Omega} \frac{1}{2\delta t} (\varrho^n |\mathbf{U}^n|^2 - \varrho^{n-1} |\mathbf{U}^{n-1}|^2) \, d\mathbf{x} &= -\frac{1}{2\delta t} \int_{\Omega} \varrho^{n-1} (\mathbf{U}^{n-1} + \mathbf{U}^n) \cdot (\mathbf{U}^{n-1} - \mathbf{U}^n) \, d\mathbf{x} \\ &\quad - \frac{1}{2} \sum_{i=1}^3 \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}} \sum_{\epsilon \in \tilde{\mathcal{E}}(D_\sigma)} F_{\epsilon, \sigma}^n |U_\sigma^n|^2. \end{aligned} \quad (5.5)$$

**Investigation of the primal continuity equation (3.10a)** : Multiplying the continuity equation by  $\mathcal{H}'(r^{n-1})$  and integrating over  $\Omega$  we obtain

$$-\frac{1}{\delta t} \int_{\Omega} (\varrho^n \mathcal{H}'(r^n) - \varrho^{n-1} \mathcal{H}'(r^{n-1})) \, d\mathbf{x} = -\frac{1}{\delta t} \int_{\Omega} \varrho^n (\mathcal{H}'(r^n) - \mathcal{H}'(r^{n-1})) \, d\mathbf{x} + \int_{\Omega} \text{div}_{\mathcal{M}}^{\text{up}}(\varrho^n \mathbf{u}^n) \mathcal{H}'(r^{n-1}) \, d\mathbf{x}. \quad (5.6)$$

Finally, thanks to the the convexity of the function  $\mathcal{H}$ , we have

$$\begin{aligned} \frac{1}{\delta t} \int_{\Omega} \left[ (r^n \mathcal{H}'(r^n) - \mathcal{H}(r^n)) - (r^{n-1} \mathcal{H}'(r^{n-1}) - \mathcal{H}(r^{n-1})) \right] \, d\mathbf{x} &= \frac{1}{\delta t} \int_{\Omega} r^n (\mathcal{H}'(r^n) - \mathcal{H}'(r^{n-1})) \, d\mathbf{x} \\ &\quad - \frac{1}{\delta t} \int_{\Omega} (\mathcal{H}(r^n) - (r^n - r^{n-1}) \mathcal{H}'(r^{n-1}) - \mathcal{H}(r^{n-1})) \, d\mathbf{x} \\ &\leq \frac{1}{\delta t} \int_{\Omega} r^n (\mathcal{H}'(r^n) - \mathcal{H}'(r^{n-1})) \, d\mathbf{x}. \end{aligned} \quad (5.7)$$

**Conclusion** : Summing (4.1), (5.2), (5.4), (5.5), (5.6) and (5.7) we obtain (5.1).  $\square$

## 5.2 Approximate relative energy inequality for the discrete problem

The exact relative energy inequality as stated in Section 5.1 is a general inequality for the given numerical scheme, however it does not immediately provide a comparison of the approximate solution with the strong solution of the compressible Navier-Stokes equations. Its right hand side has to be conveniently transformed (modulo the possible appearance of residual terms vanishing as the space and time steps tend to 0) to provide such comparison tool via a Gronwall type argument.

The goal of this section is to derive a version of the discrete relative energy inequality, still with arbitrary (sufficiently regular) test functions  $(r, \mathbf{U})$ , that will be convenient for the comparison of the discrete solution with the strong solution.

Let us introduce some notations useful for the rest of the paper. Considering a solution  $(\varrho, \mathbf{u})$  of Problem 3.10, and  $(r, \mathbf{U}) \in \mathcal{F}$  we define for  $\sigma = K|L \in \mathcal{E}_{\text{int}}$ :

$$r_\sigma^{n, \text{up}} = \begin{cases} r_K^n & \text{if } u_{\sigma, K}^n \geq 0, \\ r_L^n & \text{otherwise,} \end{cases} \quad (5.8)$$

where  $r_K^n$  and  $u_{\sigma, K}^n$  are respectively defined in (3.43) and (3.13). Note that  $r_\sigma^{n, \text{up}}$  will be not prescribe for  $\sigma \in \mathcal{E}_{\text{ext}}$  (it will be a consequence of the fact  $u_{\sigma, K}^n$  that vanishes for  $\sigma \in \mathcal{E}(K) \cap \mathcal{E}_{\text{ext}}$ ). Similarly to (3.24) we define

$$\begin{aligned} \text{for } \sigma \in \mathcal{E}_{\text{int}}, \sigma = K|L & \quad |D_\sigma| r_{D_\sigma}^n = |D_{\sigma, K}| r_K^n + |D_{\sigma, L}| r_L^n, \\ \text{for } \sigma \in \mathcal{E}_{\text{ext}}, \sigma \in \mathcal{E}(K), & \quad r_{D_\sigma}^n = r_K^n. \end{aligned} \quad (5.9)$$

For  $i = 1, \dots, d$  and  $\epsilon = D_\sigma | D_{\sigma'} \in \tilde{\mathcal{E}}_{\text{int}}^{(i)}$  we define

$$U_\epsilon^n = \frac{(\mathcal{P}_\epsilon^{(i)} U_i^n)_\sigma + (\mathcal{P}_\epsilon^{(i)} U_i^n)_{\sigma'}}{2} \quad (5.10)$$

where  $\mathcal{P}_\epsilon^{(i)}$  is defined in (3.45).

Starting from now, we shall use the following convention for the constants in estimates: We shall denote by  $c$  a positive number which can take different values even in the same formula. It always depend tacitly on the geometric and structural coefficients

$$T, |\Omega|, p_0, p_\infty, \mu, \lambda, \gamma, \quad (5.11)$$

and if not stated explicitly otherwise, on the characteristics of the strong solution

$$\underline{r}, \min_{[\underline{r}, \bar{r}]} p, \min_{[\underline{r}/2, 2\bar{r}]} p', \|p\|_{C^2([\underline{r}, \bar{r}])}, \|(r, \mathbf{U})\|_{\mathcal{F}} \quad (5.12)$$

and on

$$\mathcal{E}_{0, \mathcal{M}} \text{ in a non decreasing way, } \eta_{\mathcal{M}} \text{ in a nondecreasing way.} \quad (5.13)$$

It is always independent of the size of the discretisation  $\delta t$  and  $h_{\mathcal{M}}$ .

**Lemma 5.1** (Approximate discrete relative energy). *Let  $(\varrho, \mathbf{u}) \in Y_{\mathcal{M}, \delta t} \times \mathbf{X}_{\mathcal{E}, \delta t}$  be a solution of the discrete problem (3.10) and  $(r, \mathbf{U}) \in \mathcal{F}$  such that  $\mathbf{U}|_{\partial\Omega} = \mathbf{0}$ . Then there exists  $c$  only depending on parameters (5.11–5.13) such that for all  $m = 1, \dots, N$ :*

$$\begin{aligned} & \mathcal{E}(\varrho^m, \mathbf{u}^m | r_{\mathcal{M}}^m, \mathbf{U}_{\mathcal{E}}^m) - \mathcal{E}(\varrho^0, \mathbf{u}^0 | r_{\mathcal{M}}^0, \mathbf{U}_{\mathcal{E}}^0) \\ & \quad + \delta t \sum_{n=1}^m \left( \mu \|\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n\|_{1, \mathcal{E}, 0}^2 + (\mu + \lambda) \|\operatorname{div}_{\mathcal{M}}(\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n)\|_{L^2(\Omega)}^2 \right) \\ & \leq \delta t \sum_{n=1}^m \left( \mu [\mathbf{U}_{\mathcal{E}}^n - \mathbf{u}^n, \mathbf{U}_{\mathcal{E}}^n]_{1, \mathcal{E}, 0} + (\mu + \lambda) \int_{\Omega} \operatorname{div}_{\mathcal{M}}(\mathbf{U}_{\mathcal{E}}^n - \mathbf{u}^n) \operatorname{div}_{\mathcal{M}} \mathbf{U}_{\mathcal{E}}^n \, d\mathbf{x} \right) \\ & + \delta t \sum_{n=1}^m \int_{\Omega} \varrho^{n-1} \left( \frac{\mathbf{U}_{\mathcal{E}}^n - \mathbf{U}_{\mathcal{E}}^{n-1}}{\delta t} \right) \cdot (\mathbf{U}_{\mathcal{E}}^n - \mathbf{u}^n) + \delta t \sum_{n=1}^m \int_{\Omega} (r_{\mathcal{M}}^n - \varrho^n) \frac{p'(r_{\mathcal{M}}^n)}{r_{\mathcal{M}}^n} [\partial_t r]^n \, d\mathbf{x} \\ & \quad + \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{K \in \mathcal{M}} \sum_{j=1}^3 \sum_{\sigma \in \mathcal{E}^{(j)}(K)} |\sigma| \varrho_\sigma^{n, \text{up}} (\mathcal{P}_\epsilon^{(j)} U_j^n)_\sigma \mathbf{e}^{(j)} \cdot \mathbf{n}_{\sigma, K} \\ & \quad \times (\mathcal{R}_\epsilon^{(i, j)}(u_i^n - \mathcal{P}_\epsilon^{(i)} U_i^n)_\sigma) (\mathcal{R}_{\mathcal{M}}^{(i)}(\mathcal{P}_\epsilon^{(i)} U_i^n)_K - (\mathcal{P}_\epsilon^{(j)} U_i^n)_\sigma) \\ & - \delta t \sum_{n=1}^m \int_{\Omega} \frac{\varrho^n}{r_{\mathcal{M}}^n} p'(r_{\mathcal{M}}^n) \mathcal{R}_{\mathcal{M}}(\mathbf{u}^n) \cdot \nabla r^n \, d\mathbf{x} - \delta t \sum_{n=1}^m \int_{\Omega} p(\varrho^n) \operatorname{div} \mathbf{U}^n \, d\mathbf{x} + \mathcal{R}_{\mathcal{M}, \delta t}^m + \mathcal{G}_{\mathcal{M}, \delta t}^m \quad (5.14) \end{aligned}$$

for any pair  $(r, \mathbf{U})$  belonging to the class (3.73) such that  $\mathbf{U}|_{\partial\Omega} = \mathbf{0}$ , where

$$|\mathcal{G}_{\mathcal{M}, \delta t}^m| \leq \frac{c}{\delta} \delta t \sum_{n=1}^m \mathcal{E}(\varrho^m, \mathbf{u}^m | r_{\mathcal{M}}^m, \mathbf{U}_{\mathcal{E}}^m) + \delta \delta t \sum_{n=1}^m \|\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n\|_{1, \mathcal{E}, 0}^2, \quad (5.15)$$

with any  $\delta > 0$ ,

$$|\mathcal{R}_{\mathcal{M}, \delta t}^m| \leq c(\sqrt{\delta t} + h_{\mathcal{M}}^A), \quad (5.16)$$

and where  $A$  is given by (3.79).

*Proof.* The right hand side of the relative energy inequality (5.1), after a summation over  $n$  and a multiplication by  $\delta t$ , is a sum  $\sum_{i=1}^6 T_i$ , where

$$\begin{aligned}
T_1 &= \delta t \sum_{n=1}^m \left( \mu [\mathbf{U}_\varepsilon^n, \mathbf{U}_\varepsilon^n - \mathbf{u}^n]_{1,\varepsilon,0} + (\mu + \lambda) \int_{\Omega} \operatorname{div}_{\mathcal{M}} \mathbf{U}_\varepsilon^n \operatorname{div}_{\mathcal{M}} (\mathbf{U}_\varepsilon^n - \mathbf{u}^n) \, d\mathbf{x} \right), \\
T_2 &= \delta t \sum_{n=1}^m \int_{\Omega} \varrho^{n-1} \frac{\mathbf{U}_\varepsilon^n - \mathbf{U}_\varepsilon^{n-1}}{\delta t} \cdot \left( \frac{\mathbf{U}_\varepsilon^{n-1} + \mathbf{U}_\varepsilon^n}{2} - \mathbf{u}^{n-1} \right) \, d\mathbf{x}, \\
T_3 &= \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{\substack{\sigma \in \mathcal{E}_{\text{int}}^{(i)} \\ \varepsilon = D_\sigma | D_{\sigma'} \\ \varepsilon \in \tilde{\mathcal{E}}(D_\sigma)}} F_{\varepsilon,\sigma}^n U_\sigma^n (u_\varepsilon^n - U_\varepsilon^n) \\
T_4 &= -\delta t \sum_{n=1}^m \int_{\Omega} p(\varrho^n) \operatorname{div} \mathbf{U}^n \, d\mathbf{x}, \\
T_5 &= \delta t \sum_{n=1}^m \int_{\Omega} (r_{\mathcal{M}}^n - \varrho^n) \frac{\mathcal{H}'(r_{\mathcal{M}}^n) - \mathcal{H}'(r_{\mathcal{M}}^{n-1})}{\delta t} \, d\mathbf{x}, \\
T_6 &= \delta t \sum_{n=1}^m \int_{\Omega} \operatorname{div}_{\mathcal{M}}^{\text{up}} (\varrho^n \mathbf{u}^n) \mathcal{H}'(r_{\mathcal{M}}^{n-1}) \, d\mathbf{x}
\end{aligned}$$

The term  $T_1$  and  $T_4$  will be kept as they are; all the other terms  $T_i$  will be transformed to a more convenient form, as described in the following steps.

**Step 1:** *Term  $T_2$ .* We have  $T_2 = T_{2,1} + R_{2,1}$  with

$$\begin{cases} T_{2,1} = \delta t \sum_{n=1}^m \int_{\Omega} \varrho^{n-1} \left( \frac{\mathbf{U}_\varepsilon^n - \mathbf{U}_\varepsilon^{n-1}}{\delta t} \right) \cdot (\mathbf{U}_\varepsilon^{n-1} - \mathbf{u}^{n-1}) \, d\mathbf{x}, \\ R_{2,1} = \sum_{n=1}^m \int_{\Omega} \frac{1}{2} \varrho^{n-1} |\mathbf{U}_\varepsilon^n - \mathbf{U}_\varepsilon^{n-1}|^2 \, d\mathbf{x}. \end{cases} \quad (5.17)$$

Thanks to the mass conservation (3.16), (4.12) and the Taylor formula applied to the function  $t \rightarrow \mathbf{U}(t, \mathbf{x})$  between  $t^{n-1}$  and  $t^n$  we easily get

$$|R_{2,1}| \leq c \delta t \quad (5.18)$$

where  $c$  depends on  $\|\partial_t \mathbf{U}\|_{L^\infty([0,T] \times \bar{\Omega})^3}$  and on  $\mathcal{E}_{0,\mathcal{M}}$ . Let us now decompose the term  $T_{2,1}$  as

$$T_{2,1} = T_{2,2} + R_{2,2}, \quad \text{with} \quad T_{2,2} = \delta t \sum_{n=1}^m \int_{\Omega} \varrho^{n-1} \left( \frac{\mathbf{U}_\varepsilon^n - \mathbf{U}_\varepsilon^{n-1}}{\delta t} \right) \cdot (\mathbf{U}_\varepsilon^n - \mathbf{u}^n) \, d\mathbf{x} \quad (5.19)$$

and  $R_{2,2} = \delta t \sum_{n=1}^m R_{2,2}^n$  where

$$R_{2,2}^n = \int_{\Omega} \varrho^{n-1} \left( \frac{\mathbf{U}_\varepsilon^n - \mathbf{U}_\varepsilon^{n-1}}{\delta t} \right) \cdot (\mathbf{U}_\varepsilon^{n-1} - \mathbf{U}_\varepsilon^n) \, d\mathbf{x} - \int_{\Omega} \varrho^{n-1} \left( \frac{\mathbf{U}_\varepsilon^n - \mathbf{U}_\varepsilon^{n-1}}{\delta t} \right) \cdot (\mathbf{u}^{n-1} - \mathbf{u}^n) \, d\mathbf{x}.$$

By the same token as above, and using estimate (4.15) we may estimate the residual term as follows

$$|R_{2,2}| \leq c \sqrt{\delta t} \quad (5.20)$$

where  $c$  depends on  $\|\partial_t \mathbf{U}\|_{L^\infty((0,T) \times \Omega)^3}$  and on  $\mathcal{E}_{0,\mathcal{M}}$ .

**Step 2:** *Term  $T_3$ .* Using Lemma 3.4 we can write

$$\begin{aligned}
T_3 &= \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{K \in \mathcal{M}} \mathcal{R}_{\mathcal{M}}^{(i)}(\mathcal{P}_\varepsilon^{(i)} U_i^n)_K \sum_{j=1}^3 \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(j)}(K)} |\sigma| \varrho_\sigma^{n,\text{up}} u_{\sigma,K}^n \mathcal{R}_\varepsilon^{(i,j)}(u_i^n - \mathcal{P}_\varepsilon^{(i)} U_i^n)_\sigma \\
&\quad + \delta t \sum_{n=1}^m \sum_{i=1}^3 (R_{3,1,1,i}^n + R_{3,1,2,i}^n) = T_{3,1} + R_{3,1} \quad (5.21)
\end{aligned}$$

where the reminder  $R_{3,1,i}^n$  and  $R_{3,2,i}^n$  are respectively given by

$$R_{3,1,1,i}^n = \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} \left( (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_\sigma - \mathcal{R}_{\mathcal{M}}^{(i)} \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n)_K \right) F_{\sigma,K}^n \left( u_\sigma^n - (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_\sigma - \mathcal{R}_{\mathcal{M}}^{(i)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K \right),$$

and

$$R_{3,1,2,i}^n = \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} \left( (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_\sigma - \mathcal{R}_{\mathcal{M}}^{(i)} \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n)_K \right) \\ \times \sum_{j=1, j \neq i}^d \sum_{\tau \in \mathcal{E}_{\text{int}}^{(j)}(K)} \sum_{\sigma' \in \mathcal{N}_{\tau,\sigma}} \frac{F_{\tau,K}^n}{2} \left( \frac{u_{i,\sigma}^n + u_{i,\sigma'}^n - (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_\sigma - (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_{\sigma'}}{2} - \mathcal{R}_{\mathcal{M}}^{(i)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K \right).$$

From the definition of  $\mathcal{R}_{\mathcal{M}}^{(i)}$  and  $\mathcal{P}_{\mathcal{E}}^{(i)}$  we infer that

$$R_{3,1,1,i}^n = \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}(K)} \frac{1}{4} \frac{|K|^2}{|\sigma|^2} \delta_i(\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K \delta_i(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K F_{\sigma,K}^n$$

From (3.50) and the definition of the discrete derivative (3.29), we infer that for any  $i \in \{1, 2, 3\}$  and  $K \in \mathcal{M}$

$$|\delta_i(\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K| \leq c$$

where  $c$  depends on  $\eta_{\mathcal{M}}$  and on  $\|\nabla \mathbf{U}\|_{L^\infty((0,T) \times \Omega)^{3 \times 3}}$ . Using the Hölder's inequality we infer that

$$|R_{3,1,1,i}^n| \leq c \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}, \sigma=K|L} \sqrt{h_\sigma} |\sigma| \varrho_{D_\sigma}^n |u_\sigma^n| \|\delta_i(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))\|_{L^2(K \cup L)} \\ \leq c \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}, \sigma=K|L} \sqrt{h_\sigma} |\sigma| |D_\sigma|^{-\frac{\gamma+6}{6\gamma}} \|\delta_i(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))\|_{L^2(K \cup L)} \|\varrho^n u_i^n\|_{L^{\frac{6\gamma}{\gamma+6}}(D_\sigma)}$$

where  $c$  depends on  $\|\nabla \mathbf{U}\|_{L^\infty((0,T) \times \Omega)^{3 \times 3}}$  and on  $\eta_{\mathcal{M}}$ . We can write for all  $\sigma \in \mathcal{E}_{\text{int}}^{(i)}$ ,

$$c_1 h_\sigma^3 \leq |D_\sigma| \leq c_2 h_\sigma^3, \quad c_3 h_\sigma^2 \leq |\sigma| \leq c_4 h_\sigma^2$$

where  $c_1$  and  $c_3$  depend on  $\eta_{\mathcal{M}}$  in a nondecreasing way and  $c_2$  and  $c_4$  depend on  $\eta_{\mathcal{M}}$  in a nondecreasing way, which gives

$$\sqrt{h_\sigma} |\sigma| |D_\sigma|^{-\frac{\gamma+6}{6\gamma}} \leq c h_{\mathcal{M}}^A.$$

where  $c$  depends on  $\eta_{\mathcal{M}}$  and where  $A$  is given by (3.79). Consequently

$$|R_{3,1,1,i}^n| \leq c h_{\mathcal{M}}^A \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}, \sigma=K|L} \|\delta_i(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))\|_{L^2(K \cup L)} \|\varrho^n u_i^n\|_{L^{\frac{6\gamma}{\gamma+6}}(D_\sigma)}.$$

$$|R_{3,1,1,i}^n| \leq c h_{\mathcal{M}}^A \left( \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}, \sigma=K|L} \|\delta_i(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))\|_{L^2(K \cup L)}^p \right)^{\frac{1}{p}} \left( \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(i)}, \sigma=K|L} \|\varrho^n u_i^n\|_{L^{\frac{6\gamma}{\gamma+6}}(D_\sigma)}^q \right)^{\frac{1}{q}}.$$

where  $1 < p, q < +\infty$  and  $\frac{1}{p} + \frac{1}{q} = 1$ .

If  $\frac{3}{2} \leq \gamma \leq 3$  and then  $\frac{6\gamma}{5\gamma-6} \geq 2$  we take  $p = \frac{6\gamma}{5\gamma-6}$  and  $q = \frac{6\gamma}{\gamma+6}$  and we obtain

$$|R_{3,1,1,i}^n| \leq c h_{\mathcal{M}}^A \|\delta_i(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))\|_{L^2(\Omega)} \|\varrho^n u_i^n\|_{L^{\frac{6\gamma}{\gamma+6}}(\Omega)}$$

Now if  $\gamma \geq 3$  and then  $\frac{6\gamma}{\gamma+6} \geq 2$  we take  $p = 2$  and  $q = 2$  and we obtain

$$|R_{3,1,1,i}^n| \leq c h_{\mathcal{M}}^A \|\delta_i(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))\|_{L^2(\Omega)} \|\varrho^n u_i^n\|_{L^{\frac{6\gamma}{\gamma+6}}(\Omega)}$$

where the constant  $c$  depends on  $\|\nabla \mathbf{U}\|_{L^\infty((0,T)\times\Omega)^3}$  and on  $\eta_{\mathcal{M}}$ . Finally from the estimates (3.56), (4.9) and (4.13) we deduce that

$$\delta t \sum_{n=1}^N \sum_{i=1}^3 |R_{3,1,1,i}^n| \leq ch_{\mathcal{M}}^A.$$

where  $c$  depends on  $\|\nabla \mathbf{U}\|_{L^\infty((0,T)\times\Omega)^3}$ ,  $\mathcal{E}_{0,\mathcal{M}}$  and on  $\eta_{\mathcal{M}}$ . Let us now estimate the remainder  $R_{3,1,2,i}^n$ . Let  $K \in \mathcal{M}$  and let us consider  $\sigma \in \mathcal{E}^{(i)}(K)$ . Without loss of generality we assume that  $\sigma = K|L \in \mathcal{E}_{\text{int}}^{(i)}$ . Let  $\epsilon \in \tilde{\mathcal{E}}(D_\sigma)$  such that  $\epsilon \neq \epsilon_K$  and  $\epsilon \cap K \subset \sigma' \in \mathcal{E}^{(j)}$  for  $j \neq i$  that is  $\epsilon \in \tilde{\mathcal{N}}_{\sigma',\sigma}$ . Since the primal fluxes vanish on external faces we can assume that  $\epsilon \in \tilde{\mathcal{E}}_{\text{int}}^{(i)}$  saying  $\epsilon = \sigma|\sigma''$  where  $\sigma'' \in \tilde{\mathcal{E}}^{(i)}$ . Let  $\tilde{K} \in \mathcal{M}$  such that  $\sigma' = K|\tilde{K}$ . We define  $\sigma''' \in \mathcal{E}^{(i)}$  such that  $\tilde{K} = [\sigma''' \sigma'']$  and  $\sigma'''' \in \mathcal{E}^{(i)}$  such that  $K = [\sigma'''' \sigma]$ . Finally let  $\tilde{L}$  be the primal cell such that  $\sigma'' = \tilde{K}|\tilde{L}$ . We summarize the above notations in the figure 10.

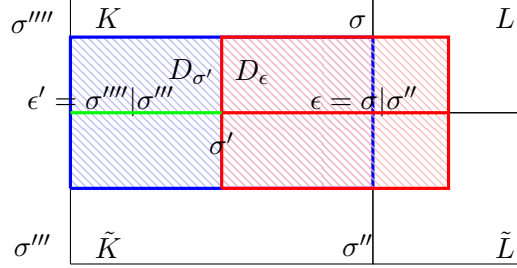


Figure 10: Decomposition of the dual grid

In accordance with the definition of  $u_\epsilon^n$  and  $U_\epsilon^n$  we can write

$$\begin{aligned} & \left| \frac{F_{\sigma',K}^n}{2} (u_\epsilon^n - U_\epsilon^n - (u_\epsilon^n - U_\epsilon^n - \mathcal{R}_{\mathcal{M}}^{(i)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K) \right| \\ & \leq c |\sigma'| \varrho_{D_{\sigma'}}^n |u_{\sigma'}^n| \left( \frac{|\tilde{K}|}{|\sigma''|} |\partial_i u_i|_{\tilde{K}} + d_{\epsilon'} |\partial_j u_i|_{D_{\epsilon'}} \right) \\ & \leq c \sqrt{h_{\sigma'}} |\sigma'| \varrho_{D_{\sigma'}}^n |u_{\sigma'}^n| \left( \|\partial_i (u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)\|_{L^2(D_{\sigma'})} + \|\partial_j (u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)\|_{L^2(D_{\sigma'})} \right) \\ & \leq ch_{\mathcal{M}}^A \|\varrho^n u_j^n\|_{L^{\frac{6\gamma}{\gamma+6}}(D_{\sigma'})} \left( \|\partial_i (u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)\|_{L^2(D_{\sigma'})} + \|\partial_j (u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)\|_{L^2(D_{\sigma'})} \right) \end{aligned}$$

We deduce from the previous computation that

$$|R_{3,1,2,i}^n| \leq ch_{\mathcal{M}}^A \sum_{j \neq i} \sum_{\sigma' \in \mathcal{E}^{(j)}} \|\varrho^n u_j^n\|_{L^{\frac{6\gamma}{\gamma+6}}(D_{\sigma'})} \left( \|\partial_i (u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)\|_{L^2(D_{\sigma'})} + \|\partial_j (u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)\|_{L^2(D_{\sigma'})} \right)$$

where the constant  $c$  depends on  $\eta_{\mathcal{M}}$ . Finally from the estimates (3.56), (4.9) and (4.13) and thanks to computation established to estimate  $R_{3,1,1,i}$  we deduce that

$$\delta t \sum_{n=1}^N \sum_{i=1}^3 |R_{3,1,2,i}^n| \leq ch_{\mathcal{M}}^A,$$

where  $c$  depends on  $\|\nabla \mathbf{U}\|_{L^\infty((0,T)\times\Omega)^3}$ ,  $\mathcal{E}_{0,\mathcal{M}}$  and on  $\eta_{\mathcal{M}}$ . Consequently we have

$$\delta t \sum_{n=1}^N \sum_{i=1}^3 (|R_{3,1,1,i}^n| + |R_{3,1,2,i}^n|) \leq ch_{\mathcal{M}}^A. \quad (5.22)$$

Evidently, for each face  $\sigma = K|L \in \mathcal{E}_{\text{int}}$ ,  $u_{\sigma,K}^n + u_{\sigma,L}^n = 0$ ; whence,

$$\begin{aligned} T_{3,1} &= \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{K \in \mathcal{M}} \sum_{j=1}^3 \sum_{\sigma \in \mathcal{E}^{(j)}(K)} |\sigma| \varrho_\sigma^{n,\text{up}} u_\sigma^n e^{(j)} \cdot \mathbf{n}_{\sigma,K} \\ & \quad \times (\mathcal{R}_{\mathcal{E}}^{(i,j)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_\sigma) (\mathcal{R}_{\mathcal{M}}^{(i)}(\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K - (\mathcal{P}_{\mathcal{E}}^{(j)} U_i^n)_\sigma) \end{aligned}$$



Consequently

$$T_{3,1} = \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{K \in \mathcal{M}} \sum_{j=1}^3 \sum_{\sigma \in \mathcal{E}^{(j)}(K)} |\sigma| \varrho_\sigma^{n,\text{up}} (\mathcal{P}_\mathcal{E}^{(j)} U_j^n)_\sigma \mathbf{e}^{(j)} \cdot \mathbf{n}_{\sigma,K} \\ \times (\mathcal{R}_\mathcal{E}^{(i,j)}(u_i^n - \mathcal{P}_\mathcal{E}^{(i)} U_i^n)_\sigma) (\mathcal{R}_\mathcal{M}^{(i)}(\mathcal{P}_\mathcal{E}^{(i)} U_i^n)_K - (\mathcal{P}_\mathcal{E}^{(j)} U_i^n)_\sigma) + R_{3,2} \quad (5.23)$$

where  $R_{3,2} = \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{K \in \mathcal{M}} \sum_{j=1}^3 \sum_{\sigma \in \mathcal{E}^{(j)}(K) \cap \mathcal{E}_{\text{int}}} R_{3,2,i,K,j,\sigma}^n$

$$R_{3,2,i,K,j,\sigma}^n = |\sigma| \varrho_\sigma^{n,\text{up}} (u_\sigma^n - (\mathcal{P}_\mathcal{E}^{(j)} U_j^n)_\sigma) \mathbf{e}^{(j)} \cdot \mathbf{n}_{\sigma,K} (\mathcal{R}_\mathcal{E}^{(i,j)}(u_i^n - \mathcal{P}_\mathcal{E}^{(i)} U_i^n)_\sigma) (\mathcal{R}_\mathcal{M}^{(i)}(\mathcal{P}_\mathcal{E}^{(i)} U_i^n)_K - (\mathcal{P}_\mathcal{E}^{(j)} U_i^n)_\sigma)$$

Using (3.50) we infer that for any  $(i,j) \in \{1,2,3\}^2$ ,  $K \in \mathcal{M}$ ,  $\sigma \in \mathcal{E}^{(j)}(K) \cap \mathcal{E}_{\text{int}}$ ,

$$|\mathcal{R}_\mathcal{M}^{(i)}(\mathcal{P}_\mathcal{E}^{(i)} U_i^n)_K - (\mathcal{P}_\mathcal{E}^{(j)} U_i^n)_\sigma| \leq c h_\sigma,$$

where  $c$  depends on  $\|\nabla \mathbf{U}\|_{L^\infty((0,T) \times \Omega)^{3 \times 3}}$  and on  $\eta_\mathcal{M}$ . Consequently we can estimate the general term of  $R_{3,2}$  as follows

$$|R_{3,2,i,K,j,\sigma}^n| = \left| |\sigma| \varrho_\sigma^{n,\text{up}} (u_\sigma^n - (\mathcal{P}_\mathcal{E}^{(j)} U_j^n)_\sigma) \mathbf{e}^{(j)} \cdot \mathbf{n}_{\sigma,K} (\mathcal{R}_\mathcal{E}^{(i,j)}(u_i^n - \mathcal{P}_\mathcal{E}^{(i)} U_i^n)_\sigma) (\mathcal{R}_\mathcal{M}^{(i)}(\mathcal{P}_\mathcal{E}^{(i)} U_i^n)_K - (\mathcal{P}_\mathcal{E}^{(j)} U_i^n)_\sigma) \right| \\ \leq c |D_\sigma| |\varrho_\sigma^{n,\text{up}}| |(u_\sigma^n - (\mathcal{P}_\mathcal{E}^{(j)} U_j^n)_\sigma)| |(\mathcal{R}_\mathcal{E}^{(i,j)}(u_i^n - \mathcal{P}_\mathcal{E}^{(i)} U_i^n)_\sigma)| \\ \leq c |D_\sigma| (\varrho_K^n + \varrho_L^n) |(u_\sigma^n - (\mathcal{P}_\mathcal{E}^{(j)} U_j^n)_\sigma)| |(\mathcal{R}_\mathcal{E}^{(i,j)}(u_i^n - \mathcal{P}_\mathcal{E}^{(i)} U_i^n)_\sigma)| \\ \leq c \int_{D_\sigma} \varrho^n |u_j^n - \mathcal{P}_\mathcal{E}^{(j)}(U_j^n)| |\mathcal{R}_\mathcal{E}^{(i,j)}(u_i^n - \mathcal{P}_\mathcal{E}^{(i)}(U_i^n))| \, d\mathbf{x},$$

where  $\sigma = K|L \in \mathcal{E}^{(j)}(K) \cap \mathcal{E}_{\text{int}}$ . Consequently using (3.66) and Hölder's inequality and then Young's inequality, we infer that

$$|R_{3,2,1}| \leq c \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \int_\Omega \varrho^n |u_j^n - \mathcal{P}_\mathcal{E}^{(j)}(U_j^n)| |\mathcal{R}_\mathcal{E}^{(i,j)}(u_i^n - \mathcal{P}_\mathcal{E}^{(i)}(U_i^n))| \, d\mathbf{x} \\ \leq \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \|\varrho^n\|_{L^{3/2}(\Omega)}^{1/2} \left( \mathcal{E}(\varrho^n, \mathbf{u}^n | r_\mathcal{M}^n, \mathbf{U}_\mathcal{E}^n) \right)^{1/2} \|u_i^n - \mathcal{P}_\mathcal{E}^{(i)}(U_i^n)\|_{1,\mathcal{E}^{(i),0}} \\ \leq \frac{c}{\delta} \delta t \sum_{n=1}^m \mathcal{E}(\varrho^n, \mathbf{u}^n | r_\mathcal{M}^n, \mathbf{U}_\mathcal{E}^n) + \delta \delta t \sum_{n=1}^m \|\mathbf{u}^n - \mathbf{U}_\mathcal{E}^n\|_{1,\mathcal{E},0}^2$$

where  $c$  depends on  $\|\nabla \mathbf{U}\|_{L^\infty((0,T) \times \Omega)}$ ,  $\mathcal{E}_{0,\mathcal{M}}$  and on  $\eta_\mathcal{M}$ .

**Step 3:** *Term  $T_5$ .* Using the Taylor formula since  $p \in C^2(\mathbb{R}_+^*)$  we get

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

where  $\bar{r}_K^n \in [\min(r_K^{n-1}, r_K^n), \max(r_K^{n-1}, r_K^n)]$ . Consequently  $T_5 = T_{5,1} + R_{5,1}$  with

$$T_{5,1} = \delta t \sum_{n=1}^m \int_\Omega (r_\mathcal{M}^n - \varrho^n) \frac{p'(r_\mathcal{M}^n)}{r_\mathcal{M}^n} \frac{r_\mathcal{M}^n - r_\mathcal{M}^{n-1}}{\delta t} \, d\mathbf{x} \quad (5.24)$$

and

$$R_{5,1} = \delta t \sum_{n=1}^m \sum_{K \in \mathcal{M}} R_{5,1}^{n,K}, \quad R_{5,1}^{n,K} = \frac{1}{2} |K| \mathcal{H}'''(\bar{r}_K^n) \frac{(r_K^n - r_K^{n-1})^2}{\delta t} (\varrho_K^n - r_K^n).$$

By the first order Taylor formula applied to function  $t \mapsto r(t, x)$  on the interval  $(t^{n-1}, t^n)$ , thanks to the relation (2.3), to the mass conservation (3.16) and (4.12) we have

$$|R_{5,1}| \leq c \delta t \quad (5.25)$$

where  $c$  depends on  $\|\partial_t r\|_{L^\infty(Q_T)}$  and on  $\mathcal{E}_{0,\mathcal{M}}$ .

Let us now decompose  $T_{5,1}$  as follows:  $T_{5,1} = T_{5,2} + R_{5,2}$  with

$$T_{5,2} = \delta t \sum_{n=1}^m \sum_{K \in \mathcal{M}} \int_K (r_{\mathcal{M}}^n - \varrho^n) \frac{p'(r_{\mathcal{M}}^n)}{r_{\mathcal{M}}^n} [\partial_t r]^n dx, \quad (5.26)$$

and

$$R_{5,2} = \delta t \sum_{n=1}^m \int_{\Omega} (r_{\mathcal{M}}^n - \varrho^n) \frac{p'(r_{\mathcal{M}}^n)}{r_{\mathcal{M}}^n} \left( \frac{r_{\mathcal{M}}^n - r_{\mathcal{M}}^{n-1}}{\delta t} - [\partial_t r]^n \right) dx$$

Using twice the Taylor formula, the Fubini Theorem and Hölder's inequality (see [24]) we can obtain

$$|R_{5,2}| \leq c \delta t, \quad (5.27)$$

where  $c$  depends on  $\underline{r}, \bar{r}, \|\partial_t^2 r\|_{L^1(0,T;L^{\gamma'}(\Omega))}$  and on  $\mathcal{E}_{0,\mathcal{M}}$ .

**Step 4:** *Term  $T_6$ .* Using the local conservativity of the flux through a primal face, we may write

$$\begin{aligned} T_6 &= T_{6,1} + R_{6,1}, \quad R_{6,1} = \delta t \sum_{n=1}^m \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}(K)} R_{6,1}^{n,\sigma,K}, \text{ with} \\ T_{6,1} &= \delta t \sum_{n=1}^m \sum_{\sigma \in \mathcal{E}(K) \cap \mathcal{E}_{\text{int}}} |\sigma| \varrho_K^n \left( \mathcal{H}'(r_K^{n-1}) - \mathcal{H}'(r_\sigma^{n-1}) \right) u_{\sigma,K}^n, \text{ and} \\ R_{6,1}^{n,\sigma,K} &= |\sigma| \left( \varrho_\sigma^{n,\text{up}} - \varrho_K^n \right) \left( \mathcal{H}'(r_K^{n-1}) - \mathcal{H}'(r_\sigma^{n-1}) \right) u_{\sigma,K}^n, \quad \sigma \in \mathcal{E}(K) \cap \mathcal{E}_{\text{int}}. \end{aligned} \quad (5.28)$$

Motivated by (4.16), we may write for  $\sigma = K|L \in \mathcal{E}_{\text{int}}$

$$\begin{aligned} |R_{6,1}^{n,\sigma,K}| &\leq c \sqrt{h_{\mathcal{M}}} |\sigma| \\ &\times \left( \frac{|\varrho_\sigma^{n,\text{up}} - \varrho_K^n|}{\max(\varrho_K^n, \varrho_L^n)^{(2-\gamma)^+/2}} \sqrt{|u_{\sigma,K}^n| 1_{\bar{\varrho}_\sigma^n \geq 1}} \sqrt{h_K} (\varrho_K^n + \varrho_L^n)^{(2-\gamma)^+/2} \sqrt{|u_{\sigma,K}^n|} \right. \\ &\quad \left. + |\varrho_\sigma^{n,\text{up}} - \varrho_K^n| \sqrt{|u_{\sigma,K}^n| 1_{\bar{\varrho}_\sigma^n < 1}} \sqrt{h_K} \sqrt{|u_{\sigma,K}^n|} \right), \end{aligned} \quad (5.29)$$

where  $c$  depends on  $\underline{r}, \|\nabla r\|_{L^\infty((0,T) \times \Omega)^3}$  and where the numbers  $\bar{\varrho}_\sigma^n$  are defined in Theorem 4.1. Here we have used the first order Taylor formula applied to function  $\mathcal{H}'$  between endpoints  $r_K^{n-1}, r_\sigma^{n-1}$ . Consequently the Hölder and Young inequalities gives

$$\begin{aligned} |R_{6,1}| &\leq c \sqrt{h_{\mathcal{M}}} \delta t \sum_{n=1}^m \left[ \left( \sum_{K \in \mathcal{M}} \sum_{\sigma=K|L \in \mathcal{E}(K)} |\sigma| \frac{(\varrho_\sigma^{n,\text{up}} - \varrho_K^n)^2}{\max(\varrho_K^n, \varrho_L^n)^{(2-\gamma)^+}} |u_{\sigma,K}^n| 1_{\bar{\varrho}_\sigma^n \geq 1} \right)^{1/2} \right. \\ &\quad \times \left( \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}(K)} |\sigma| h_\sigma (\varrho_K^n)^{(2-\gamma)^+} |u_{\sigma,K}^n| \right)^{1/2} \\ &\quad \left. + \left( \sum_{K \in \mathcal{M}} \sum_{\sigma=K|L \in \mathcal{E}(K)} |\sigma| h_\sigma (\varrho_\sigma^{n,\text{up}} - \varrho_K^n)^2 |u_{\sigma,K}^n| 1_{\bar{\varrho}_\sigma^n < 1} \right)^{1/2} \left( \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}(K)} |\sigma| h_\sigma |u_{\sigma,K}^n| \right)^{1/2} \right] \\ &\leq c \sqrt{h_{\mathcal{M}}} \delta t \sum_{n=1}^m \left[ \left( \sum_{K \in \mathcal{M}} \sum_{\sigma=K|L \in \mathcal{E}(K)} |\sigma| \frac{(\varrho_\sigma^{n,\text{up}} - \varrho_K^n)^2}{\max(\varrho_K^n, \varrho_L^n)^{(2-\gamma)^+}} |u_{\sigma,K}^n| 1_{\bar{\varrho}_\sigma^n \geq 1} \right. \right. \\ &\quad \left. \left. + \left( \sum_{K \in \mathcal{M}} |K| (\varrho_K^n)^{6(2-\gamma)^+/5} \right)^{5/6} \left( \sum_{\sigma \in \mathcal{E}} |\sigma| h_\sigma |u_{\sigma,K}^n|^6 \right)^{1/6} \right. \right. \\ &\quad \left. \left. + \sum_{K \in \mathcal{M}} \sum_{\sigma=K|L \in \mathcal{E}(K)} |\sigma| h_\sigma (\varrho_\sigma^{n,\text{up}} - \varrho_K^n)^2 |u_{\sigma,K}^n| 1_{\bar{\varrho}_\sigma^n < 1} + |\Omega|^{5/6} \left( \sum_{\sigma \in \mathcal{E}} |\sigma| h_\sigma |u_{\sigma,K}^n|^6 \right)^{1/6} \right] \\ &\leq c \sqrt{h_{\mathcal{M}}} \end{aligned} \quad (5.30)$$

where  $c$  depends on  $\underline{r}, \bar{r}, \|\nabla r\|_{L^\infty((0,T)\times\Omega)^3}, \mathcal{E}_{0,\mathcal{M}}$  provided  $\gamma \geq 12/11$ . Here we have used estimate (4.16), estimate (4.10), (4.12) of Corollary 4.1.

Let us now decompose the term  $T_{6,1}$  as  $T_{6,1} = T_{6,2} + R_{6,2}$  with

$$T_{6,2} = \delta t \sum_{n=1}^m \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}(K) \cap \mathcal{E}_{\text{int}}} |\sigma| \varrho_K^n \mathcal{H}''(r_K^{n-1})(r_K^{n-1} - r_\sigma^{n-1}) u_{\sigma,K}^n, \quad (5.31)$$

where

$$R_{6,2} = \delta t \sum_{n=1}^m \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}(K) \cap \mathcal{E}_{\text{int}}} R_{6,2}^{n,\sigma,K},$$

and

$$R_{6,2}^{n,\sigma,K} = |\sigma| \varrho_K^n \left( \mathcal{H}'(r_K^{n-1}) - \mathcal{H}'(r_\sigma^{n-1}) - \mathcal{H}''(r_K^{n-1})(r_K^{n-1} - r_\sigma^{n-1}) \right) u_{\sigma,K}^n$$

Therefore, by virtue of the second order Taylor formula applied to function  $\mathcal{H}'$ , Hölder's inequality, (3.50), (3.51), (4.9), (4.13) in Corollary 4.1 we have,

$$|R_{6,2}| \leq ch_{\mathcal{M}} \quad (5.32)$$

where  $c$  depends on  $\underline{r}, \bar{r}, \|\nabla r\|_{L^\infty((0,T)\times\Omega)^3}, \mathcal{E}_{0,\mathcal{M}}$  and on  $\eta_{\mathcal{M}}$ .

Let us now deal with the term  $T_{6,2}$ . First of all, let us remark that  $\int_K \nabla r^{n-1} \, d\mathbf{x} = \sum_{\sigma \in \mathcal{E}(K)} |\sigma| (r_\sigma^{n-1} - r_K^{n-1}) \mathbf{n}_{\sigma,K}$ . Therefore we may write

$$T_{6,2} = T_{6,3} + R_{6,3},$$

with

$$T_{6,3} = -\delta t \sum_{n=1}^m \int_{\Omega} \varrho^n \mathcal{H}''(r_{\mathcal{M}}^{n-1}) \mathcal{R}_{\mathcal{M}}(\mathbf{u}^n) \cdot \nabla r^{n-1} \, d\mathbf{x}, \quad (5.33)$$

where  $\mathcal{R}_{\mathcal{M}}$  is defined in (3.65) and where the remainder  $R_{6,3}$  is given by

$$R_{6,3} = \delta t \sum_{n=1}^m \sum_{K \in \mathcal{M}} \sum_{j=1}^3 \sum_{\sigma \in \mathcal{E}^{(j)}(K)} |\sigma| \varrho_K^n \mathcal{H}''(r_K^{n-1})(r_K^{n-1} - r_\sigma^{n-1})(u_\sigma^n - (\mathcal{R}_{\mathcal{M}}^{(j)} u_j^n)_K) \mathbf{e}^{(j)} \cdot \mathbf{n}_{\sigma,K},$$

Now in accordance with the proof of the remainder  $R_{6,3}$  in Lemma 6.1 of [24] and by virtue of the Hölder's inequality, (3.50), (3.51), and (4.9), (4.12) in Corollary 4.1,

$$|R_{6,3}| \leq ch_{\mathcal{M}}^A \quad (5.34)$$

where  $c$  depends on  $\underline{r}, \bar{r}, \|\nabla r\|_{L^\infty(Q_T; \mathbb{R}^3)}, \mathcal{E}_{0,\mathcal{M}}$  and where  $A$  is defined in (3.79).

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

$$\begin{aligned} T_{6,4} &= -\delta t \sum_{n=1}^m \int_{\Omega} \varrho^n \frac{p'(r_{\mathcal{M}}^n)}{r_{\mathcal{M}}^n} \mathcal{R}_{\mathcal{M}}(\mathbf{u}^n) \cdot \nabla r^n \, d\mathbf{x}, \\ R_{6,4} &= \delta t \sum_{n=1}^m \int_{\Omega} \varrho^n \left( \mathcal{H}''(r_{\mathcal{M}}^n) \nabla r^n - \mathcal{H}''(r_{\mathcal{M}}^{n-1}) \nabla r^{n-1} \right) \cdot \mathcal{R}_{\mathcal{M}}(\mathbf{u}^n) \, d\mathbf{x}, \end{aligned} \quad (5.35)$$

where by the same token as above the remainder  $R_{6,4}$  satisfies

$$|R_{6,4}| \leq c \delta t. \quad (5.36)$$

Here the constant  $c$  depends on  $\underline{r}, \bar{r}, \|\nabla r, \partial_t r\|_{L^\infty(Q_T)^7}, \|\partial_t \nabla r\|_{L^2(0,T; L^{\frac{6\gamma}{5\gamma-6}}(\Omega))^3}$  and on  $\mathcal{E}_{0,\mathcal{M}}$ .

We are now in position to conclude the proof of Lemma 5.1: we obtain the inequality (5.14) by gathering the principal terms (5.19), (5.23), (5.26), (5.35) and the residual terms estimated in (5.18), (5.20), (5.22), (5.25), (5.27), (5.30), (5.32), (5.34), (5.36) at the right hand side  $\sum_{i=1}^6 T_i$  of the discrete relative energy inequality (5.1).  $\square$

## 6 A consistency error

This section is devoted to the derivation of a discrete identity satisfied by any strong solution. This identity is stated in Lemma 6.1 below. It will be used in combination with the approximate relative energy inequality stated in Lemma 5.1 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 6.1** (Consistency error). *Let  $(\varrho, \mathbf{u}) \in Y_{\mathcal{M},\delta t} \times \mathbf{X}_{\mathcal{E},\delta t}$  be a solution of the discrete problem (3.10). Let  $(r, \mathbf{U})$  belonging to the class (3.73) such that  $\mathbf{U}|_{(0,T) \times \partial\Omega} = 0$  and satisfying (1.1). Then there exists  $c$  only depending on parameters (5.11–5.13) such that for any  $m = 1, \dots, N$ , the following identity holds:*

$$\begin{aligned} & \delta t \sum_{n=1}^m \left( \mu [\mathbf{U}_{\mathcal{E}}^n, \mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n]_{1,\mathcal{E},0} + (\mu + \lambda) \int_{\Omega} \operatorname{div} \mathbf{U}^n \operatorname{div}_{\mathcal{M}}(\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n) \, d\mathbf{x} \right) \\ & \quad + \delta t \sum_{n=1}^m \int_{\Omega} r_{\mathcal{M}}^{n-1} \frac{\mathbf{U}_{\mathcal{E}}^n - \mathbf{U}_{\mathcal{E}}^{n-1}}{\delta t} \cdot (\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n) \, d\mathbf{x} \\ & \quad + \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{K \in \mathcal{M}} \sum_{j=1}^3 \sum_{\sigma \in \mathcal{E}^{(i)}(K)} \left[ |\sigma| r_{\sigma}^{n,\text{up}} (\mathcal{P}_{\mathcal{E}}^{(j)} U_j^n)_{\sigma} \mathbf{e}^{(j)} \cdot \mathbf{n}_{\sigma,K} \mathcal{R}_{\mathcal{E}}^{(i,j)} (u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_{\sigma} \right. \\ & \quad \quad \quad \left. \times ((\mathcal{R}_{\mathcal{E}}^{(i,j)} U_i^n)_{\sigma} - \mathcal{R}_{\mathcal{M}}^{(i)} (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K) \right] \\ & \quad + \delta t \sum_{n=1}^m \int_{\Omega} p(r_{\mathcal{M}}^n) \operatorname{div} \mathbf{U}^n \, d\mathbf{x} + \delta t \sum_{n=1}^m \int_{\Omega} p'(r_{\mathcal{M}}^n) \mathcal{R}_{\mathcal{M}}(\mathbf{u}^n) \cdot \nabla r^n \, d\mathbf{x} + \mathcal{K}_{\mathcal{M},\delta t}^m = 0, \quad (6.1) \end{aligned}$$

where the remainder  $\mathcal{K}_{\mathcal{M},\delta t}^m$  satisfies

$$|\mathcal{K}_{\mathcal{M},\delta t}^m| \leq c(h_{\mathcal{M}} + \delta t).$$

*Proof.* Since  $(r, \mathbf{U})$  satisfies (1.1) and belongs to the class (3.73), Equation (1.1b) can be rewritten in the form

$$r \partial_t \mathbf{U} + r \mathbf{U} \cdot \nabla \mathbf{U} + \nabla p(r) = \mu \Delta \mathbf{U} + (\mu + \lambda) \nabla \operatorname{div} \mathbf{u} \text{ in } (0, T) \times \Omega. \quad (6.2)$$

We write equation (6.2) at  $t = t^n$ , multiply scalarly by  $\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n$ , and integrate over  $\Omega$ . We get, after summation from  $n = 1$  to  $m$ ,  $\sum_{i=1}^5 Q_i$  where

$$\begin{aligned} Q_1 &= \delta t \sum_{n=1}^m \int_{\Omega} r^n \partial_t \mathbf{U}^n \cdot (\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n) \, d\mathbf{x}, \\ Q_2 &= \delta t \sum_{n=1}^m \int_{\Omega} r^n \mathbf{U}^n \cdot \nabla \mathbf{U}^n \cdot (\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n) \, d\mathbf{x}, \\ Q_3 &= \delta t \sum_{n=1}^m \int_{\Omega} \nabla p(r^n) \cdot (\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n) \, d\mathbf{x} \\ Q_4 &= -\delta t \sum_{n=1}^m \int_{\Omega} \mu \Delta \mathbf{U}^n \cdot (\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n) \, d\mathbf{x}, \\ Q_5 &= -\delta t \sum_{n=1}^m \int_{\Omega} (\mu + \lambda) \nabla \operatorname{div} \mathbf{u}^n \cdot (\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n) \, d\mathbf{x}. \end{aligned}$$

An adaptation of the proof of Lemma 7.1 in [24] gives

$$\begin{aligned} Q_1 + Q_3 &= \delta t \sum_{n=1}^m \int_{\Omega} r_{\mathcal{M}}^{n-1} \frac{\mathbf{U}_{\mathcal{E}}^n - \mathbf{U}_{\mathcal{E}}^{n-1}}{\delta t} (\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n) \, d\mathbf{x} + \delta t \sum_{n=1}^m \int_{\Omega} p(r_{\mathcal{M}}^n) \operatorname{div} \mathbf{U}^n \, d\mathbf{x} \\ & \quad + \delta t \sum_{n=1}^m \int_{\Omega} p'(r_{\mathcal{M}}^n) \mathcal{R}_{\mathcal{M}}(\mathbf{u}^n) \cdot \nabla r^n \, d\mathbf{x} + R_{\mathcal{M},\delta t}^m, \quad (6.3) \end{aligned}$$

where the remainder  $R_{\mathcal{M},\delta t}^m$  satisfies

$$|R_{\mathcal{M},\delta t}^m| \leq c(h_{\mathcal{M}} + \delta t).$$

and where the constant  $c$  depends on  $\bar{r}$ ,  $|p|_{C^2([\underline{r},\bar{r}])}$ ,  $\|\nabla r\|_{L^\infty((0,T)\times\Omega)}$ ,  $\|\partial_t \mathbf{U}\|_{L^\infty((0,T)\times\Omega)}$ ,  $\|\nabla \mathbf{U}\|_{L^\infty((0,T)\times\Omega)}$  and on  $\|\partial_t^2 \mathbf{U}\|_{L^2(0,T;L^{\frac{6}{5}}(\Omega))}$ ,  $\|\partial_t \nabla \mathbf{U}\|_{L^2(0,T;L^{\frac{6}{5}}(\Omega))}$ ,  $\mathcal{E}_{0,\mathcal{M}}$ .

By virtue of the Stoke's formula we transform the term  $T_4$  as follows, using (3.39), (3.41) and  $d_\epsilon|\epsilon| = |D_\epsilon|$ ,

$$\begin{aligned} Q_4 &= -\delta t \sum_{n=1}^m \int_{\Omega} \mu \Delta \mathbf{U}^n \cdot (\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n) \, d\mathbf{x} = -\delta t \mu \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{\substack{\epsilon \in \tilde{\mathcal{E}}^{(i)} \\ \epsilon \perp \mathbf{e}^{(j)}}} \int_{D_\epsilon} \frac{\partial^2}{\partial x_j^2} U_i^n (u_i^n - (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)) \, d\mathbf{x} \\ &= \delta t \mu \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{\substack{\epsilon \in \tilde{\mathcal{E}}^{(i)} \\ \epsilon \perp \mathbf{e}^{(j)}}} d_\epsilon |\epsilon| \bar{\partial}_j (u_i^n - (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n))_{D_\epsilon} \frac{1}{|\epsilon|} \int_{\epsilon} \frac{\partial}{\partial x_j} U_i^n \, d\gamma \\ &= \delta t \mu \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{\substack{\epsilon \in \tilde{\mathcal{E}}^{(i)} \\ \epsilon \perp \mathbf{e}^{(j)}}} d_\epsilon |\epsilon| \bar{\partial}_j (u_i^n - (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n))_{D_\epsilon} \bar{\partial}_j (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_{D_\epsilon} + R_{\mathcal{M},\delta t}^m \\ &= \delta t \sum_{n=1}^m \mu [\mathbf{U}_{\mathcal{E}}^n, \mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n]_{1,\mathcal{E},0} + R_{\mathcal{M},\delta t}^m \end{aligned}$$

where the remainder  $R_{\mathcal{M},\delta t}^m$  is given by

$$\delta t \mu \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{\substack{\epsilon \in \tilde{\mathcal{E}}^{(i)} \\ \epsilon \perp \mathbf{e}^{(j)}}} d_\epsilon |\epsilon| \bar{\partial}_j (u_i^n - (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n))_{D_\epsilon} \left( \frac{1}{|\epsilon|} \int_{\epsilon} \frac{\partial}{\partial x_j} U_i^n \, d\gamma - \bar{\partial}_j (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_{D_\epsilon} \right)$$

Moreover by virtue of (3.52) and (3.53) in Lemma 3.2 we can write for  $\epsilon = \overrightarrow{\sigma|\sigma'} \in \tilde{\mathcal{E}}_{\text{int}}^{(i)}$ ,  $\epsilon \perp \mathbf{e}^{(j)}$ ,

$$\begin{aligned} \bar{\partial}_j (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_{D_\epsilon} - \frac{1}{|\epsilon|} \int_{\epsilon} \frac{\partial}{\partial x_j} U_i^n \, d\gamma &= \frac{1}{d_\epsilon} (U_i(\mathbf{x}_{\sigma'}) - U_i(\mathbf{x}_\sigma)) - \frac{\partial}{\partial x_j} U_i^n(\mathbf{x}_\epsilon) + R_\epsilon^n \\ &= \frac{\partial}{\partial x_j} U_i^n(\mathbf{x}_{\sigma,\sigma'}) - \frac{\partial}{\partial x_j} U_i^n(\mathbf{x}_\epsilon) + R_\epsilon^n \end{aligned}$$

where  $\mathbf{x}_{\sigma,\sigma'} \in [\mathbf{x}_\sigma, \mathbf{x}_{\sigma'}]$  and where the remainder  $R_\epsilon^n$  satisfies

$$|R_\epsilon^n| \leq ch_{\mathcal{M}}.$$

Note that the case  $\epsilon \in \tilde{\mathcal{E}}_{\text{ext}}^{(i)}$  can be treated in the same way. Consequently we have inequality

$$\left| \frac{1}{|\epsilon|} \int_{\epsilon} \frac{\partial}{\partial x_j} U_i^n \, d\gamma - \bar{\partial}_j (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_{D_\epsilon} \right| \leq ch_{\mathcal{M}}, \quad \forall (i,j) \in \{1,2,3\}^2, \forall \epsilon \in \tilde{\mathcal{E}}^{(i)}, \epsilon \perp \mathbf{e}^{(j)},$$

where the constant  $c$  depends on  $\|\nabla^2 \mathbf{U}\|_{L^\infty((0,T)\times\Omega)}$ . Therefore

$$|R_{\mathcal{M},\delta t}^m| \leq ch_{\mathcal{M}} \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{\substack{\epsilon \in \tilde{\mathcal{E}}^{(i)} \\ \epsilon \perp \mathbf{e}^{(j)}}} |D_\epsilon| |\bar{\partial}_j (u_i^n - (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n))_{D_\epsilon}| \leq ch_{\mathcal{M}} \delta t \sum_{n=1}^m \|\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}\|_{1,\mathcal{E},0}$$

where  $c$  depends on  $\|\nabla^2 \mathbf{U}\|_{L^\infty((0,T)\times\Omega)}$ . Consequently by virtue of (3.56) and (4.9) we have

$$Q_4 = \delta t \sum_{n=1}^m \mu [\mathbf{U}_{\mathcal{E}}^n, \mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n]_{1,\mathcal{E},0} + R_{\mathcal{M},\delta t}^m, \quad (6.4)$$

where the remainder  $R_{\mathcal{M},\delta t}^m$  satisfies

$$|R_{\mathcal{M},\delta t}^m| \leq ch_{\mathcal{M}}$$

and where  $c$  depends on  $\|\nabla \mathbf{U}\|_{L^\infty((0,T)\times\Omega)}$ ,  $\|\nabla^2 \mathbf{U}\|_{L^\infty((0,T)\times\Omega)}$ ,  $\eta_{\mathcal{M}}$  and on  $\mathcal{E}_{0,\mathcal{M}}$ .

The term  $Q_5$  can be treated exactly in the same way as  $Q_4$  in order to obtain

$$Q_5 = -\delta t \sum_{n=1}^m (\mu + \lambda) \int_{\Omega} \operatorname{div} \mathbf{U}^n \operatorname{div}_{\mathcal{M}}(\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n) \, d\mathbf{x} + R_{\mathcal{M},\delta t}^m, \quad (6.5)$$

where the remainder  $R_{\mathcal{M},\delta t}^m$  satisfies

$$|R_{\mathcal{M},\delta t}^m| \leq ch_{\mathcal{M}}.$$

where the constant  $c$  depends on  $\|\nabla \mathbf{U}\|_{L^\infty((0,T)\times\Omega)}$ ,  $\|\nabla^2 \mathbf{U}\|_{L^\infty((0,T)\times\Omega)}$ ,  $\eta_{\mathcal{M}}$  and on  $\mathcal{E}_{0,\mathcal{M}}$ .

Let us deal with the term  $Q_2$ . We have

$$\begin{aligned} Q_2 &= \delta t \sum_{n=1}^m \sum_{i=1}^3 \int_{\Omega} r^n U^n \cdot \nabla U_i^n (u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n)) \, d\mathbf{x} \\ &= \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{K \in \mathcal{M}} \int_K r_K^n \mathcal{R}_{\mathcal{M}}^{(j)}(\mathcal{P}_{\mathcal{E}}^{(j)} U_j^n)_K \partial_j U_i^n \mathcal{R}_{\mathcal{M}}^{(i)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))_K \, d\mathbf{x} + R_{\mathcal{M},\delta t}^m \end{aligned}$$

where the remainder  $R_{\mathcal{M},\delta t}^m$  is given by

$$\begin{aligned} R_{\mathcal{M},\delta t}^m &= \delta t \sum_{n=1}^m \int_{\Omega} (r^n - \mathcal{P}_{\mathcal{M}}(r^n)) U^n \cdot \nabla U^n \cdot (\mathbf{u}^n - \mathcal{P}_{\mathcal{E}}(U^n)) \, d\mathbf{x} \\ &\quad + \delta t \sum_{n=1}^m \int_{\Omega} \mathcal{P}_{\mathcal{M}}(r^n) (U^n - \mathcal{R}_{\mathcal{M}} \mathcal{P}_{\mathcal{E}} U^n) \cdot \nabla U^n \cdot (\mathbf{u}^n - \mathcal{P}_{\mathcal{E}}(U^n)) \, d\mathbf{x} \\ &\quad + \delta t \sum_{n=1}^m \int_{\Omega} \mathcal{P}_{\mathcal{M}}(r^n) \mathcal{R}_{\mathcal{M}} \mathcal{P}_{\mathcal{E}} U^n \cdot \nabla U^n \cdot (\mathbf{u}^n - \mathcal{P}_{\mathcal{E}}(U^n) - \mathcal{R}_{\mathcal{M}}(\mathbf{u}^n - \mathcal{P}_{\mathcal{E}}(U^n))) \, d\mathbf{x}. \end{aligned}$$

By virtue of (3.54), (3.55), (3.67) and (4.9) the remainder  $R_{\mathcal{M},\delta t}^m$  satisfies

$$|R_{\mathcal{M},\delta t}^m| \leq ch_{\mathcal{M}},$$

where the constant  $c$  depends on  $\bar{r}$ ,  $\|\nabla r\|_{L^\infty((0,T)\times\Omega)}$ ,  $\|\mathbf{U}\|_{L^\infty((0,T)\times\Omega)^3}$ ,  $\|\nabla \mathbf{U}\|_{L^\infty((0,T)\times\Omega)}$  and on  $\mathcal{E}_{0,\mathcal{M}}$ . Using the Stoke's formula we infer that

$$\begin{aligned} &\delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{K \in \mathcal{M}} \int_K r_K^n \mathcal{R}_{\mathcal{M}}^{(j)}(\mathcal{P}_{\mathcal{E}}^{(j)} U_j^n)_K \partial_j U_i^n \mathcal{R}_{\mathcal{M}}^{(i)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))_K \, d\mathbf{x} \\ &= \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}^{(j)}(K)} \left[ |\sigma| r_K^n \mathcal{R}_{\mathcal{M}}^{(j)}(\mathcal{P}_{\mathcal{E}}^{(j)} U_j^n)_K \right. \\ &\quad \left. \times ((\mathcal{P}_{\mathcal{E}}^{(j)} U_i^n)_{\sigma} - \mathcal{R}_{\mathcal{M}}^{(i)}(\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K) \mathbf{e}^{(j)} \cdot \mathbf{n}_{\sigma,K} \mathcal{R}_{\mathcal{M}}^{(i)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))_K \right], \end{aligned}$$

where we have used the identity

$$\int_K \partial_j U_i^n \, d\mathbf{x} = \int_K \partial_j (U_i^n - \mathcal{R}_{\mathcal{M}}^{(i)}(\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K) \, d\mathbf{x}.$$

Finally keeping in mind the definition of the quantity  $r_\sigma^{n,\text{up}}$  (see (5.8)) we obtain

$$\begin{aligned} & \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}^{(j)}(K)} \left[ |\sigma| r_K^n \mathcal{R}_{\mathcal{M}}^{(j)}(\mathcal{P}_{\mathcal{E}}^{(j)} U_j^n)_K ((\mathcal{P}_{\mathcal{E}}^{(j)} U_i^n)_\sigma - \mathcal{R}_{\mathcal{M}}^{(i)}(\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K) \mathbf{e}^{(j)} \cdot \mathbf{n}_{\sigma,K} \right. \\ & \quad \left. \times \mathcal{R}_{\mathcal{M}}^{(i)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))_K \right] \\ & = \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(j)}(K)} \left[ |\sigma| r_\sigma^{n,\text{up}}(\mathcal{P}_{\mathcal{E}}^{(j)} U_j^n)_\sigma ((\mathcal{P}_{\mathcal{E}}^{(j)} U_i^n)_\sigma - \mathcal{R}_{\mathcal{M}}^{(i)}(\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K) \mathbf{e}^{(j)} \cdot \mathbf{n}_{\sigma,K} \right. \\ & \quad \left. \times \mathcal{R}_{\mathcal{M}}^{(i)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))_K \right] + R_{\mathcal{M},\delta t}^m \end{aligned}$$

where by virtue of (3.50), (3.51) the remainder  $R_{\mathcal{M},\delta t}^m$  satisfies

$$|R_{\mathcal{M},\delta t}^m| \leq c \delta t \sum_{n=1}^m \int_{\Omega} \|\mathcal{P}_{\mathcal{E}} U^n\| \|\mathcal{R}_{\mathcal{M}}(\mathbf{u}^n - \mathcal{P}_{\mathcal{E}}(\mathbf{U}^n))\| \, d\mathbf{x}$$

where  $c$  depends on  $\|\nabla r\|_{L^\infty((0,T) \times \Omega)}$  and on  $\|\mathbf{U}\|_{L^\infty((0,T) \times \Omega)^3}$ . Consequently by virtue of (3.67) and (4.9)

$$|R_{\mathcal{M},\delta t}^m| \leq ch_{\mathcal{M}}.$$

Now we write

$$\begin{aligned} & \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(j)}(K)} \left[ |\sigma| r_\sigma^{n,\text{up}}(\mathcal{P}_{\mathcal{E}}^{(j)} U_j^n)_\sigma ((\mathcal{P}_{\mathcal{E}}^{(j)} U_i^n)_\sigma - \mathcal{R}_{\mathcal{M}}^{(i)}(\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K) \mathbf{e}^{(j)} \cdot \mathbf{n}_{\sigma,K} \right. \\ & \quad \left. \times \mathcal{R}_{\mathcal{M}}^{(i)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))_K \right] \\ & = \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(j)}(K)} \left[ |\sigma| r_\sigma^{n,\text{up}}(\mathcal{P}_{\mathcal{E}}^{(j)} U_j^n)_\sigma \mathbf{e}^{(j)} \cdot \mathbf{n}_{\sigma,K} \right. \\ & \quad \left. \times \mathcal{R}_{\mathcal{E}}^{(i,j)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_\sigma ((\mathcal{P}_{\mathcal{E}}^{(j)} U_i^n)_\sigma - \mathcal{R}_{\mathcal{M}}^{(i)}(\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K) \right] + R_{\mathcal{M},\delta t}^m \end{aligned}$$

where by virtue of (3.50), (3.66), (3.67) and (4.9) the remainder  $R_{\mathcal{M},\delta t}^m$  satisfies

$$\begin{aligned} R_{\mathcal{M},\delta t}^m & = \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(j)}(K)} \left[ |\sigma| r_\sigma^{n,\text{up}}(\mathcal{P}_{\mathcal{E}}^{(j)} U_j^n)_\sigma \mathbf{e}^{(j)} \cdot \mathbf{n}_{\sigma,K} ((\mathcal{P}_{\mathcal{E}}^{(j)} U_i^n)_\sigma - \mathcal{R}_{\mathcal{M}}^{(i)}(\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K) \right. \\ & \quad \left. \times (\mathcal{R}_{\mathcal{M}}^{(i)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))_K - \mathcal{R}_{\mathcal{E}}^{(i,j)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_\sigma) \right] \end{aligned}$$

Consequently

$$\begin{aligned} |R_{\mathcal{M},\delta t}^m| & \leq c \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(j)}(K)} |\sigma| |(\mathcal{P}_{\mathcal{E}}^{(j)} U_i^n)_\sigma - \mathcal{R}_{\mathcal{M}}^{(i)}(\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K| \\ & \quad \times |\mathcal{R}_{\mathcal{M}}^{(i)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))_K - \mathcal{R}_{\mathcal{E}}^{(i,j)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_\sigma| \end{aligned}$$

From (3.50) we infer that for any  $(i, j) \in \{1, 2, 3\}^2$ ,  $K \in \mathcal{M}$ ,  $\sigma \in \mathcal{E}_{\text{int}}^{(j)}(K)$ ,

$$|(\mathcal{P}_{\mathcal{E}}^{(j)} U_i^n)_\sigma - \mathcal{R}_{\mathcal{M}}^{(i)}(\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K| \leq ch_K,$$

which gives

$$\begin{aligned} |R_{\mathcal{M},\delta t}^m| & \leq c \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(j)}(K)} |\sigma| h_\sigma |\mathcal{R}_{\mathcal{M}}^{(i)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))_K - \mathcal{R}_{\mathcal{E}}^{(i,j)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_\sigma| \\ & \leq ch_{\mathcal{M}} \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{j=1}^3 \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(j)}(K)} \|\check{\partial}_j(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)\|_{L^1(D_\sigma)}, \end{aligned}$$

which gives by virtue of (4.9) and (3.56),

$$|R_{\mathcal{M},\delta t}^m| \leq ch_{\mathcal{M}}$$

where  $c$  depends on  $\bar{r}$ ,  $\|\mathbf{U}\|_{L^\infty((0,T)\times\Omega)^3}$ ,  $\|\nabla r\|_{L^\infty((0,T)\times\Omega)}$ ,  $\|\nabla \mathbf{U}\|_{L^\infty((0,T)\times\Omega)}$ ,  $\mathcal{E}_{0,\mathcal{M}}$  and on  $\eta_{\mathcal{M}}$ . Consequently

$$\begin{aligned} Q_2 = \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{K \in \mathcal{M}} \sum_{j=1}^3 \sum_{\sigma \in \mathcal{E}^{(j)}(K)} & \left( |\sigma| r_{\sigma}^{n,\text{up}} (\mathcal{P}_{\mathcal{E}}^{(j)} U_j^n)_{\sigma} \mathbf{e}^{(j)} \cdot \mathbf{n}_{\sigma,K} \mathcal{R}_{\mathcal{E}}^{(i,j)} (u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_{\sigma} \right. \\ & \left. \times ((\mathcal{P}_{\mathcal{E}}^{(j)} U_i^n)_{\sigma} - \mathcal{R}_{\mathcal{M}}^{(i)} (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K) \right) + R_{\mathcal{M},\delta t}^m \end{aligned} \quad (6.6)$$

where the remainder  $R_{\mathcal{M},\delta t}^m$  satisfies

$$|R_{\mathcal{M},\delta t}^m| \leq ch_{\mathcal{M}}.$$

Summing (6.3) to (6.6) we obtain the expected result that is (6.1).  $\square$

## 7 End of the proof of the error estimate Theorem 3.3

In this Section we put together the relative energy inequality (5.14) and the identity (6.1) derived in the previous section to obtain a discrete version of inequality (2.17). The final inequality resulting from this manipulation is formulated in the following lemma.

**Lemma 7.1.** *Under assumptions of Theorem 3.3 there exists  $c$  depending on parameters (5.11–5.13) such that for all  $m = 1, \dots, N$ , there holds:*

$$\begin{aligned} & \mathcal{E}(\varrho^m, \mathbf{u}^m | r_{\mathcal{M}}^m, \mathbf{U}_{\mathcal{E}}^m) + \delta t \frac{\mu}{2} \sum_{n=1}^m \|\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n\|_{1,\mathcal{E},0}^2 \\ & \leq c \left[ h_{\mathcal{M}}^A + \sqrt{\delta t} + \mathcal{E}(\varrho^0, \mathbf{u}^0 | r_{\mathcal{M}}^0, \mathbf{U}_{\mathcal{E}}^0) \right] + c \delta t \sum_{n=1}^m \mathcal{E}(\varrho^n, \mathbf{u}^n | r_{\mathcal{M}}^n, \mathbf{U}_{\mathcal{E}}^n), \end{aligned}$$

where  $A$  is defined in (3.79).

*Proof.* Gathering the formulae (5.14) and (6.1), one gets

$$\mathcal{E}(\varrho^m, \mathbf{u}^m | r_{\mathcal{M}}^m, \mathbf{U}_{\mathcal{E}}^m) - \mathcal{E}(\varrho^0, \mathbf{u}^0 | r_{\mathcal{M}}^0, \mathbf{U}_{\mathcal{E}}^0) + \mu \delta t \sum_{n=1}^m \|\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n\|_{1,\mathcal{E},0}^2 \leq \mathcal{P}_1 + \mathcal{P}_2 + \mathcal{P}_3 + \mathcal{Q} \quad (7.1)$$

where

$$\begin{aligned} \mathcal{P}_1 &= \delta t \sum_{n=1}^m \int_{\Omega} (\varrho^{n-1} - r_{\mathcal{M}}^{n-1}) \frac{\mathbf{U}_{\mathcal{E}}^n - \mathbf{U}_{\mathcal{E}}^{n-1}}{\delta t} \cdot (\mathbf{U}_{\mathcal{E}}^n - \mathbf{u}^n) \, d\mathbf{x}, \\ \mathcal{P}_2 &= \delta t \sum_{n=1}^m \sum_{i=1}^3 \sum_{K \in \mathcal{M}} \sum_{j=1}^3 \sum_{\sigma \in \mathcal{E}^{(j)}(K)} \left( |\sigma| (\varrho_{\sigma}^{n,\text{up}} - r_{\sigma}^{n,\text{up}}) (\mathcal{P}_{\mathcal{E}}^{(j)} U_j^n)_{\sigma} \mathbf{e}^{(j)} \cdot \mathbf{n}_{\sigma,K} \right. \\ & \quad \left. \times (\mathcal{R}_{\mathcal{E}}^{(i,j)} (\mathcal{P}_{\mathcal{E}}^{(i)} (U_i^n)_{\sigma} - u_i^n)_{\sigma}) (\mathcal{R}_{\mathcal{M}}^{(i)} (\mathcal{P}_{\mathcal{E}}^{(i)} U_i^n)_K - (\mathcal{P}_{\mathcal{E}}^{(j)} U_i^n)_{\sigma}) \right), \\ \mathcal{P}_3 &= \delta t \sum_{n=1}^m \int_{\Omega} \left( p(r_{\mathcal{M}}^n) - p(\varrho^n) \right) \operatorname{div} \mathbf{U}^n \, d\mathbf{x} \\ & \quad + \delta t \sum_{n=1}^m \int_{\Omega} \left( \frac{r_{\mathcal{M}}^n - \varrho^n}{r_{\mathcal{M}}^n} p'(r_{\mathcal{M}}^n) \mathcal{R}_{\mathcal{M}}(\mathbf{u}^n) \cdot \nabla r^n + \frac{r_{\mathcal{M}}^n - \varrho_{\mathcal{M}}^n}{r_{\mathcal{M}}^n} p'(r_{\mathcal{M}}^n) [\partial_t r]^n \right) \, d\mathbf{x}, \\ \mathcal{Q} &= \mathcal{R}_{\mathcal{M},\delta t}^m + \mathcal{G}_{\mathcal{M},\delta t}^m + \mathcal{K}_{\mathcal{M},\delta t}^m, \end{aligned}$$



and where the remainders  $\mathcal{R}_{\mathcal{M},\delta t}^m$ ,  $\mathcal{G}_{\mathcal{M},\delta t}^m$  and  $\mathcal{K}_{\mathcal{M},\delta t}^m$  are explicated in Lemma 5.1 and Lemma 6.1.

**Step 1: Term  $\mathcal{P}_1$ .** Writing  $\mathcal{P}_1 = \delta t \sum_{n=1}^m \mathcal{P}_1^n$ , an application of the Taylor formula and of Lemma 2.1 gives, since  $\gamma \geq \frac{6}{5}$ :

$$\begin{aligned} |\mathcal{P}_1^n| &\leq c \int_{\Omega} |\varrho^{n-1} - r_{\mathcal{M}}^{n-1}| |\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n| \, d\mathbf{x} \\ &\leq c \int_{\Omega} (\sqrt{E(\varrho^{n-1}, r_{\mathcal{M}}^{n-1})} + (E(\varrho^{n-1}, r_{\mathcal{M}}^{n-1}))^{5/6}) |\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n| \, d\mathbf{x} \\ &\leq c \left( \int_{\Omega} E(\varrho^{n-1}, r_{\mathcal{M}}^{n-1})^{3/5} + E(\varrho^{n-1}, r_{\mathcal{M}}^{n-1}) \, d\mathbf{x} \right)^{5/6} \|\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n\|_{L^6(\Omega, \mathbb{R}^3)} \\ &\leq \frac{c}{\delta} \left[ \left( \int_{\Omega} (E(\varrho^{n-1}, r_{\mathcal{M}}^{n-1}) \, d\mathbf{x}) \right)^{5/3} + \int_{\Omega} E(\varrho^{n-1}, r_{\mathcal{M}}^{n-1}) \, d\mathbf{x} \right] + \delta \|\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n\|_{L^6(\Omega, \mathbb{R}^3)}^2 \\ &\leq \frac{c}{\delta} \mathcal{E}(\varrho^{n-1}, \mathbf{u}^{n-1} | r_{\mathcal{M}}^{n-1}, \mathbf{U}_{\mathcal{E}}^{n-1}) + \delta \|\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n\|_{1,\mathcal{E},0}^2, \end{aligned}$$

with any  $\delta > 0$ , where  $c$  depends on  $\underline{r}, \bar{r}, \|\partial_t \mathbf{U}\|_{L^\infty((0,T) \times \Omega)^3}$ . Here we have used Theorem 3.1 to get a bound on  $\|\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n\|_{L^6(\Omega)^3}^2$  by  $\|\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n\|_{1,\mathcal{E},0}^2$ , the Jensen inequality and the Young inequality to perform the before last inequality. Consequently

$$|\mathcal{P}_1| \leq \frac{c}{\delta} \left( \mathcal{E}(\varrho^0, r_{\mathcal{M}}^0 | \mathbf{u}^0, \mathbf{U}_{\mathcal{E}}^0) + \delta t \sum_{n=1}^m \mathcal{E}(\varrho^n, \mathbf{u}^n | r_{\mathcal{M}}^n, \mathbf{U}_{\mathcal{E}}^n) \right) + \delta \sum_{n=1}^m \|\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n\|_{1,\mathcal{E},0}^2. \quad (7.2)$$

**Step 2: Term  $\mathcal{P}_2$ .** We write  $\mathcal{P}_2 = \delta t \sum_{n=1}^m \mathcal{P}_2^n$  where Lemma 2.1, the Hölder inequality yield, since  $\gamma \geq \frac{3}{2}$ ,

$$\begin{aligned} |\mathcal{P}_2^n| &\leq c \sum_{i=1}^3 \sum_{j=1}^3 \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}^{(j)}(K) \cap \mathcal{E}_{\text{int}}} h_K |\sigma| |\varrho_{\sigma}^{n,\text{up}} - r_{\sigma}^{n,\text{up}}| |\mathcal{R}_{\mathcal{E}}^{(i,j)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))_{\sigma}| \\ &\leq c \left[ \left( \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}(K) \cap \mathcal{E}_{\text{int}}} |\sigma| h_{\sigma} \left( E(\varrho_{\sigma}^{n,\text{up}} | r_{\sigma}^{n,\text{up}}) \right)^{1/2} + \right. \right. \\ &\quad \left. \left. \left( \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}(K) \cap \mathcal{E}_{\text{int}}} |\sigma| h_{\sigma} E(\varrho_{\sigma}^{n,\text{up}} | r_{\sigma}^{n,\text{up}}) \right)^{2/3} \right] \right. \\ &\quad \left. \times \left( \sum_{i=1}^3 \sum_{j=1}^3 \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(j)}(K)} h_{\sigma} |\sigma| |\mathcal{R}_{\mathcal{E}}^{(i,j)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))_{\sigma}|^6 \right)^{1/6} \end{aligned}$$

where  $c$  depends on  $\|\mathbf{U}\|_{L^\infty((0,T) \times \Omega)^3}, \|\nabla \mathbf{U}\|_{L^\infty((0,T) \times \Omega)^9}$  and on  $\eta_{\mathcal{M}}$ . Next, we observe that the contribution of the face  $\sigma = K|L$  to the sums  $\sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}(K)} |\sigma| h_{\sigma} E(\varrho_{\sigma}^{n,\text{up}} | r_{\sigma}^{n,\text{up}})$  is less or equal than  $2|\sigma| h_{\sigma} (E(\varrho_K^n | r_K^n) + E(\varrho_L^n | r_L^n))$ . Moreover using (3.60) and (3.66) we have

$$\left( \sum_{i=1}^3 \sum_{j=1}^3 \sum_{K \in \mathcal{M}} \sum_{\sigma \in \mathcal{E}_{\text{int}}^{(j)}(K)} h_K |\sigma| |\mathcal{R}_{\mathcal{E}}^{(i,j)}(u_i^n - \mathcal{P}_{\mathcal{E}}^{(i)}(U_i^n))_{\sigma}|^6 \right)^{1/6} \leq c \|\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n\|_{L^6(\Omega)^3} \leq c \|\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n\|_{1,\mathcal{E},0}.$$

where the constant  $c$  depends on  $\eta_{\mathcal{M}}$  in a nondecreasing way.

Consequently, we get by the same reasoning as in the previous step, under assumption  $\gamma \geq 3/2$ ,

$$|\mathcal{P}_2| \leq \frac{c}{\delta} \delta t \sum_{n=1}^m \mathcal{E}(\varrho^n, \mathbf{u}^n | r_{\mathcal{M}}^n, \mathbf{U}_{\mathcal{E}}^n) + \delta \delta t \sum_{n=1}^m \|\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n\|_{1,\mathcal{E},0}^2. \quad (7.3)$$

where  $c$  depends on  $\underline{r}, \bar{r}, \|\mathbf{U}\|_{L^\infty((0,T) \times \Omega)^3}, \|\nabla \mathbf{U}\|_{L^\infty((0,T) \times \Omega)^9}$  and  $\eta_{\mathcal{M}}$  in a nondecreasing way.

**Step 3: Term  $\mathcal{P}_3$ .** Since the pair  $(r, \mathbf{U})$  satisfies continuity equation (1.1a) in the classical sense, we have for all  $n = 1, \dots, N$ ,

$$[\partial_t r]^n + \mathbf{U}^n \cdot \nabla r^n = -r^n \operatorname{div} \mathbf{U}^n,$$

where we recall that  $[\partial_t r]^n(x) = \partial_t r(t^n, x)$  in accordance with (3.77). Using this identity we write

$$\begin{aligned} \mathcal{P}_3 &= \mathcal{P}_{3,1} + \mathcal{P}_{3,2} + \mathcal{P}_{3,3}, \quad \mathcal{P}_{3,i} = \delta t \sum_{n=1}^m \mathcal{P}_{3,i}^n, \\ \text{with } \mathcal{P}_{3,1}^n &= - \int_{\Omega} \left( p(\varrho^n) - p'(r_{\mathcal{M}}^n)(\varrho^n - r_{\mathcal{M}}^n) - p(r_{\mathcal{M}}^n) \right) \operatorname{div} \mathbf{U}^n \, d\mathbf{x} \\ \mathcal{P}_{3,2}^n &= \int_{\Omega} \frac{r_{\mathcal{M}}^n - \varrho^n}{r_{\mathcal{M}}^n} p'(r_{\mathcal{M}}^n) (\mathcal{R}_{\mathcal{M}}(\mathbf{u}^n) - \mathbf{U}^n) \cdot \nabla r^n \, d\mathbf{x}, \\ \text{and } \mathcal{P}_{3,3}^n &= \int_{\Omega} \frac{r_{\mathcal{M}}^n - \varrho^n}{r_{\mathcal{M}}^n} p'(r_{\mathcal{M}}^n) (r_{\mathcal{M}}^n - r^n) \operatorname{div} \mathbf{U}^n \, d\mathbf{x} \end{aligned}$$

From the asymptotic behaviour (1.5) for large values of the pressure and Lemma 2.1 we easily deduce that

$$|\mathcal{P}_{3,1}| \leq c \delta t \sum_{n=1}^m \mathcal{E}(\varrho^n, \mathbf{u}^n | r_{\mathcal{M}}^n, \mathbf{U}_{\mathcal{E}}^n). \quad (7.4)$$

where  $c$  depends on  $\underline{r}, \bar{r}, \min_{[\underline{r}, \bar{r}]} p, \min_{[\underline{r}/2, 2\bar{r}]} p'$  and  $\|\nabla \mathbf{U}\|_{L^\infty((0,T) \times \Omega)}$ . From the total mass conservation (3.16) and (3.51) we deduce

$$|\mathcal{P}_{3,3}| \leq c h_{\mathcal{M}} \quad (7.5)$$

where  $c$  depends on  $\underline{r}, \bar{r}, \|\nabla r\|_{L^\infty((0,T) \times \Omega)^3}, \|\nabla \mathbf{U}\|_{L^\infty((0,T) \times \Omega)^3}$  and on  $\mathcal{E}_{0,\mathcal{M}}$ .

Last but not least, the same reasoning as in Step 2 leads to the estimate

$$|\mathcal{P}_{3,2}| \leq \frac{c}{\delta} \left( h_{\mathcal{M}} + \delta t \sum_{n=1}^m \mathcal{E}(\varrho^n, \mathbf{u}^n | r_{\mathcal{M}}^n, \mathbf{U}_{\mathcal{E}}^n) \right) + \delta \delta t \sum_{n=1}^m \|\mathbf{u}^n - \mathbf{U}_{\mathcal{E}}^n\|_{1,\mathcal{E},0}^2. \quad (7.6)$$

with any  $\delta > 0$ , where  $c$  depends on  $\underline{r}, \bar{r}, \|\nabla r\|_{L^\infty((0,T) \times \Omega)^3}, \|\nabla \mathbf{U}\|_{L^\infty((0,T) \times \Omega)^3}$  and on  $\mathcal{E}_{0,\mathcal{M}}$  in a non increasing way. Gathering the formulae (7.1)-(7.6) with  $\delta$  sufficiently small (with respect to  $\mu$ ), we conclude the proof of Lemma 7.1.  $\square$

Finally, Lemma 7.1 in combination with the bound (4.14) yields

$$\mathcal{E}(\varrho^m, \mathbf{u}^m | r_{\mathcal{M}}^m, \mathbf{U}_{\mathcal{E}}^m) \leq c \left( h_{\mathcal{M}}^A + \delta t + \mathcal{E}(\varrho^0, \mathbf{u}^0 | r_{\mathcal{M}}^0, \mathbf{U}_{\mathcal{E}}^0) \right) + c \delta t \sum_{n=1}^{m-1} \mathcal{E}(\varrho^n, \mathbf{u}^n | r_{\mathcal{M}}^n, \mathbf{U}_{\mathcal{E}}^n)$$

whence Theorem 3.3 is a direct consequence of the standard discrete version of Gronwall's lemma. Theorem 3.3 is thus proved.

## A Existence of a discrete solution

This section is devoted to the proof of Theorem 3.2. More precisely we are going to prove the following Proposition

**Proposition A.1.** *Consider a MAC grid  $\mathcal{D} = (\mathcal{M}, \mathcal{E})$  of  $\Omega$  of size  $h_{\mathcal{M}}$ . Let  $\delta t > 0$ . Let  $p : \mathbb{R} \rightarrow \mathbb{R}$  such that  $p \in C^1(\mathbb{R}_+^*)$ . Let  $(\varrho^*, \mathbf{u}^*) \in L_{\mathcal{M}} \times \mathbf{H}_{\mathcal{E},0}$  such that  $\varrho^* > 0$  a.e in  $\Omega$ . Then there exists  $(\varrho, \mathbf{u}) \in L_{\mathcal{M}} \times \mathbf{H}_{\mathcal{E},0}$  such that  $\varrho > 0$  a.e in  $\Omega$  which satisfies*

$$\frac{1}{\delta t} (\varrho - \varrho^*) + \operatorname{div}_{\mathcal{M}}^{\text{up}}(\varrho \mathbf{u}) = 0, \quad (\text{A.1a})$$

$$\begin{aligned} \frac{1}{\delta t} (\widehat{\varrho}^{(i)} u_i - \widehat{\varrho}^{*(i)} u_i^*) + \operatorname{div}_{\mathcal{E}}^{(i)}(\varrho \mathbf{u} u_i) - \mu \Delta_{\mathcal{E}}^{(i)} u_i \\ - (\mu + \lambda) \widehat{\partial}_i \operatorname{div}_{\mathcal{M}} \mathbf{u} + \widehat{\partial}_i p(\varrho) = 0, \quad \forall i = 1, \dots, d. \end{aligned} \quad (\text{A.1b})$$

*Proof.* Let us state the abstract theorem which will be used hereafter.

**Theorem A.1.** *Let  $N$  and  $M$  be two positive integers and  $V$  be defined as follows:*

$$V = \{(x, y) \in \mathbb{R}^N \times \mathbb{R}^M, y > 0\},$$

where, for any real number  $c$ , the notation  $y > c$  means that each component of  $y$  is greater than  $c$ . Let  $F$  be a continuous function from  $V \times [0, 1]$  to  $\mathbb{R}^N \times \mathbb{R}^M$  satisfying:

1.  $\forall \zeta \in [0, 1]$ , if  $v \in V$  is such that  $F(v, \zeta) = 0$  then  $v \in W$  where  $W$  is defined as follows:

$$W = \{(x, y) \in \mathbb{R}^N \times \mathbb{R}^M, \|x\| \leq C_1, \text{ and } \epsilon < y < C_2\},$$

with  $C_1$ ,  $C_2$  and  $\epsilon$  three positive constants and  $\|\cdot\|$  a norm defined over  $\mathbb{R}^N$ ;

2. the topological degree of  $F(\cdot, 0)$  with respect to 0 and  $W$  is equal to  $d_0 \neq 0$ .

Then the topological degree of  $F(\cdot, 1)$  with respect to 0 and  $W$  is also equal to  $d_0 \neq 0$ ; consequently, there exists at least a solution  $v \in W$  such that  $F(v, 1) = 0$ .

We shall now prove the existence of a solution to (3.10). Let us define

$$V = \{(\mathbf{u}, \varrho) \in \mathbf{H}_{\mathcal{E},0} \times L_{\mathcal{M}}, \varrho_K > 0 \forall K \in \mathcal{M}\}.$$

and consider the mapping

$$\begin{aligned} F : V \times [0, 1] &\longrightarrow \mathbf{H}_{\mathcal{E},0} \times L_{\mathcal{M}} \\ (\mathbf{u}, \varrho, \zeta) &\mapsto F(\mathbf{u}, \varrho, \zeta) = (\hat{\mathbf{u}}, \hat{\varrho}), \end{aligned}$$

where  $(\hat{\mathbf{u}}, \hat{\varrho}) \in \mathbf{H}_{\mathcal{E},0} \times L_{\mathcal{M}}$  is such that

$$\begin{aligned} \int_{\Omega} \hat{\mathbf{u}} \cdot \mathbf{v} \, d\mathbf{x} &= \int_{\Omega} \frac{\varrho \mathbf{u} - \varrho^* \mathbf{u}^*}{\delta t} \cdot \mathbf{v} \, d\mathbf{x} + \mu [\mathbf{u}, \mathbf{v}]_{1,\mathcal{E},0} + (\mu + \lambda) \int_{\Omega} \operatorname{div}_{\mathcal{M}} \mathbf{u} \operatorname{div}_{\mathcal{M}} \mathbf{v} \, d\mathbf{x} \\ &\quad + \zeta \int_{\Omega} \operatorname{div}_{\mathcal{E}}(\varrho \mathbf{u} \otimes \mathbf{u}) \cdot \mathbf{v} \, d\mathbf{x} - \zeta \int_{\Omega} p(\varrho) \operatorname{div}_{\mathcal{M}} \mathbf{v} \, d\mathbf{x}, \quad \forall \mathbf{v} \in \mathbf{H}_{\mathcal{E},0}, \end{aligned} \quad (\text{A.2a})$$

$$\int_{\Omega} \hat{\varrho} \, q \, d\mathbf{x} = \int_{\Omega} \frac{\varrho - \varrho^*}{\delta t} q \, d\mathbf{x} + \zeta \int_{\Omega} \operatorname{div}_{\mathcal{M}}^{\text{up}}(\varrho \mathbf{u}) \, q \, d\mathbf{x}, \quad \forall q \in L_{\mathcal{M}}. \quad (\text{A.2b})$$

Any solution of  $F(\mathbf{u}, \varrho, 1) = 0$  is a solution of Problem A.1. Note also that in (A.2a) the fluxes  $F_{\epsilon,\sigma}(\varrho, \mathbf{u})$  which determine  $\operatorname{div}_{\mathcal{E}}(\varrho \mathbf{u} \otimes \mathbf{u})$  are constructed from the fluxes  $F_{\sigma,K}(\varrho, \mathbf{u})$  which determine  $\operatorname{div}_{\mathcal{M}}^{\text{up}}(\varrho \mathbf{u})$  as in (3.19) and (3.20).

It is easily checked that  $F$  is indeed a one to one mapping, since the values of  $\hat{u}_i; i = 1, \dots, d$ , and  $\hat{\varrho}$  are readily obtained by setting in this system  $v_i = 1_{D_{\sigma}}$ ,  $v_j = 0, j \neq i$  in (A.2a) and  $q = 1_K$  in (A.2b). Moreover, the mapping  $F$  is clearly continuous.

Let  $(\mathbf{u}, \varrho) \in \mathbf{H}_{\mathcal{E},0} \times L_{\mathcal{M}}$  and  $\zeta \in [0, 1]$  such that  $F(\mathbf{u}, \varrho, \zeta) = (0, 0)$  (in particular  $\varrho > 0$ ). Then for any  $(\mathbf{v}, q) \in \mathbf{H}_{\mathcal{E},0} \times L_{\mathcal{M}}$ ,

$$\begin{aligned} \int_{\Omega} \frac{\varrho \mathbf{u} - \varrho^* \mathbf{u}^*}{\delta t} \cdot \mathbf{v} \, d\mathbf{x} + \zeta \int_{\Omega} \operatorname{div}_{\mathcal{E}}(\varrho \mathbf{u} \otimes \mathbf{u}) \cdot \mathbf{v} \, d\mathbf{x} + \mu [\mathbf{u}, \mathbf{v}]_{1,\mathcal{E},0} \\ + (\mu + \lambda) \int_{\Omega} \operatorname{div}_{\mathcal{M}} \mathbf{u} \operatorname{div}_{\mathcal{M}} \mathbf{v} \, d\mathbf{x} - \zeta \int_{\Omega} p(\varrho) \operatorname{div}_{\mathcal{M}} \mathbf{v} \, d\mathbf{x} = 0 \end{aligned} \quad (\text{A.3a})$$

$$\int_{\Omega} \frac{\varrho - \varrho^*}{\delta t} q \, d\mathbf{x} + \zeta \int_{\Omega} \operatorname{div}_{\mathcal{M}}^{\text{up}}(\varrho \mathbf{u}) \, q \, d\mathbf{x} = 0. \quad (\text{A.3b})$$

Taking  $q = 1$  as a test function in (A.3b), and using the conservativity of the fluxes we obtain

$$\int_{\Omega} \varrho \, d\mathbf{x} = \|\varrho\|_{L^1(\Omega)} = \int_{\Omega} \varrho^* \, d\mathbf{x} > 0. \quad (\text{A.4})$$

This relation provides a bound for  $\varrho$  in the  $L^1$  norm, and therefore in all norms since the problem is of finite dimension.

Taking  $\mathbf{u}$  as a test function in (A.3a) and following the proof of Theorem 4.1 gives

$$\|\mathbf{u}\|_{1,\mathcal{E},0} \leq C_1 \quad (\text{A.5})$$

where the constant  $C_1$  depends only on the data of the problem. Now a straightforward computation gives

$$\varrho_K \geq \frac{\min_{K \in \mathcal{M}} |K| \min_{K \in \mathcal{M}} \varrho_K^*}{|\Omega| + \delta t \sum_{\sigma \in \mathcal{E}_{\text{int}}, \sigma=K|L} |u_{\sigma,K}|}.$$

Consequently by virtue of (A.5) there exists  $\epsilon > 0$  such that

$$\varrho_K \geq \epsilon, \quad \forall K \in \mathcal{M}, \quad (\text{A.6})$$

where the constant  $\epsilon$  depends only on the data of the problem. Clearly from (A.4) one has also

$$\varrho_K \leq \frac{\int_{\Omega} \varrho^* \, d\mathbf{x}}{\min_{K \in \mathcal{M}} |K|} = C_2, \quad \forall K \in \mathcal{M}. \quad (\text{A.7})$$

Moreover  $\zeta = 0$  the system  $F(\mathbf{u}, \varrho, 0) = 0$  reads:

$$\int_{\Omega} \frac{\varrho \mathbf{u} - \varrho^* \mathbf{u}^*}{\delta t} \cdot \mathbf{v} \, d\mathbf{x} + \mu [\mathbf{u}, \mathbf{v}]_{1,\mathcal{E},0} + (\mu + \lambda) \int_{\Omega} \operatorname{div}_{\mathcal{M}} \mathbf{u} \operatorname{div}_{\mathcal{M}} \mathbf{v} \, d\mathbf{x} = 0, \quad \forall \mathbf{v} \in \mathbf{H}_{\mathcal{E},0}, \quad (\text{A.8a})$$

$$\varrho_K = \varrho_K^*, \quad \forall K \in \mathcal{M}. \quad (\text{A.8b})$$

which has clearly one and only one solution. Let  $W$  defined by

$$W = \{(\mathbf{u}, \varrho) \in \mathbf{H}_{\mathcal{E},0} \times L_{\mathcal{M}} \text{ such that } \|\mathbf{u}\| \leq C_1, \epsilon \leq \varrho_K \leq C_2\}$$

It is quite easy to see that the determinant of the Jacobian matrix does not vanish for the solution of the system (A.8). Therefore the topological degree  $d_0$  of  $F(\cdot, \cdot, 0)$  with respect to 0 and  $W$  is not zero. Since the topological degree of  $F(\cdot, \cdot, 0)$  with respect to 0 and  $W$  does not vanish and by virtue of inequalities (A.5), (A.6), (A.7), Theorem A.1 applies, which concludes the proof.  $\square$

## B Error estimates for a class of staggered schemes

In this section we present some alternative numerical schemes for the approximation of problem (1.1)-(1.5), called staggered schemes. The space discretization in these schemes is staggered using nonconforming low-order finite element approximations, namely the Rannacher and Turek element (RT) [37] for quadrilateral or hexahedric meshes, or the lowest degree Crouzeix-Raviart element (CR) [8] for simplicial meshes. By the approach presented in this paper, it is possible to establish for these schemes similar error estimates as those established in Theorem 3.3 for the MAC scheme. The exact result is stated in Theorem B.1. We invite the reader wishing to read more about the discretizations of compressible flows via the staggered schemes to consult [21], [13], [20], [26].

### B.1 Space and time discretization

From now, let  $\Omega \subset \mathbb{R}^3$  be a bounded polyhedral domain. Let  $\mathcal{M}$  be a decomposition of the domain  $\Omega$  in simplices, which we call hereafter a triangulation of  $\Omega$ , regardless of the space dimension. By  $\mathcal{E}(K)$ , we denote the set of the edges (d=2) or faces (d=3)  $\sigma$  of the element  $K \in \mathcal{M}$ ; for short, each edge or face will be called an edge hereafter. The set of all edges of the mesh is denoted by  $\mathcal{E}$ ; the set of edges included in the boundary of  $\Omega$  is denoted by  $\mathcal{E}_{\text{ext}}$  and the set of internal edges (i.e  $\mathcal{E} \setminus \mathcal{E}_{\text{ext}}$ ) is denoted by  $\mathcal{E}_{\text{int}}$ . The triangulation  $\mathcal{M}$  verifies the following assumption:  $\bar{\Omega} = \cup_{K \in \mathcal{M}} \bar{K}$ ; if  $K, L \in \mathcal{M}$ , then  $\bar{K} \cap \bar{L} = \emptyset$ ,  $\bar{K} \cap \bar{L}$  is a vertex or  $\bar{K} \cap \bar{L}$  is a common edge of  $K$  and  $L$ , which is denoted by  $K|L$ . For each internal edge of the mesh  $\sigma = K|L$ ,  $\mathbf{n}_{KL}$  stands for the normal vector of  $\sigma$ , oriented from  $K$  to  $L$  (so that  $\mathbf{n}_{KL} = -\mathbf{n}_{LK}$ ). By  $|K|$  and  $|\sigma|$  we denote the ( $d$  and  $d - 1$  dimensional) measure, respectively, of an element  $K$  and of

an edge  $\sigma$ , and  $h_K$  and  $h_\sigma$  stand for the diameter of  $K$  and  $\sigma$ , respectively. As in the MAC case, we measure the size of the mesh through the parameter  $h_{\mathcal{M}}$  defined by

$$h_{\mathcal{M}} = \max\{h_K, K \in \mathcal{M}\}, \quad (\text{B.1})$$

where  $h_K$  stands for the diameter of  $K$ . We measure the regularity of the mesh through the parameter  $\theta_{\mathcal{M}}$  defined by

$$\theta_{\mathcal{M}} = \min\left\{\frac{\xi_K}{h_K}, K \in \mathcal{M}\right\}, \quad (\text{B.2})$$

where  $\xi_K$  stands for the diameter of the largest ball included in  $K$ .

Let us briefly describe the Crouzeix-Raviart element for simplicial meshes (see [8] for the seminal paper and, for instance, [10, p. 83-85], for a synthetic presentation), and the so-called 'rotated bilinear element' introduced by Rannacher and Turek for quadrilateral or hexahedric meshes [37]. The reference element for the Crouzeix-Raviart element is the unit  $d$ -simplex and the discrete function space is the space  $\mathbb{P}_1$  of affine polynomials. The reference element  $\hat{K}$  for the rotated bilinear element is the unit  $d$ -cube (with edges parallel to the coordinate axes); the discrete function space on  $\hat{K}$  is  $\tilde{\mathcal{Q}}_1(\hat{K})$ , where  $\tilde{\mathcal{Q}}_1(\hat{K})$  is defined as follows

$$\tilde{\mathcal{Q}}_1(\hat{K}) = \text{span}\{1, (x_i)_{i=1,\dots,d}, (x_i^2 - x_{i+1}^2)_{i=1,\dots,d-1}\}.$$

For both velocity elements used here, the degrees of freedom are determined by the following set of nodal functionals:

$$\{m_{\sigma,i}, \sigma \in \mathcal{E}(K), i = 1, \dots, d\}, \quad m_{\sigma,i}(\mathbf{v}) = \frac{1}{|\sigma|} \int_{\sigma} v_i \, d\mathbf{x}, \quad \mathbf{v} = (v_1, \dots, v_d). \quad (\text{B.3})$$

The mapping from the reference element to the actual one is, for the Rannacher-Turek element, the standard  $Q_1$  mapping and, for the Crouzeix-Raviart element, the standard affine mapping. Finally, in both cases, the continuity of the average value of discrete velocities (i.e., for a discrete velocity field  $\mathbf{v}$ ,  $m_{\sigma,i}(\mathbf{v})$ ,  $1 \leq i \leq d$ ) across each edge of the mesh is required, thus the discrete space  $\mathbf{W}_{\mathcal{E},0}(\Omega)$  is defined as follows:

$$\begin{aligned} \mathbf{W}_{\mathcal{E},0}(\Omega) = [W_{\mathcal{E},0}(\Omega)]^d = \{ & \mathbf{v} \in L^2(\Omega)^d, \forall K \in \mathcal{M}, \mathbf{v}|_K \in W(K)^d \text{ and } \forall \sigma = K|L \in \mathcal{E}_{\text{int}}, \\ & m_{\sigma,i}(\mathbf{v}|_K) = m_{\sigma,i}(\mathbf{v}|_L), \forall \sigma \in \mathcal{E}_{\text{ext}}, m_{\sigma,i}(\mathbf{v}) = 0\} \end{aligned}$$

where  $W(K)$  is the space of functions on  $K$  generated by  $\tilde{\mathcal{Q}}_1(\hat{K})$  through the  $Q_1$  mapping from  $\hat{K}$  to  $K$  for the Rannacher-Turek element and the space of affine functions on  $K$  for the Crouzeix-Raviart element.

From the definition (B.3), each velocity degree of freedom can be uniquely associated to an element edge. More precisely the degrees of freedom for the velocity components are located at the center of the faces of the mesh. Hence, the velocity degrees of freedom may be indexed by the number of the component and the associated edge, and the set of velocity degrees of freedom reads:

$$\{\mathbf{u}_\sigma, \sigma \in \mathcal{E}\}.$$

Finally, we need to deal with the Dirichlet boundary condition. Since the velocity unknowns lie on the boundary (and not inside the cells), these conditions are taken into account in the definition of the discrete spaces by setting zero to the velocity unknowns that lie on the boundary

$$\forall \sigma \in \mathcal{E}_{\text{ext}}, \quad \mathbf{u}_\sigma = 0. \quad (\text{B.4})$$

Since only the continuity of the integral over each edge of the mesh is imposed, the functions of  $\mathbf{W}_{\mathcal{E},0}(\Omega)$  are discontinuous through each edge; the discretization is thus nonconforming in  $H^1(\Omega)^d$ .

We denote by  $\varphi_\sigma$  the function of  $W_{\mathcal{E},0}(\Omega)$  such that

$$\int_{\sigma'} \varphi_\sigma \, d\gamma = |\sigma'| \delta_{\sigma,\sigma'} \text{ for any } \sigma, \sigma' \in \mathcal{E}_{\text{int}}. \quad (\text{B.5})$$

The degrees of freedom for the density (*i.e.* the discrete density unknowns) are associated to the cells of the mesh  $\mathcal{M}$ , and are denoted by:

$$\{\varrho_K, K \in \mathcal{M}\}.$$

We now introduce a dual mesh, which will be used for the finite volume approximation of the time derivative and convection terms in the momentum balance equation. In contrast with the MAC scheme, the dual mesh is the same for all velocity components. When  $K \in \mathcal{M}$  is a simplex, a rectangle or a cuboid, for  $\sigma \in \mathcal{E}(K)$ , we define  $D_{\sigma,K}$  as the cone with basis  $\sigma$  and with vertex the mass center of  $K$  (see Figure 1). We thus obtain a partition of  $K$  in  $m$  sub-volumes, where  $m$  is the number of faces of the mesh, each sub-volume having the same measure  $|D_{\sigma,K}| = |K|/m$ . We extend this definition to general quadrangles and hexahedra, by supposing that we have built a partition still of equal-volume sub-cells, and with the same connectivities. Note that this is of course always possible, but that such a volume  $D_{\sigma,K}$  may be no longer a cone; indeed, if  $K$  is far from a parallelogram, it may not be possible to build a cone having  $\sigma$  as basis, the opposite vertex lying in  $K$  and a volume equal to  $|K|/m$ . The volume  $D_{\sigma,K}$  is referred to as the half-diamond cell associated to  $K$  and  $\sigma$ .

For  $\sigma \in \mathcal{E}_{\text{int}}$ ,  $\sigma = K|L$ , we now define the diamond cell  $D_\sigma$  associated to  $\sigma$  by  $D_\sigma = D_{\sigma,K} \cup D_{\sigma,L}$ ; for an external face  $\sigma \in \mathcal{E}_{\text{ext}} \cap \mathcal{E}(K)$ ,  $D_\sigma$  is just the same volume as  $D_{\sigma,K}$ . We define the space  $\mathbf{S}_{\mathcal{E}}(\Omega)$  of vector valued functions constant on every  $D_\sigma$ ,  $\sigma \in \mathcal{E}$ . We denote by  $\mathbf{S}_{\mathcal{E},0}(\Omega)$  the subspace of functions from  $\mathbf{S}_{\mathcal{E}}(\Omega)$  that are zero on every  $D_\sigma$ ,  $\sigma \in \mathcal{E}_{\text{ext}}$ . We then introduce the following operator

$$\mathcal{P}_{\mathcal{E}} : \begin{cases} \mathbf{W}_{\mathcal{E},0}(\Omega) \longrightarrow \mathbf{S}_{\mathcal{E},0}(\Omega) \\ \mathbf{u} \longmapsto \mathcal{P}_{\mathcal{E}} \mathbf{u} = \sum_{\sigma \in \mathcal{E}_{\text{int}}} \mathbf{u}_\sigma \mathcal{X}_{D_\sigma}(\mathbf{x}), \end{cases} \quad (\text{B.6})$$

which is clearly a one to one mapping.

The density on a dual cell is given by:

$$\begin{aligned} \text{for } \sigma \in \mathcal{E}_{\text{int}}, \sigma = K|L & \quad |D_\sigma| \varrho_{D_\sigma} = |D_{\sigma,K}| \varrho_K + |D_{\sigma,L}| \varrho_L, \\ \text{for } \sigma \in \mathcal{E}_{\text{ext}}, \sigma \in \mathcal{E}(K), & \quad \varrho_{D_\sigma} = \varrho_K. \end{aligned} \quad (\text{B.7})$$

and we denote

$$\hat{\varrho} = \sum_{\sigma \in \mathcal{E}} \varrho_{D_\sigma} \mathcal{X}_{D_\sigma}(\mathbf{x}).$$

For the the time discretization of problem (1.1)-(1.5), we consider a partition  $0 = t^0 < t^1 < \dots < t^N = T$  of the time interval  $(0, T)$ , and, for the sake of simplicity, a constant time step  $\delta t = t^n - t^{n-1}$ ; hence  $t^n = n\delta t$  for  $n \in \{0, \dots, N\}$ . We denote respectively by  $\{\mathbf{u}_\sigma^n, \sigma \in \mathcal{E}_{\text{int}}, n \in \{0, \dots, N\}\}$ , and  $\{\varrho_K^n, K \in \mathcal{M}, n \in \{1, \dots, N\}\}$  the sets of discrete velocity and density unknowns. For  $\sigma \in \mathcal{E}_{\text{int}}$ , the value  $\mathbf{u}_\sigma^n$  is an expected approximation of the mean value over  $(t^{n-1}, t^n) \times D_\sigma$  of the velocity of a weak solution, while for  $K \in \mathcal{M}$  the value  $\varrho_K^n$  is an expected approximation of the mean value over  $(t^{n-1}, t^n) \times K$  of the density of a weak solution. To the discrete unknowns, we associate piecewise constant functions on time intervals and on primal or dual meshes, which are expected approximation of weak solutions, For the velocity, this constant function is of the form:

$$\mathbf{u}(t, \mathbf{x}) = \sum_{n=1}^N \sum_{\sigma \in \mathcal{E}_{\text{int}}} \mathbf{u}_\sigma^n \mathcal{X}_{D_\sigma}(\mathbf{x}) \mathcal{X}_{(t^{n-1}, t^n)}(t),$$

where  $\mathcal{X}_{(t^{n-1}, t^n)}$  is the characteristic function of the interval  $(t^{n-1}, t^n)$ . We denote by  $\mathbf{X}_{\mathcal{E}, \delta t}$  the set of such piecewise constant functions on time intervals and dual cells. For the density, the constant function is of the form:

$$\varrho(t, \mathbf{x}) = \varrho_K^n \text{ for } \mathbf{x} \in K \text{ and } t \in (t^{n-1}, t^n),$$

and we denote by  $Y_{\mathcal{M}, \delta t}$  the space of such piecewise constant functions.

For a given  $\mathbf{u} \in \mathbf{X}_{\mathcal{E}, \delta t}$  associated to the set of discrete velocity unknowns  $\{\mathbf{u}_\sigma^n, \sigma \in \mathcal{E}_{\text{int}}, n \in \{1, \dots, N\}\}$ , and for  $n \in \{1, \dots, N\}$ , we denote by  $\mathbf{u}^n \in \mathbf{S}_{\mathcal{E},0}(\Omega)$  the piecewise constant function defined by  $\mathbf{u}^n(\mathbf{x}) = \mathbf{u}_\sigma^n$  for  $\mathbf{x} \in D_\sigma, \sigma \in \mathcal{E}_{\text{int}}$ . In a same way, given  $\varrho \in Y_{\mathcal{M}, \delta t}$  associated to the discrete

density unknowns  $\{\varrho_K^n, K \in \mathcal{M}, n \in \{1, \dots, N\}\}$  we denote by  $\varrho^n \in L_{\mathcal{M}}$  the piecewise constant function defined by  $\varrho^n(\mathbf{x}) = \varrho_K^n$  for  $\mathbf{x} \in K, K \in \mathcal{M}$ .

We consider an implicit-in-time scheme, which reads in its fully discrete form, for  $1 \leq n \leq N$  and  $1 \leq i \leq d$ :

$$\frac{1}{\delta t}(\varrho^n - \varrho^{n-1}) + \operatorname{div}_{\mathcal{M}}^{\text{up}}(\varrho^n \mathbf{u}^n) = 0, \quad (\text{B.8a})$$

$$\begin{aligned} \frac{1}{\delta t}(\widehat{\varrho^n \mathbf{u}^n} - \widehat{\varrho^{n-1} \mathbf{u}^{n-1}}) + \operatorname{div}_{\mathcal{E}}(\varrho^n \mathbf{u}^n \otimes \mathbf{u}^n) - \mu \Delta_{\mathcal{E}} \mathbf{u}^n \\ - (\mu + \lambda) \nabla_{\mathcal{E}} \operatorname{div}_{\mathcal{M}} \mathbf{u}^n + \nabla_{\mathcal{E}} p(\varrho^n) = 0, \end{aligned} \quad (\text{B.8b})$$

where the terms introduced for each discrete equation are defined hereafter.

### B.1.1 Mass balance equation

As for the MAC scheme, equation (3.10a) is a finite volume discretization of the mass balance (1.1a) over the primal mesh. The discrete "upwind" divergence is defined by

$$\operatorname{div}_{\mathcal{M}}^{\text{up}} : \left\{ \begin{array}{l} S_{\mathcal{M}}(\Omega) \times \mathcal{S}_{\mathcal{E},0}(\Omega) \longrightarrow S_{\mathcal{M}}(\Omega) \\ (\varrho, \mathbf{u}) \longmapsto \operatorname{div}_{\mathcal{M}}^{\text{up}}(\varrho \mathbf{u}) = \sum_{K \in \mathcal{M}} \frac{1}{|K|} \sum_{\sigma \in \mathcal{E}(K)} F_{\sigma,K}(\varrho, \mathbf{u}) \chi_K, \end{array} \right. \quad (\text{B.9})$$

where  $F_{\sigma,K}(\varrho, \mathbf{u})$  stands for the mass flux across  $\sigma$  outward  $K$ , which, because of the Dirichlet boundary conditions, vanishes on external faces and is given on the internal faces by:

$$\forall \sigma = K|L \in \mathcal{E}_{\text{int}}, \quad F_{\sigma,K}(\varrho, \mathbf{u}) = |\sigma| \varrho_{\sigma}^{\text{up}} u_{\sigma,K}, \quad (\text{B.10})$$

where  $u_{\sigma,K}$  is an approximation of the normal velocity to the face  $\sigma$  outward  $K$ , defined by:

$$u_{\sigma,K} = \mathbf{u}_{\sigma} \cdot \mathbf{n}_{\sigma,K} \text{ for } \sigma \in \mathcal{E}(K). \quad (\text{B.11})$$

Thanks to the boundary conditions,  $u_{\sigma,K}$  vanishes for any external face  $\sigma$ . The density at the internal face  $\sigma = K|L$  is obtained by an upwind technique:

$$\varrho_{\sigma}^{\text{up}} = \begin{cases} \varrho_K & \text{if } u_{\sigma,K} \geq 0, \\ \varrho_L & \text{otherwise.} \end{cases} \quad (\text{B.12})$$

### B.1.2 The momentum equation

We now turn to the discrete momentum balances (3.10b), which are obtained by discretizing the momentum balance equation (1.1b) on the dual cells associated to the faces of the mesh.

**The discrete convective operator** - The discrete divergence of the convective term  $\varrho \mathbf{u} \otimes \mathbf{u}$  is defined by

$$\operatorname{div}_{\mathcal{E}} : \left\{ \begin{array}{l} S_{\mathcal{M}}(\Omega) \times \mathcal{S}_{\mathcal{E},0}(\Omega) \longrightarrow \mathcal{S}_{\mathcal{E},0}(\Omega) \\ (\varrho, \mathbf{u}) \longmapsto \operatorname{div}_{\mathcal{E}}(\varrho \mathbf{u} \otimes \mathbf{u}) = \sum_{\sigma \in \mathcal{E}_{\text{int}}} \frac{1}{|D_{\sigma}|} \sum_{\epsilon \in \tilde{\mathcal{E}}(D_{\sigma})} F_{\epsilon,\sigma}(\varrho, \mathbf{u}) \mathbf{u}_{\epsilon} \chi_{D_{\sigma}}, \end{array} \right. \quad (\text{B.13})$$

where for  $\sigma \in \mathcal{E}_{\text{int}}$  and  $\epsilon \in \mathcal{E}(D_{\sigma})$  the quantity  $F_{\epsilon,\sigma} = F_{\epsilon,\sigma}(\varrho, \mathbf{u})$  stands for a mass flux through the dual faces of the mesh and are defined hereafter while  $u_{\epsilon}$  stands for an approximation of  $i^{\text{th}}$  component of the velocity over  $\epsilon$  in the case of  $\sigma \in \mathcal{E}^{(i)}$ . First of all by virtue of the Dirichlet boundary condition, that the flux through a dual face included in the boundary is taken equal to zero. For  $K \in \mathcal{M}$  and  $\sigma \in \mathcal{E}(K)$ , let  $\xi_K^{\sigma}$  be given by:

$$\xi_K^{\sigma} = \frac{|D_{\sigma,K}|}{|K|}. \quad (\text{B.14})$$

With the definition of the dual mesh adopted here, the value of the coefficients  $\xi_K^\sigma$  is independent of the cell and the face. For the Rannacher-Turek elements, we have  $\xi_K^\sigma = 1/(2d)$  and, for the Crouzeix-Raviart elements,  $\xi_K^\sigma = 1/(d+1)$ . We suppose first that the flux through the external dual faces, which are also faces of the primal mesh, is equal to zero.

Then the mass fluxes through the inner dual faces are supposed to satisfy the following properties.

**Definition B.1** (Definition of the dual fluxes from the primal ones). *The fluxes through the faces of the dual mesh are defined so as to satisfy the following three constraints:*

(H1) *The discrete mass balance over the half-diamond cells is satisfied, in the following sense. For all primal cell  $K$  in  $\mathcal{M}$ , the set  $(F_{\epsilon,\sigma})_{\epsilon \subset K}$  of dual fluxes included in  $K$  solves the following linear system*

$$F_{\sigma,K} + \sum_{\epsilon \in \tilde{\mathcal{E}}(D_\sigma), \epsilon \subset K} F_{\epsilon,\sigma} = \xi_K^\sigma \sum_{\sigma' \in \mathcal{E}(K)} F_{\sigma',K}, \quad \sigma \in \mathcal{E}(K). \quad (\text{B.15})$$

(H2) *The dual fluxes are conservative, i.e. for any dual face  $\epsilon = D_\sigma|D_{\sigma'}$ , we have  $F_{\epsilon,\sigma} = -F_{\epsilon,\sigma'}$ .*

(H3) *The dual fluxes are bounded with respect to the primal fluxes  $(F_{\sigma,K})_{\sigma \in \mathcal{E}(K)}$ , in the sense that there exists a constant real number  $C$  such that:*

$$|F_{\epsilon,\sigma}| \leq C \max \{|F_{\sigma,K}|, \sigma \in \mathcal{E}(K)\}, \quad K \in \mathcal{M}, \sigma \in \mathcal{E}(K), \epsilon \in \tilde{\mathcal{E}}(D_\sigma), \epsilon \subset K. \quad (\text{B.16})$$

In fact, definition B.1 is not complete, since the system of equations (B.15) has an infinite number of solutions, which makes necessary to impose in addition the constraint (B.16); however, assumptions (H1)-(H3) are sufficient for the subsequent developments of this paper. A detailed process of the dual fluxes construction can be found in [1, 25].

Since the flux across a dual face lying on the boundary is zero, the values  $u_\epsilon$  are only needed at the internal dual faces, and we make the centered choice for their discretization, i.e. for  $\epsilon = D_\sigma|D_{\sigma'} \in \tilde{\mathcal{E}}_{\text{int}}$ ,

$$\mathbf{u}_\epsilon = \frac{\mathbf{u}_\sigma + \mathbf{u}_{\sigma'}}{2}. \quad (\text{B.17})$$

**The discrete divergence and gradient** - The discrete divergence  $\text{div}_{\mathcal{M}} \in \mathcal{L}(\mathcal{S}_{\mathcal{E},0}(\Omega), S_{\mathcal{M}}(\Omega))$  of the velocity (or more generally of a function  $\mathcal{S}_{\mathcal{E},0}(\Omega)$ ) has a natural approximation:

$$\text{for } K \in \mathcal{M}, \quad (\text{div}_{\mathcal{M}} \mathbf{u})_K = \frac{1}{|K|} \sum_{\sigma \in \mathcal{E}(K)} |\sigma| u_{\sigma,K}. \quad (\text{B.18})$$

The term  $(\nabla_{\mathcal{E}} p)_\sigma$  stands for the discrete pressure gradient at the face  $\sigma$ . This gradient operator, which belongs to  $\mathcal{L}(S_{\mathcal{M}}(\Omega), \mathcal{S}_{\mathcal{E},0}(\Omega))$  is built as the transpose of the discrete operator for the divergence of the velocity, i.e. in such a way that the following duality relation with respect to the  $L^2$  inner product holds:

$$\sum_{K \in \mathcal{M}} |K| p_K (\text{div}_{\mathcal{M}} \mathbf{u})_K + \sum_{\sigma \in \mathcal{E}_{\text{int}}} |D_\sigma| \mathbf{u}_\sigma \cdot (\nabla_{\mathcal{E}} p)_\sigma = 0. \quad (\text{B.19})$$

This yields to the following expression:

$$\text{for } \sigma = K|L \in \mathcal{E}_{\text{int}}, \quad (\nabla_{\mathcal{E}} p)_\sigma = \frac{|\sigma|}{|D_\sigma|} (p_L - p_K) \mathbf{n}_{\sigma,K}. \quad (\text{B.20})$$

Note that, because of the Dirichlet boundary conditions, the discrete gradient is not defined at the external faces.

**Discrete Laplace operator** - The discrete Laplace operator  $\Delta_{\mathcal{E}} \in \mathcal{L}(\mathcal{S}_{\mathcal{E},0}(\Omega), \mathcal{S}_{\mathcal{E},0}(\Omega))$  reads for  $\mathbf{u} \in \mathcal{S}_{\mathcal{E},0}(\Omega)$  and  $\sigma \in \mathcal{E}_{\text{int}}$ :

$$(-\Delta_{\mathcal{E}} \mathbf{u})_\sigma = \int_{\Omega} \nabla_{\mathcal{M}} \mathcal{P}_{\mathcal{E}}^{-1} \mathbf{u} : \nabla_{\mathcal{M}} \varphi_\sigma \, dx,$$

where  $\varphi_\sigma = (\varphi_\sigma, \dots, \varphi_\sigma) \in \mathbf{W}_{\mathcal{E},0}(\Omega)$ , where the shape function  $\varphi_\sigma$  is introduced in (B.5) and where  $\mathcal{P}_{\mathcal{E}}$  is defined in (B.6). In the above formula and for a function  $\mathbf{v} \in \mathbf{W}_{\mathcal{E},0}(\Omega)$ , the quantity  $\nabla \mathbf{v}$  is equal to the gradient of the function  $\mathbf{v}$  almost everywhere in  $\Omega$ .



Here again let us introduce the discrete relative energy functional

$$\mathcal{E}(\varrho^n, \mathbf{u}^n | r_{\mathcal{M}}^n, \mathbf{U}_{\mathcal{E}}^n) = \sum_{\sigma \in \mathcal{E}_{\text{int}}} \frac{1}{2} |D_{\sigma}| \varrho_{D_{\sigma}}^n |\mathbf{u}_{\sigma}^n - \mathbf{U}_{\sigma}^n|^2 + \sum_{K \in \mathcal{M}} |K| E(\varrho_K^n | r_K^n) \quad (\text{B.21})$$

where

$$r^n = r(t^n, \cdot), \quad \mathbf{U}^n = \mathbf{U}(t^n, \cdot), \quad r_K^n = \frac{1}{|K|} \int_K r^n \, d\mathbf{x}, \quad \mathbf{U}_{\sigma}^n = \frac{1}{|\sigma|} \int_{\sigma} \mathbf{U}^n \, d\gamma. \quad (\text{B.22})$$

Now, we are ready to state the result about the error estimate for these alternative discretizations.

**Theorem B.1** (Error estimate). *Let  $\Omega \subset \mathbb{R}^3$  be a bounded polyhedral domain. Assume that the viscosity coefficients satisfy assumptions (1.4) and that the pressure  $p$  satisfy (1.5). Let  $\mathcal{M}$  be a decomposition of the domain  $\Omega$  in simplices, with step size  $h_{\mathcal{M}}$  (see (B.1)) and regularity  $\theta_{\mathcal{M}}$  where  $\theta_{\mathcal{M}}$  is defined in (B.2). Let us consider a partition  $0 = t^0 < t^1 < \dots < t^N = T$  of the time interval  $[0, T]$ , which, for the sake of simplicity, we suppose uniform where  $\delta t$  stands for the constant time step. Let  $(\varrho, \mathbf{u}) \in Y_{\mathcal{M}, \delta t} \times \mathbf{X}_{\mathcal{E}, \delta t}$  be a solution of the discrete problem (B.8) emanating from  $(\varrho^0, \mathbf{u}^0) \in S_{\mathcal{M}}(\Omega) \times \mathcal{S}_{\mathcal{E}, 0}(\Omega)$  such that  $\varrho^0 > 0$  and  $(r, \mathbf{U}) \in \mathcal{F}$  (see (3.73)) be a (strong) solution of problem (1.1)-(1.5). Then there exists a constant  $c > 0$  only depending on  $T, \Omega, p_0, p_{\infty}, \mu, \gamma, \alpha, \underline{\tau}, \min_{[\underline{\tau}, \bar{\tau}]} p, \min_{[\underline{\tau}/2, 2\bar{\tau}]} p', \text{on } \|(r, \mathbf{U})\|_{\mathcal{F}}$  in a nondecreasing way, on  $\mathcal{E}_{0, \mathcal{M}}$  in a nondecreasing way and on  $\theta_{\mathcal{M}}$  in a nonincreasing way such that*

$$\max_{0 \leq n \leq N} \mathcal{E}(\varrho^n, \mathbf{u}^n | r_{\mathcal{M}}^n, \mathbf{U}_{\mathcal{E}}^n) \leq c \left( \mathcal{E}(\varrho^0, \mathbf{u}^0 | r_{\mathcal{M}}^0, \mathbf{U}_{\mathcal{E}}^0) + h_{\mathcal{M}}^A + \sqrt{\delta t} \right), \quad (\text{B.23})$$

where  $A$  is given by

$$A = \min\left(\frac{2\gamma - 3}{\gamma}, \frac{1}{2}\right). \quad (\text{B.24})$$

**Remark 4.** 1. *The discrete problem (B.8) admits a solution. As for the MAC case, the proof is based on a topological degree argument.*

2. *Note that the exponent  $A$  is the same for all discretizations investigated in this paper.*

*does not differ from the discretization used. It is a consequence of the used for the continuity equation which is the same for each discretization.*

3. *The items listed in Remark 2 remain valid also for discretizations described in this section.*

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