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Stability of the $\mathbf{P}_{nc}^1 - (P^0 + P^1)$ element

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1 Stokes problem

A popular low-order method for solving the Stokes problem is the nonconforming Crouzeix-Raviart mixed finite element method [1, Example 4] (cf. [2, 3] for higher orders). The discrete velocity is piecewise affine, continuous in the barycentre of the interfaces between elements, but not globally continuous, \mathbf{P}_{nc}^1 ; and the discrete pressure is piecewise constant, P^0 . This method introduces some consistency error on the discrete velocity, which may lead to an unphysical solution when solving the Navier-Stokes equations, especially when the source field is a strong gradient [4, 5]. To recover consistency, the discrete pressure space can be generated by P^1 -continuous plus P^0 basis functions, cf. the TrioCFD code [6, 7]. This leads to the $\mathbf{P}_{nc}^1 - (P^0 + P^1)$ mixed finite element method, which exhibits interesting numerical features. However, only an incomplete proof of the stability is available in [8, 9]. Our goal here is to gather evidence regarding the inf-sup condition. Let us consider Stokes problem set in an open, bounded, connected subset Ω of \mathbb{R}^d , $d = 2, 3$, with a Lipschitz boundary $\partial\Omega$:

$$\text{Find } (\mathbf{u}, p) \text{ such that } -\nu \Delta \mathbf{u} + \nabla p = \mathbf{f} \text{ and } \operatorname{div} \mathbf{u} = 0 \text{ in } \Omega. \quad (1)$$

with Dirichlet boundary conditions for the velocity \mathbf{u} and a normalisation condition for the pressure p : $\mathbf{u} = 0$ on $\partial\Omega$, $\int_{\Omega} p = 0$. Given D an open subset of \mathbb{R}^d , let

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us set $\mathbf{L}^2(D) = (L^2(D))^d$, and $L^2_{zmv}(D) = \{q \in L^2(D) \mid \int_D q = 0\}$. We denote by $(\cdot, \cdot)_D$ the $L^2(D)$ or $\mathbf{L}^2(D)$ scalar product, and $\|\cdot\|_D$ the associated norm. Let $\mathbf{H}_0^1(D) = (H_0^1(D))^d$, and $\mathbf{H}^{-1}(D) = (H^{-1}(D))^d$ its dual space. Due Poincaré-Steklov inequality [10, Lemma 3.24], the semi-norm in $H_0^1(\Omega)$ is equivalent to the natural norm, so that $(v, w)_{H_0^1(\Omega)} = (\nabla v, \nabla w)_\Omega$ and $\|v\|_{H_0^1(\Omega)} = \|\nabla v\|_\Omega$. Let $\mathbf{v} \in \mathbf{H}_0^1(\Omega)$. We denote by $(v_i)_{i=1}^d$ the components of \mathbf{v} , and we set $\underline{\nabla} \mathbf{v} = (\partial_j v_i)_{i,j=1}^d \in [L^2(\Omega)]^{d \times d}$. Let us set $\mathbf{V} = \{\mathbf{v} \in \mathbf{H}_0^1(\Omega) \mid \operatorname{div} \mathbf{v} = 0\}$ which is a closed subset of $\mathbf{H}_0^1(\Omega)$. We denote by \mathbf{V}^\perp the orthogonal of \mathbf{V} in $\mathbf{H}_0^1(\Omega)$.

Proposition 1 *The operator $\operatorname{div} : \mathbf{H}_0^1(\Omega) \rightarrow L^2(\Omega)$ is an isomorphism of \mathbf{V}^\perp onto $L^2_{zmv}(\Omega)$. We call $C_{\operatorname{div}} > 1$ the constant such that: $\forall p \in L^2_{zmv}(\Omega), \exists ! \mathbf{v}_p \in \mathbf{V}^\perp \mid \operatorname{div} \mathbf{v}_p = p$ and $\|\mathbf{v}_p\|_{\mathbf{H}_0^1(\Omega)} \leq C_{\operatorname{div}} \|p\|_\Omega$ [11, Theorem 3.1 (e)].*

Let $\mathbf{f} \in \mathbf{H}^{-1}(\Omega)$. The variational formulation of Problem (1) reads:
Find $(\mathbf{u}, p) \in \mathbf{H}_0^1(\Omega) \times L^2_{zmv}(\Omega)$ such that $\forall (\mathbf{v}, q) \in \mathbf{H}_0^1(\Omega) \times L^2_{zmv}(\Omega)$:

$$v(\mathbf{u}, \mathbf{v})_{\mathbf{H}_0^1(\Omega)} - (p, \operatorname{div} \mathbf{v})_\Omega - (q, \operatorname{div} \mathbf{u})_\Omega = \langle \mathbf{f}, \mathbf{v} \rangle_{\mathbf{H}_0^1(\Omega)}. \quad (2)$$

One can prove that Problem (2) is well-posed with the T-coercivity theory [12, 13, 14], using Poincaré-Steklov inequality [10, Lemma 3.24] and Proposition 1.

2 Discretization

Consider $(\mathcal{T}_h)_h$ a family of simplicial triangulations of Ω . For a given $\mathcal{T}_h := \{K\}$, we call $\mathcal{F}_h := \{F\}$ its set of $(d-1)$ -simplices, called facets (faces if $d=3$, edges if $d=2$), and $\mathcal{V}_h := \{S\}$ its set of vertices. In the bounds, we will use \lesssim and \gtrsim for (hidden) constants independent of \mathcal{T}_h .

- For all $K \in \mathcal{T}_h$, we call h_K and ρ_K the diameters of K and its inscribed sphere respectively, and we let: $\sigma_K = \frac{h_K}{\rho_K}$. When the $(\mathcal{T}_h)_h$ is a shape-regular triangulation family (see e.g. [10, def. 11.2]), there exists a constant $\sigma > 1$, called the shape regularity parameter, such that for all h , for all $K \in \mathcal{T}_h$, $\sigma_K \leq \sigma$.
- Let $\mathcal{F}_h = \mathcal{F}_h^i \cup \mathcal{F}_h^b$, where $\mathcal{F}_h^b := \{F \in \mathcal{F}_h \mid F \subset \partial\Omega\}$, $\mathcal{F}_h^i = \mathcal{F}_h \setminus \mathcal{F}_h^b$. For all $K \in \mathcal{T}_h$, we set $\mathcal{F}_K^i = \{F \in \mathcal{F}_h^i \mid F \subset \partial K\}$.

For all $F \in \mathcal{F}_h$, M_F denotes the barycentre of F , and \mathbf{n}_F its unit normal (outward oriented if $F \subset \partial\Omega$). For all $K \in \mathcal{T}_h$ and $F \subset \partial K$, we denote by $\mathbf{n}_{F,K}$ the normal vector of F outgoing from K . Let \hat{K} be the reference simplex. For all $K \in \mathcal{T}_h$, we denote by $T_K : \hat{K} \rightarrow K$ the geometric mapping such that $\forall \hat{\mathbf{x}} \in \hat{K}$, $\mathbf{x}_{|K} = T_K(\hat{\mathbf{x}}) = \mathbb{B}_K \hat{\mathbf{x}} + \mathbf{b}_K$, where $\mathbb{B}_K \in \mathbb{R}^{d \times d}$ and $\mathbf{b}_K \in \mathbb{R}^d$. Let us set $J_K = \det(\mathbb{B}_K)$. Recall that [10, Lemma 11.1]: $|J_K| = |K|/|\hat{K}|$, $\|\mathbb{B}_K\| \leq h_K/\rho_{\hat{K}}$, $\|\mathbb{B}_K^{-1}\| \leq h_{\hat{K}}/\rho_K$. For all $v \in L^2(\Omega)$, we set: $v_K = v|_K$, $\underline{v}_K = \int_K v / |K|$, $\tilde{v}_K = v_K - \underline{v}_K$, $\hat{v}_K = v \circ T_K$. By changing the variable, we get: $\|v\|_K^2 = |J_K| \|\hat{v}_K\|_{\hat{K}}^2$. Let $v \in H^1(K)$. By changing the variable, we get: $\nabla v|_K = (\mathbb{B}_K^{-1})^T \nabla_{\hat{\mathbf{x}}} \hat{v}$, and $\|\nabla v\|_K^2 \leq \|\mathbb{B}_K^{-1}\|^2 |J_K| \|\nabla_{\hat{\mathbf{x}}} \hat{v}\|_{\hat{K}}^2$,

$$\|\nabla_{\hat{\mathbf{x}}}\hat{v}\|_{\hat{K}}^2 \leq \|\mathbb{B}_K\|^2 |J_K|^{-1} \|\nabla v\|_K^2.$$

We set $\mathcal{P}_h H^1 = \{v \in L^2(\Omega); \forall K \in \mathcal{T}_h, v|_K \in H^1(K)\}$, endowed with: $(v, w)_h := \sum_{K \in \mathcal{T}_h} (\nabla v, \nabla w)_K$, $\|v\|_h^2 = \sum_{K \in \mathcal{T}_h} \|\nabla v\|_K^2$. We define the operator ∇_h such that: $\forall q \in \mathcal{P}_h H^1$, $\nabla_h q \in \mathbf{L}^2(\Omega)$ is such that $\forall \mathbf{v} \in \mathbf{L}^2(\Omega)$, $(\nabla_h q, \mathbf{v})_\Omega = \sum_{K \in \mathcal{T}_h} (\nabla q, \mathbf{v})_K$. Let $K \in \mathcal{T}_h$ and $F \subset \partial K$, we denote by $T_{F,K}$ the geometric mapping such that $\forall \mathbf{x} \in F$, $T_{F,K}(T_K^{-1}(\mathbf{x})) = \mathbf{x}$. We let $\hat{F}_{F,K} = T_K^{-1}(F)$. For all $v \in \mathcal{P}_h H^1$, for all $K \in \mathcal{T}_h$ and for all $F \subset \partial K$, we set: $v_{F,K} = (v|_K)|_F$, $\underline{v}_{F,K} = \int_F v|_K / |F|$, $\tilde{v}_{F,K} = v|_K - \underline{v}_{F,K}$, $\hat{v}_{F,K} = v \circ T_{F,K}$. By changing the variable, we get $\|v_{F,K}\|_F^2 = (|F|/|\hat{F}_{F,K}|) \|\hat{v}_{F,K}\|_{\hat{F}_{F,K}}^2$. According to Equation [1, (3.17)], it holds:

$$\forall K \in \mathcal{T}_h, \forall F \subset \partial K, \quad |F| |K|^{-1} \lesssim \rho_K^{-1}. \quad (3)$$

We set $\mathcal{P}_h \mathbf{H}^1 = [\mathcal{P}_h H^1]^d$ and for all $\mathbf{v} \in \mathcal{P}_h \mathbf{H}^1$: $\underline{\nabla}_h \mathbf{v} = ((\nabla_h v_i)^T)_{i=1}^d \in [L^2(\Omega)]^{d \times d}$.

Let $F \in \mathcal{F}_h^i$ such that $F = \partial K_L \cap \partial K_R$ and $\mathbf{n}_F = \mathbf{n}_{F,K_L}$. The jump of $v \in \mathcal{P}_h H^1$ across F is defined by: $[v]_F := v|_{K_L} - v|_{K_R}$. For $F \in \mathcal{F}_h^b$, we set: $[v]_F := v|_F$.

For a subset D of \mathbb{R}^d , for $k \in \mathbb{N}$, we call $P^k(D)$ the set of degree k polynomials on D , $\mathbf{P}^k(D) = (P^k(D))^d$, and $\mathcal{P}_{disc}^k(\mathcal{T}_h) = \{q \in L^2(\Omega); \forall K \in \mathcal{T}_h, q|_K \in P^k(K)\}$.

For $k > 0$ we define $\mathcal{P}^k(\mathcal{T}_h) = C^0(\overline{\Omega}) \cap \mathcal{P}_{disc}^k(\mathcal{T}_h)$. We call $\pi_0 : L^2(\Omega) \mapsto \mathcal{P}_{disc}^0(\mathcal{T}_h)$ the L^2 -orthogonal projection onto $\mathcal{P}_{disc}^0(\mathcal{T}_h)$, such that $\forall q \in L^2(\Omega)$, $\pi_0(q) = \sum_{K \in \mathcal{T}_h} \pi_0(q)(K) \mathbb{1}_K$ where $\forall K \in \mathcal{T}_h$, $\pi_0(q)(K) = \int_K q / |K|$.

For $K \in \mathcal{T}_h$ and a vertex S of K , $\lambda_{S,K}$ denotes the barycentric coordinate related to S . We can endow $\mathcal{P}^1(\mathcal{T}_h)$ with the basis $(\phi_S)_{S \in \mathcal{V}_h}$ such that: $\forall K \in \mathcal{T}_h$, $\phi_S|_K = \lambda_{S,K}$ if $S \in K$, zero otherwise, so that $\mathcal{P}^1(\mathcal{T}_h) = \text{vect}((\phi_S)_{S \in \mathcal{V}_h})$.

Let $k \in \mathbb{N}^*$, $v \in H^1(K) \cap P^k(K)$. Using the discrete trace inequality [15, Thm. 5] and Poincaré-Steklov inequality [10, Lemma 12.11], we have:

$$\|(\widehat{v}_{F,K})_{F,K}\|_{\hat{F}_{F,K}}^2 \lesssim \|(\widehat{v}_{F,K})_K\|_{\hat{K}}^2 \lesssim \|\nabla_{\hat{\mathbf{x}}}\hat{v}_K\|_{\hat{K}}^2. \quad (4)$$

Proposition 2 For all $K \in \mathcal{T}_h$, $\forall v \in H^1(K) \cap P^1(K)$, $\|\nabla v\|_K \lesssim (\rho_K)^{-1} \|\tilde{v}\|_K$.

Proof. We follow the proof of [16, Lemma 2]: changing the variable, we have $\|\nabla v\|_{L^2(K)} \lesssim \|\mathbb{B}_K^{-1}\| |K|^{1/2} \|\int_{\hat{K}} \nabla_{\hat{\mathbf{x}}}\hat{v}_K\|$. Integrating by parts in the reference element, it holds: $|\int_{\hat{K}} \nabla_{\hat{\mathbf{x}}}\hat{v}_K| = |\int_{\partial \hat{K}} \hat{v}_K \hat{\mathbf{n}}|_{\partial \hat{K}}$. We get the result using Cauchy-Schwarz, [15, Thm. 5] and changing the variable again. \square

We set $\mathcal{P}_h \mathbf{H}(\text{div}) = \{\mathbf{v} \in \mathbf{L}^2(\Omega); \forall K \in \mathcal{T}_h, \mathbf{v}|_K \in \mathbf{H}(\text{div}; K)\}$.

We define the operator div_h such that: $\forall \mathbf{v} \in \mathcal{P}_h \mathbf{H}(\text{div})$, $\text{div}_h \mathbf{v} \in L^2(\Omega)$ is such that $\forall q \in L^2(\Omega)$, $(\text{div}_h \mathbf{v}, q)_\Omega = \sum_{K \in \mathcal{T}_h} (\text{div} \mathbf{v}, q)_K$.

Let $\mathbf{X}_{0,h}$ be the space of the discrete velocity of the nonconforming Crouzeix-Raviart mixed finite element method, defined by:

$$\begin{aligned} \mathbf{X}_h &= (X_h)^d, \quad X_h = \{v_h \in \mathcal{P}_{disc}^1(\mathcal{T}_h); \forall F \in \mathcal{F}_h^i, \int_F [v_h] = 0\}; \\ \mathbf{X}_{0,h} &= (X_{0,h})^d, \quad X_{0,h} = \{v_h \in X_h; \forall F \in \mathcal{F}_h^b, \int_F v_h = 0\}. \end{aligned} \quad (5)$$

The condition on the jumps of v_h on the inner facets is often called the patch-test condition. Due to this condition, one can prove that [1, Lemma 2]:

Proposition 3 *The broken norm $v_h \rightarrow \|v_h\|_h$ is a norm over $X_{0,h}$.*

For all $K \in \mathcal{T}_h$, for all $F \subset \partial K$, $\lambda_{F,K}$ denotes the barycentric coordinate related to the vertex $S_{F,K}$ opposite to facet F in K . We can endow X_h with the basis $(\psi_F)_{F \in \mathcal{F}_h}$ such that for all $K \in \mathcal{T}_h$, $\psi_{F|K} = 1 - d\lambda_{F,K}$ if $F \subset \partial K$ and zero otherwise. We then have $\psi_{F|F} = 1$, so that $[\psi_F]_F = 0$ if $F \in \mathcal{F}_h^i$, and for all $F' \neq F$, $\int_{F'} \psi_F = 0$. We have: $X_h = \text{vect}((\psi_F)_{F \in \mathcal{F}_h})$ and $X_{0,h} = \text{vect}((\psi_F)_{F \in \mathcal{F}_h^i})$.

Let $\Pi_h : \mathbf{H}^1(\Omega) \mapsto \mathbf{X}_h$ be the Crouzeix-Raviart interpolation operator, such that: $\forall \mathbf{v} \in \mathbf{H}^1(\Omega)$, $\Pi_h(\mathbf{v}) = \sum_{F \in \mathcal{F}_h} \Pi_F \mathbf{v} \psi_F$, $\Pi_F \mathbf{v} = \underline{\mathbf{v}}_F = \int_F \mathbf{v} / |F|$.

Proposition 4 *The interpolation operator Π_h is such that [16, Lemma 2]: $\forall \mathbf{v}_h \in \mathbf{H}_0^1(\Omega)$, $\|\Pi_h(\mathbf{v}_h)\|_h \leq \|\mathbf{v}_h\|_{\mathbf{H}_0^1(\Omega)}$.*

However, due to the consistency error on the discrete velocity, it is well-known [17, 18] that choosing the space of the discrete pressures equal to $\mathcal{P}_{disc}^0(\mathcal{T}_h) \cap L_{zmv}^2(\Omega)$ yields inaccurate results when solving Navier-Stokes equations. Starting from [19], a new element is proposed in [8]. The space of the discrete pressures is then: $Q_h = Q_{0,h} + Q_{1,h}$, where $Q_{0,h} := \mathcal{P}_{disc}^0(\mathcal{T}_h) \cap L_{zmv}^2$ and for $k > 0$, $Q_{k,h} := \mathcal{P}^k(\mathcal{T}_h) \cap L_{zmv}^2(\Omega)$. One can build an L^2 -orthogonal sum letting $\tilde{Q}_{1,h} = \{q_h \in Q_h \mid \forall K \in \mathcal{T}_h, \int_K q_h = 0\}$.

Proposition 5 *We have: $Q_h = Q_{0,h} \oplus \tilde{Q}_{1,h}$. Let $q_h \in Q_h$ and $\tilde{q}_{1,h} := q_h - \pi_0(q_h)$, it holds: $\|q_h\|_Q^2 = \|\pi_0(q_h)\|_\Omega^2 + \|\tilde{q}_{1,h}\|_\Omega^2$.*

To prove the discrete inf-sup condition of $\mathbf{X}_{0,h} \times Q_h$, we need some Lemmas.

Lemma 1 *Let $k \in \mathbb{N}^*$ and $(\mathbf{v}_h, q_{k,h}) \in \mathbf{X}_{0,h} \times Q_{k,h}$. We then have:*

$$|\sum_{K \in \mathcal{T}_h} \sum_{F \subset \partial K} (\mathbf{v}_h \cdot \mathbf{n}_{F,K}, q_{k,h})_F| \lesssim \sigma \|\mathbf{v}_h\|_h \|\tilde{q}_{k,h}\|_\Omega. \quad (6)$$

Proof. We start with the proof of [19, Lemma 3.1]. Using the patch-test, one obtains:

$$\sum_{K \in \mathcal{T}_h} \sum_{F \subset \partial K} (\mathbf{v}_h \cdot \mathbf{n}_{F,K}, q_{k,h}|_K)_F = \sum_{K \in \mathcal{T}_h} \sum_{F \subset \partial K} (\tilde{\mathbf{v}}_{F,K} \cdot \mathbf{n}_{F,K}, \tilde{q}_{k,h}|_K)_F.$$

We can compute the following estimates, using (4) twice and (3):

$$|(\tilde{\mathbf{v}}_{F,K} \cdot \mathbf{n}_{F,K}, \tilde{q}_{k,h}|_K)_F| \lesssim |F| \|\widehat{\tilde{\mathbf{v}}}_{F,K}\|_{\hat{F}_{F,K}} \|\widehat{(\tilde{q}_{k,h})}_K\|_{\hat{F}_{F,K}} \lesssim \sigma_K \|\underline{\mathbf{v}}_h\|_K \|\tilde{q}_{k,h}\|_K.$$

Summing and using the discrete Cauchy-Schwarz inequality, we obtain (6). \square

Let us set $\mathbf{X}_{N,h} := \{\mathbf{v}_h \in \mathbf{X}_{0,h} \mid \forall F \in \mathcal{F}_h^i, \mathbf{v}_h \times \mathbf{n}_F = 0\}$. We can build an explicit right inverse of div_h from Q_h to $\mathbf{X}_{N,h}$.

Lemma 2 *For all $q_h \in Q_h$, there exists $\mathbf{v}_{N,h} \in \mathbf{X}_{N,h}$ such that:*

$$-(\text{div}_h \mathbf{v}_{N,h}, \pi_0(q_h))_\Omega = v^{-1} \|\pi_0(q_h)\|_\Omega^2, \quad (7)$$

$$\|\mathbf{v}_{N,h}\|_h \leq C_{\text{div}} v^{-1} \|\pi_0(q_h)\|_\Omega. \quad (8)$$

Proof. Let $q_h \in Q_h$. From Proposition 1, $\exists \mathbf{v}_N \in \mathbf{H}_0^1(\Omega) \mid \operatorname{div} \mathbf{v}_N = -\nu^{-1} \pi_0(q_h)$ and $\|\mathbf{v}_N\|_{\mathbf{H}_0^1(\Omega)} \leq C_{\operatorname{div}} \nu^{-1} \|\pi_0(q_h)\|_{\Omega}$. Let $\mathbf{v}_{N,h} \in \mathbf{X}_{N,h} \mid \forall F \in \mathcal{F}_h^i, \mathbf{v}_{N,h}(M_F) = (\Pi_h(\mathbf{v}_N))(M_F) \cdot \mathbf{n}_F \mathbf{n}_F$. Integrating by part twice, we get: $\forall K \in \mathcal{T}_h, \int_K \operatorname{div} \mathbf{v}_{N,h} = \int_K \operatorname{div} \mathbf{v}_N$, hence (7). Using Proposition 4, we get (8). \square

We can also build an explicit right inverse of the discrete divergence operator from $Q_{1,h}$ to $\mathbf{X}_{T,h} := \{\mathbf{v}_h \in \mathbf{X}_{0,h} \mid \forall F \in \mathcal{F}_h^i, \mathbf{v}_h \cdot \mathbf{n}_F = 0\}$, if [19, Hyp. 4.1] holds:

Hypothesis 1. *We suppose that \mathcal{T}_h is such that $\partial\Omega$ contains at most one edge for $d = 2$ and at most two facets for $d = 3$, of the same element $K \in \mathcal{T}_h$.*

Lemma 3 *Assuming Hypothesis 1, $\forall q_{1,h} \in Q_{1,h}, \exists \mathbf{v}_{T,h} \in \mathbf{X}_{T,h}$ such that:*

$$(\nabla q_{1,h}, \mathbf{v}_{T,h})_{\Omega} \gtrsim \nu^{-1} \sigma^{-2(d-2)} \|\tilde{q}_{1,h}\|_{\Omega}^2, \quad (9)$$

$$(\operatorname{div} \mathbf{v}_{T,h}, q_{0,h})_K = 0 \quad \forall q_{0,h} \in Q_{0,h}, \quad (10)$$

$$\|\mathbf{v}_{T,h}\|_h \lesssim \nu^{-1} \sigma^2 \|\tilde{q}_{1,h}\|_{\Omega}. \quad (11)$$

Proof. Let us consider $q_{1,h} \in Q_{1,h}$. For all $K \in \mathcal{T}_h$, we let $q_K := q_{1,h}|_K$ and $\hat{q}_K = q_K \circ T_K$. Since $q_{1,h} \in H^1(\Omega)$ we have (see e.g. [20, Prop. 2.2.10]): $\forall F \in \mathcal{F}_h^i \mid F = K \cap K', \nabla q_K \times \mathbf{n}_F = \nabla q_{K'} \times \mathbf{n}_F$. We construct $\mathbf{v}_{T,h} \in \mathbf{X}_{T,h} \mid \forall F \in \mathcal{F}_h^i, \mathbf{v}_{T,h}(M_F) = \nu^{-1} h_F^2 \mathbf{n}_F \times (\nabla q_{1,h} \times \mathbf{n}_F)$, where h_F is the diameter of F . We have $\forall K \in \mathcal{T}_h$:

$$(\nabla q_{1,h}, \mathbf{v}_{T,h})_K = \nu^{-1} \frac{|K|}{d+1} \sum_{F \in \mathcal{F}_K^i} h_F^2 |\nabla q_K \times \mathbf{n}_F|^2. \quad (12)$$

Let $\mathbf{n}_{\hat{F}_{F,K}}$ be the unit normal vector of the facet $\hat{F}_{F,K}$ outgoing from \hat{K} . We have: $\mathbf{n}_{F,K} = |K| (\mathbb{B}_K^{-1})^T |\hat{F}_{F,K}| |F|^{-1} \mathbf{n}_{\hat{F}_{F,K}}$.

Consider $d = 2$. Changing the variable, assuming Hypothesis 1, we get:

$$\sum_{F \in \mathcal{F}_K^i} h_F^2 |\nabla q_K \times \mathbf{n}_F|^2 = \sum_{F \in \mathcal{F}_K^i} |\hat{F}_{F,K}|^2 |\nabla_{\hat{\mathbf{x}}} \hat{q}_K \times \mathbf{n}_{\hat{F}_{F,K}}|^2 \gtrsim |\nabla_{\hat{\mathbf{x}}} \hat{q}_K|^2. \quad (13)$$

Consider $d = 3$. It holds that $|\nabla q_K \times \mathbf{n}_F| = |\hat{F}_{F,K}| |F|^{-1} |\mathbb{B}_K \nabla_{\hat{\mathbf{x}}} \hat{q}_K \times \mathbf{n}_{\hat{F}_{F,K}}|$ changing the variable. Hence: $|\nabla q_K \times \mathbf{n}_F| \gtrsim |F|^{-1} \|\mathbb{B}_K^{-1}\|^{-1} |\nabla_{\hat{\mathbf{x}}} \hat{q}_K \times \mathbf{n}_{\hat{F}_{F,K}}|$. Notice that $h_F |F|^{-1} \|\mathbb{B}_K^{-1}\|^{-1} \gtrsim \sigma_K^{-1}$. Assuming Hypothesis 1, we then have:

$$\sum_{F \in \mathcal{F}_K^i} h_F^2 |\nabla q_K \times \mathbf{n}_F|^2 \gtrsim \sigma_K^{-2} |\nabla_{\hat{\mathbf{x}}} \hat{q}_K|^2. \quad (14)$$

Using Poincaré-Steklov inequality [10, Lemma 12.11] in \hat{K} , we have: $|\nabla_{\hat{\mathbf{x}}} \hat{q}_K|^2 \gtrsim \|\hat{q}_K - \underline{\hat{q}}_K\|_{\hat{K}}^2$. Using (13) and (14) in (12), it holds:

$$(\nabla q_{1,h}, \mathbf{v}_{T,h})_K \gtrsim \nu^{-1} \sigma_K^{-2(d-2)} |K| |\nabla_{\hat{\mathbf{x}}} \hat{q}_K|^2 \gtrsim \nu^{-1} \sigma_K^{-2(d-2)} \|\tilde{q}_K\|_{\hat{K}}^2. \quad (15)$$

We obtain (9) by summation. Remark that $\nabla \psi_{F|K} = |K|^{-1} |F| \mathbf{n}_{F,K}$. Let us prove (10). Since $\nabla \psi_{F|K} \perp \mathbf{v}_{T,h}(M_F)$, $(\operatorname{div} \mathbf{v}_{T,h}, q_{0,h})_K = |K| q_{0,h}(K) \sum_{F \in \mathcal{F}_K^i} \nabla \psi_{F|K} \cdot \mathbf{v}_{T,h}(M_F) = 0$. Let us prove (11). For all $K \in \mathcal{T}_h$, $\underline{\mathbf{v}}_{T,h|K} = \sum_{F \in \mathcal{F}_K^i} \mathbf{v}_{T,h}(M_F) \otimes$

$\nabla\psi_{F|K}$. Hence: $\|\underline{\nabla}\mathbf{v}_{T,h}\|_K^2 \lesssim \nu^{-2} \sum_{F \in \mathcal{F}_K^i} |F|^2 |K|^{-1} h_F^4 |\nabla q_K \times \mathbf{n}_F|^2$. Using (3), and assuming Hypothesis 1, we get: $\|\underline{\nabla}\mathbf{v}_{T,h}\|_K^2 \lesssim \nu^{-2} \sigma_K^2 h_K^2 |K| \sum_{F \in \mathcal{F}_K^i} |\nabla q_K \times \mathbf{n}_F|^2 \lesssim \nu^{-2} \sigma_K^2 h_K^2 \|\nabla q_K\|_K^2$. From Proposition 2: $\|\underline{\nabla}\mathbf{v}_{T,h}\|_K \lesssim \nu^{-1} \sigma_K^2 \|\tilde{q}_K\|_K$. \square

Let $b_h : \mathbf{X}_h \times \mathcal{Q}_h \mapsto \mathbb{R} \mid \forall (\mathbf{v}_h, q_h) \in \mathbf{X}_h \times \mathcal{Q}_h, b_h(\mathbf{v}_h, q_h) = -(\operatorname{div}_h \mathbf{v}_h, q_{0,h})_\Omega + (\mathbf{v}_h, \nabla q_{1,h})_\Omega$ with $q_h = q_{0,h} + q_{1,h}$ such that $(q_{0,h}, q_{1,h}) \in \mathcal{Q}_{0,h} \times \mathcal{Q}_{1,h}$.

Theorem 1 *The following continuity property holds:*

$$\forall (\mathbf{v}_h, q_h) \in \mathbf{X}_{0,h} \times \mathcal{Q}_h, \quad |b_h(\mathbf{v}_h, q_h)| \lesssim \sigma \|\mathbf{v}_h\|_h \|q_h\|_\Omega. \quad (16)$$

Assuming Hypothesis 1, the following inf-sup condition holds:

$$\forall q_h \in \mathcal{Q}_h, \exists \mathbf{v}_h \in \mathbf{X}_{0,h}, \quad b_h(\mathbf{v}_h, q_h) \gtrsim \frac{1}{\sqrt{2}} C_{\operatorname{div}}^{-2} \sigma^{-2d} \|\mathbf{v}_h\|_h \|q_h\|_\Omega. \quad (17)$$

Proof. Let us prove (16). Let $(\mathbf{v}_h, q_h) \in \mathbf{X}_{0,h} \times \mathcal{Q}_h$. Integrating by parts, we have:

$$b_h(\mathbf{v}_h, q_h) = -(\operatorname{div}_h \mathbf{v}_h, \pi_0(q_h))_\Omega + \sum_{K \in \mathcal{T}_h} \sum_{F \subset \partial K} (\mathbf{v}_h \cdot \mathbf{n}_{F,K}, q_{1,h})_F. \quad (18)$$

Using Cauchy-Schwarz, we have: $|(\operatorname{div}_h \mathbf{v}_h, \pi_0(q_h))_\Omega| \leq \sqrt{d} \|\mathbf{v}_h\|_h \|\pi_0(q_h)\|_\Omega$. Using (6) in (18), we obtain (16) from Proposition 5. Let us prove (17), starting from the proof of [19, Lemma 4.2]. Let $q_h \in \mathcal{Q}_h \setminus \{0\}$, where $q_h = q_{0,h} + q_{1,h}$ is such that $(q_{0,h}, q_{1,h}) \in \mathcal{Q}_{0,h} \times \mathcal{Q}_{1,h}$. Let $\mathbf{v}_{N,h} := \mathbf{v}_{N,h}(q_h)$ be like in Lemma 2. Using (18) with $\mathbf{v}_h = \mathbf{v}_{N,h}$, (6) and (7), we have:

$$b_h(\mathbf{v}_{N,h}, q_h) \gtrsim \nu^{-1} \|\pi_0(q_h)\|_\Omega^2 - \sigma \|\mathbf{v}_{N,h}\|_h \|\tilde{q}_{1,h}\|_\Omega. \quad (19)$$

Using (8) and Young inequality, we have for all $\varepsilon > 0$:

$$-\|\mathbf{v}_{N,h}\|_h \|\tilde{q}_{1,h}\|_\Omega \geq -\frac{1}{2} C_{\operatorname{div}} \nu^{-1} (\varepsilon \|\pi_0(q_h)\|_\Omega^2 + \varepsilon^{-1} \|\tilde{q}_{1,h}\|_\Omega^2). \quad (20)$$

We now insert the bound (20) in (19) to get:

$$b_h(\mathbf{v}_{N,h}, q_h) \gtrsim \nu^{-1} \left(\left(1 - \frac{\varepsilon}{2} C_{\operatorname{div}} \sigma\right) \|\pi_0(q_h)\|_\Omega^2 - \frac{C_{\operatorname{div}}}{2\varepsilon} \sigma \|\tilde{q}_{1,h}\|_\Omega^2 \right). \quad (21)$$

Let $\mathbf{v}_{T,h} := \mathbf{v}_{T,h}(q_{1,h})$ be like in Lemma 3. Using (9) and (10), we get:

$$b_h(\mathbf{v}_{T,h}, q_{1,h}) = (\nabla q_{1,h}, \mathbf{v}_{T,h})_\Omega \gtrsim \nu^{-1} \sigma^{-2(d-2)} \|\tilde{q}_{1,h}\|_\Omega^2 \quad (22)$$

Last, we consider $\mathbf{v}_h^* = \mu \mathbf{v}_{N,h} + \mathbf{v}_{T,h}$, where $\mu > 0$. Using (21) and (22), we have:

$$\begin{aligned} b_h(\mathbf{v}_h^*, q_h) &= \mu b_h(\mathbf{v}_{N,h}, q_h) + b_h(\mathbf{v}_{T,h}, q_h), \\ &\gtrsim \nu^{-1} \left(\mu \left(1 - \frac{\varepsilon}{2} C_{\operatorname{div}} \sigma\right) \|\pi_0(q_h)\|_\Omega^2 + \left(\sigma^{-2(d-2)} - \frac{\mu C_{\operatorname{div}}}{2\varepsilon} \sigma\right) \|\tilde{q}_{1,h}\|_\Omega^2 \right). \end{aligned}$$

Let us choose $\varepsilon = (C_{\operatorname{div}} \sigma)^{-1} < 1$ and $\mu = \sigma^{-2(d-2)} \varepsilon^2$. We obtain that:

$$b_h(\mathbf{v}_h^*, q_h) \gtrsim C_{\min} \nu^{-1} \|q_h\|_{\Omega}^2 \text{ with } C_{\min} = \varepsilon^2 \sigma^{-2(d-2)} = C_{\text{div}}^{-2} \sigma^{-2(d-1)}. \quad (23)$$

We will now bound $\|\mathbf{v}_h^*\|_h$ by $\|q_h\|_{\Omega}$. We have: $\|\mathbf{v}_h^*\|_h^2 \leq 2(\mu^2 \|\mathbf{v}_{N,h}\|_h^2 + \|\mathbf{v}_{T,h}\|_h^2)$. Using (8) and (11) $\|\mathbf{v}_h^*\|_h^2 \leq 2\nu^{-2}(\mu^2 C_{\text{div}}^2 \|\pi_0(q_h)\|_{\Omega}^2 + \sigma^4 \|\tilde{q}_{1,h}\|_{\Omega}^2)$, hence:

$$\|\mathbf{v}_h^*\|_h^2 \leq C_{\max}^2 \nu^{-2} \|q_h\|_{\Omega}^2 \text{ with } C_{\max} = \sqrt{2} \sigma^2. \quad (24)$$

Using (24) in (23), we get (17) with $C_{\min} C_{\max}^{-1} = \frac{1}{\sqrt{2}} C_{\text{div}}^{-2} \sigma^{-2d}$. \square

Let $\mathbf{V}_h := \{\mathbf{v}_h \in \mathbf{X}_{0,h} \mid \forall q_h \in Q_h, b_h(\mathbf{v}_h, q_h) = 0\}$. Let $(\mathbf{v}_h, q_{1,h}) \in \mathbf{V}_h \times Q_{1,h}$. Integrating by parts, we have $0 = b_h(\mathbf{v}_h, q_{1,h}) = -(\text{div}_h \mathbf{v}, \pi_0(q_{1,h}))_{\Omega} + \sum_{F \in \mathcal{F}_h} \int_F q_{1,h}[\mathbf{v}_h] \cdot \mathbf{n}_F = 0 + \sum_{F \in \mathcal{F}_h} \int_F q_{1,h}[\mathbf{v}_h] \cdot \mathbf{n}_F$. Hence:

Lemma 4 For all $(\mathbf{v}_h, q_{1,h}) \in \mathbf{V}_h \times Q_{1,h}$, it holds: $\sum_{F \in \mathcal{F}_h} \int_F q_{1,h}[\mathbf{v}_h] \cdot \mathbf{n}_F = 0$.

Let $\ell_{\mathbf{f}} \in \mathcal{L}(\mathbf{X}_h, \mathbb{R})$ be such that $\forall \mathbf{v}_h \in \mathbf{X}_h$, $\ell_{\mathbf{f}}(\mathbf{v}_h) = (\mathbf{f}, \mathbf{v}_h)_{\Omega}$ if $\mathbf{f} \in \mathbf{L}^2(\Omega)$, $\ell_{\mathbf{f}}(\mathbf{v}_h) = \langle \mathbf{f}, \mathcal{I}_h(\mathbf{v}_h) \rangle_{\mathbf{H}_0^1(\Omega)}$ if $\mathbf{f} \notin \mathbf{L}^2(\Omega)$, where $\mathcal{I}_h : \mathbf{X}_{0,h} \rightarrow \mathbf{Y}_{0,h}$ is for instance an averaging operator [10, §22.4.1], with $\mathbf{Y}_{0,h} = \{\mathbf{v}_h \in \mathbf{H}_0^1(\Omega) \mid \forall K \in \mathcal{T}_h, \mathbf{v}_h|_K \in \mathbf{P}^k(K)\}$. The discretization of Problem (1) with the $\mathbf{P}_{nc}^1 - (P^0 + P^1)$ element reads: Find $(\mathbf{u}_h, p_h) \in \mathbf{X}_{0,h} \times Q_h$ such that $\forall (\mathbf{u}_h, p_h) \in \mathbf{X}_{0,h} \times Q_h$

$$\nu(\mathbf{u}_h, \mathbf{v}_h)_h + b_h(\mathbf{v}_h, p_h) + b_h(\mathbf{u}_h, q_h) = \ell_{\mathbf{f}}(\mathbf{v}_h). \quad (25)$$

Due to Proposition 3 and Theorem 1, Problem (25) is well posed. We can derive error estimates similar to those given by [1, Theorems 3, 4, 6].

3 Convergence estimates

3.1 Optimal estimates in 2D

When $\Omega \subset \mathbb{R}^2$, we have the two Lemmas below.

Lemma 5 For all $(\mathbf{v}_h, q_h) \in \mathbf{V}_h \times Q_{2,h}$, $(\nabla q_h, \mathbf{v}_h)_{\Omega} = 0$.

Proof. Let $(\mathbf{v}_h, q_h) \in \mathbf{V}_h \times Q_{2,h}$. Integrating by parts and using Lemma 4, we get that $\forall q_{1,h} \in Q_{1,h}$: $(\nabla q_h, \mathbf{v}_h)_{\Omega} = -\sum_{F \in \mathcal{F}_h} \int_F q_h[\mathbf{v}_h] \cdot \mathbf{n}_F = -\sum_{F \in \mathcal{F}_h} \int_F (q_h - q_{1,h})[\mathbf{v}_h] \cdot \mathbf{n}_F = \sum_{F \in \mathcal{F}_h} \int_F (q_h - q_{1,h})[\mathbf{v}_h - \mathbf{v}_h(M_F)] \cdot \mathbf{n}_F$. Hence, we obtain: $(\nabla q_h, \mathbf{v}_h)_{\Omega} = -\sum_{K \in \mathcal{T}_h} \sum_{F \subset \partial K} \int_F (q_h - q_{1,h})(\mathbf{v}_h - \mathbf{v}_h(M_F)) \cdot \mathbf{n}_{F,K}$. Choose $q_{1,h}$ such that $\forall S \in \mathcal{V}_h$, $q_{1,h}(S) = q_{2,h}(S)$. Then, $\forall F \in \mathcal{F}_h$, the degree 3 polynomial $(q_h - q_{1,h})(\mathbf{v}_h - \mathbf{v}_h(M_F))$ vanishes at the quadrature points of Simpson's rule. Since it is exact for degree 3 polynomials, $\forall F \in \mathcal{F}_h$, $\int_F (q_h - q_{1,h})(\mathbf{v}_h - \mathbf{v}_h(M_F)) \cdot \mathbf{n}_{F,K} = 0$ and $(\nabla q_h, \mathbf{v}_h)_{\Omega} = 0$. \square

Lemma 6 Let $\phi \in H^3(\Omega) \cap L_{zmv}^2(\Omega)$ such that $|\phi|_{H^3(\Omega)} \neq 0$.

Then, $\forall \mathbf{v}_h \in \mathbf{V}_h$, $(\nabla \phi, \mathbf{v}_h)_{\Omega} \lesssim \sigma h^2 |\phi|_{H^3(\Omega)} \|\mathbf{v}_h\|_{\Omega}$.

Proof. Let $\mathbf{v}_h \in \mathbf{V}_h$. Using Lemma 5 and Cauchy-Schwarz, it holds: $|(\nabla\phi, \mathbf{v}_h)_\Omega| = |(\nabla(\phi - q_h), \mathbf{v}_h)_\Omega|$ for all $q_h \in \mathcal{Q}_{2,h}$. We then use Bramble-Hilbert Lemma [10, Lemma 11.9] to conclude. \square

Theorem 2 *Suppose that Ω is convex. Let $\phi \in H^3(\Omega) \cap L^2_{zmv}(\Omega)$ such that $|\phi|_{H^3(\Omega)} \neq 0$. Let (\mathbf{u}_h, p_h) be the solution of Problem (25) with $\mathbf{f} = \nabla\phi$. The solution of Problem (1) is then $(\mathbf{u}, p) = (0, \phi)$. It holds:*

$$\nu \|\mathbf{u}_h\|_h \lesssim \sigma^2 h^3 |\phi|_{H^3(\Omega)}; \quad \nu \|\mathbf{u}_h\|_\Omega \lesssim \sigma^3 h^4 |\phi|_{H^3(\Omega)}.$$

Proof. Setting $\mathbf{v}_h = \mathbf{u}_h$ as test-function in Problem (25) and using Lemma 6, it holds: $\nu \|\mathbf{u}_h\|_h^2 = (\nabla\phi, \mathbf{u}_h)_\Omega \lesssim \sigma h^2 |\phi|_{H^3(\Omega)} \|\mathbf{u}_h\|_\Omega$. From [1, Theorem 4], have: $\|\mathbf{u}_h\|_\Omega \lesssim \sigma h \|\mathbf{u}_h\|_h$. We deduce that $\nu \|\mathbf{u}_h\|_h \lesssim \sigma^2 h^3 |\phi|_{H^3(\Omega)}$. Using this estimate, we get that $\nu \|\mathbf{u}_h\|_\Omega \lesssim \sigma^3 h^4 |\phi|_{H^3(\Omega)}$. \square

3.2 Extension to 3D

When $\Omega \subset \mathbb{R}^3$, let \mathcal{E}_h be the set of edges of \mathcal{T}_h . Let $E := S_i S_j \in \mathcal{E}_h$. We set $\phi_E := 4\lambda_i \lambda_j$ where λ_i (resp. λ_j) is the barycentric coordinate related to vertex S_i (resp. S_j). Let $\tilde{P}^2(\mathcal{T}_h) = \text{vect}((\tilde{\phi}_E)_{E \in \mathcal{E}_h})$, where for every edge E , $\tilde{\phi}_E$ is the canonical extension of ϕ_E to all simplices intersecting with $\text{int}(E)$. In order to obtain optimal results in 3D similar to those obtained in 2D, the discrete pressure space can be $\mathcal{Q}_h = \mathcal{Q}_{0,h} + \mathcal{Q}_{1,h} + \tilde{\mathcal{Q}}_{2,h}$, where $\tilde{\mathcal{Q}}_{2,h}$ is a subspace of $\tilde{P}^2(\mathcal{T}_h) \cap L^2_{zmv}(\Omega)$ [9]. One can then prove Lemma 5 in 3D using a 7-point quadrature rule on a triangle, exact for polynomials of degree 3. The quadrature points are the barycentre of the triangle, its vertices and the midpoints of its edges. Lemma 6 follows. Finally, in [9, Theorem 4.4.6, page 92], it is claimed that one obtains a convergence result identical to the one of Theorem 2, now in 3D.

4 Numerical results for the stationary Navier-Stokes model

Let us consider stationary Navier-Stokes equations set in $\Omega = (0, 1)^d$:

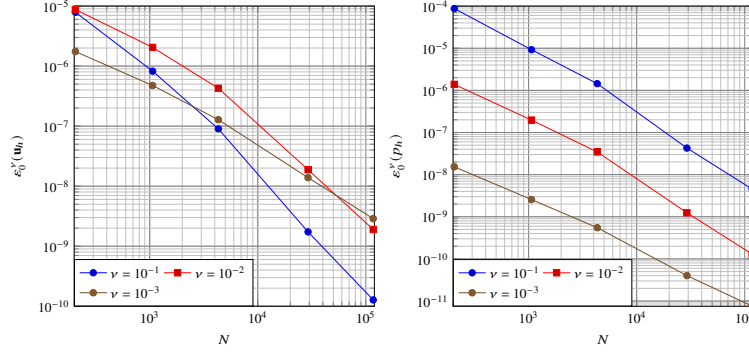
$$\text{Find } (\mathbf{u}, p) \text{ such that } -\nu \Delta \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u} + \nabla p = \mathbf{f} \text{ and } \text{div } \mathbf{u} = 0 \text{ in } \Omega, \quad (26)$$

with Dirichlet boundary conditions on the velocity. Computations are done with the TrioCFD code [6, 7] with the $\mathbf{P}_{nc}^1 - (P^0 + P^1)$ finite element. The convection term is discretized using the MUSCL scheme [6]. Let us set: $\|(\mathbf{u}, p)\|_\nu^2 := \|\nabla \mathbf{u}\|_\Omega^2 + \nu^{-2} \|p\|_\Omega^2$. The discrete errors values are $\varepsilon_0^\nu(\mathbf{u}_h) := \|\mathbf{u} - \mathbf{u}_h\|_\Omega / \|(\mathbf{u}, p)\|_\nu$ for the velocity and $\varepsilon_0^\nu(p_h) := \nu^{-1} \|p - p_h\|_\Omega / \|(\mathbf{u}, p)\|_\nu$ for the pressure.

We first consider the 2D case and the prescribed solution $\mathbf{u} = (y, -x)^T$, $p = (x^2 + y^2)/2 - 1/3$ so that $\mathbf{f} = 0$. Figure 1 shows $\varepsilon_0^\nu(\mathbf{u}_h)$ (left) and $\varepsilon_0^\nu(p_h)$ (right) against

the number of degrees of freedom N , for $\nu = 10^{-1}$, $\nu = 10^{-2}$ and $\nu = 10^{-3}$. Table

Fig. 1 2D case. Plots of $\varepsilon_0^\nu(\mathbf{u}_h)$ and $\varepsilon_0^\nu(p_h)$ for $\nu = 10^{-1}$, $\nu = 10^{-2}$ or $\nu = 10^{-3}$.



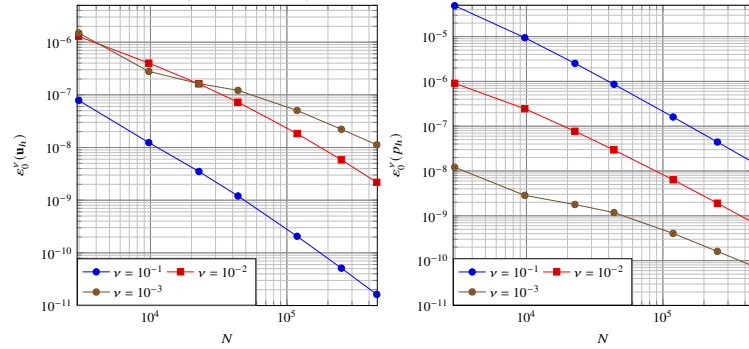
1 shows the convergence rates for the velocity $\tau_{\mathbf{u}}$ (left) and for the pressure τ_p (right), where $h \approx N^{-1/2}$. We then consider the 3D case and the prescribed solution

Table 1 2D case, convergence rates.

ν	10^{-1}	10^{-2}	10^{-3}
$\tau_{\mathbf{u}}$	3.9	3.3	2.3
τ_p	3.4	3.4	2.5

$\mathbf{u} = (y - z, z - x, x - y)^T$, $p = \frac{1}{2}(x^2 + y^2 + z^2) - xy - xz - yz - 1/4$ so that $\mathbf{f} = 0$. Figure 2 shows $\varepsilon_0^\nu(\mathbf{u}_h)$ (left) and $\varepsilon_0^\nu(p_h)$ (right) against the number of degrees of freedom N , for $\nu = 10^{-1}$, $\nu = 10^{-2}$ and $\nu = 10^{-3}$. Table 2 shows the convergence

Fig. 2 3D case. Plots of $\varepsilon_0^\nu(\mathbf{u}_h)$ and $\varepsilon_0^\nu(p_h)$ for $\nu = 10^{-1}$, $\nu = 10^{-2}$ or $\nu = 10^{-3}$.



rates for the velocity $\tau_{\mathbf{u}}$ (left) and for the pressure τ_p (right), where $h \approx N^{-1/3}$. More

Table 2 3D case, convergence rates.

ν	10^{-1}	10^{-2}	10^{-3}	ν	10^{-1}	10^{-2}	10^{-3}
τ_u	5.6	4.7	3.3	τ_p	5.2	4.8	3.7

numerical results are available in [8, 9, 6, 21]. The $\mathbf{P}_{nc}^1 - (P^0 + P^1)$ scheme has good approximation properties and can therefore be used to solve the Navier-Stokes equations in the context of industrial simulation. We plan to study discrete pressure enrichment to higher order nonconforming Crouzeix-Raviart mixed FEM [2, 3].

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