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Analysis and Discontinuous Galerkin approximation of the Boussinesq system with Navier-type boundary condition

AFAF BOUHARGUANE*, NOUR SELOULA†

Abstract

In this work, we study the nonlinear coupled Navier–Stokes/temperature (or Boussinesq) equations with Navier-type boundary condition for the velocity. The well-posedness of the continuous problem is achieved by using a fixed-point strategy. Next, we propose a discontinuous Galerkin (DG) scheme for discretizing the equations. Existence, uniqueness and stability of numerical solutions are shown for the DG method under a small data condition and by using the Brouwer fixed point theorem. We provide *a priori* error estimates in terms of a natural energy norms for the velocity, the pressure and the temperature. To our knowledge, it is the first time that a discontinuous Galerkin approximation for the full nonlinear coupled Boussinesq system, with Navier-type boundary condition for the velocity, is proposed and completely analyzed in both, continuous and discrete settings.

Key words: Stationary Boussinesq equations; discontinuous Galerkin method; Navier boundary condition; fixed point theory, existence, *a priori* error estimate, discrete inequality.

Mathematics subject classifications (2020): 65N12, 65N15, 65N22 65N30, 35Q30, 35Q79.

1 Introduction

Over the past few decades, the community of numerical analysts of partial differential equations has extensively focused on developing precise and efficient new finite element methods for the Boussinesq problem. This model is well-known for its relevance in engineering sciences as it deals with fluid motion generated by density differences caused by temperature gradients. Mathematically, it is a nonlinear system of PDEs which is composed of the stationary incompressible Navier–Stokes equations for the velocity and pressure variables and a convection–diffusion equation for the temperature variable. Such coupling is done by means of a buoyancy term in the Navier–Stokes equations depending on the temperature and convective term in the heat equation depending on the velocity of the fluid. The Boussinesq approximation was justified and used to study several applications such as in geophysics to model climate prediction [12], in oceanography for studying oceanic flows [20, 22] and also in magnetohydrodynamic flows, see [10]. Moreover, simulations that combine fluid flow and temperature are invaluable in predicting the performance of physical designs across a wide range of engineering applications. By conducting these simulations before the manufacturing process, it becomes possible to significantly reduce the costs associated with the development of new products [27, 29].

Various numerical methods have been investigated for the stationary Boussinesq system. Existing discretizations mostly deal with Dirichlet boundary condition for the fluid. Let us describe some of these contributions. Bernardi et al. [3], proved existence and uniqueness of the weak solution for the

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Boussinesq system and proposed a finite element approximation. Farhfoul et al. [13] proposed a new mixed formulation for the two-dimensional Boussinesq system where the existence of solutions and convergence of the numerical scheme have been proved near a non-singular solution. Colmenares et al. [24] analyzed a new finite element method with exactly divergence-free velocities for the numerical simulation of a generalized Boussinesq problem where the viscosity and the thermal conductivity depend on the temperature of the fluid. More recently, Colmenares et al. [23] proposed another new divergence-Conforming DG-Mixed Finite Element Method for the Stationary Boussinesq Problem.

However, it has been showed that the Dirichlet boundary condition for the fluid is inadequate in some situations such as in the mechanics of thin films, multiple interfaces problems, the flow of rarefied fluids, the flow of a fluid in perforated domains, flow of blood through blood vessels (see e.g. [19]). In these cases, the French engineer Claude Navier ([21]) proposed that the tangential velocity should be proportional to the tangential stress on the boundary together with the impermeability condition $\mathbf{u} \cdot \mathbf{n} = 0$. These conditions are known as the Navier boundary conditions. A generalization of the Navier condition can be written as:

$$\mathbf{u} \cdot \mathbf{n} = 0 \quad \text{and} \quad 2[D(\mathbf{u})\mathbf{n}]_\tau + \alpha \mathbf{u}_\tau = \mathbf{0} \quad \text{on } \Gamma, \quad (1.1)$$

where $\alpha \geq 0$ is the coefficient of friction and

$$D(\mathbf{u})_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right), \quad 1 \leq i, j \leq 3.$$

The subscript τ denotes the vectorial tangential trace of any vector, defined by $\mathbf{v}_\tau := \mathbf{v} - (\mathbf{v} \cdot \mathbf{n})\mathbf{n}$. Note that, when α tends to infinity, we formally recover the Dirichlet conditions. In the case of a flat boundary and zero friction coefficient α , this Navier condition is equivalent to the following Navier-type conditions:

$$\mathbf{u} \cdot \mathbf{n} = 0 \quad \text{and} \quad \mathbf{curl} \mathbf{u} \times \mathbf{n} = 0 \quad \text{on } \Gamma, \quad (1.2)$$

Concerning the study of Boussinesq system with the above boundary conditions, the literature is rather scarce. The idea is originally described in [1], where the steady Boussinesq problem with Navier boundary condition (1.1) has been investigated and the existence of weak solutions in the Hilbertian case and the L^p -regularity of these weak solutions are proved. In [30], the authors study the time-dependent 2D Boussinesq equations with the Navier type boundary conditions (1.1) and prove the global existence and uniqueness under minimal regularity assumptions on the initial data. To our knowledge, there has been no numerical analysis for the Boussinesq system with such a Navier-type boundary condition (1.2).

In the current paper, we propose and analyze an interior penalty discontinuous Galerkin method for the Boussinesq model with Navier-type boundary conditions (1.2) for the velocity and homogeneous boundary condition for the temperature. More precisely, given a fluid occupying the region Ω , a force per unit mass \mathbf{g} and a heat source f , the model of interest reads: Find a velocity field \mathbf{u} , a pressure field p and a temperature field θ such that:

$$-\nu \mathbf{curl} \mathbf{curl} \mathbf{u} + \mathbf{curl} \mathbf{u} \times \mathbf{u} + \nabla p - \theta \mathbf{g} = 0 \quad \text{in } \Omega, \quad (1.3a)$$

$$\operatorname{div} \mathbf{u} = 0, \quad \text{in } \Omega, \quad (1.3b)$$

$$-\kappa \Delta \theta + \mathbf{u} \cdot \nabla \theta = f \quad \text{in } \Omega, \quad (1.3c)$$

$$\mathbf{u} \cdot \mathbf{n} = 0 \quad \text{and} \quad \mathbf{curl} \mathbf{u} \times \mathbf{n} = 0 \quad \text{on } \Gamma, \quad (1.3d)$$

$$\theta = 0 \quad \text{on } \Gamma, \quad (1.3e)$$

Here $\Omega \subset \mathbb{R}^3$ is an open convex domain. ν is the kinematic viscosity of the fluid, κ is the thermal diffusivity of the fluid.

DG method is a type of finite element method where the solution is approximated by a piecewise polynomial function that is discontinuous across element boundaries. These methods are attractive because they are element-wise conservative, easily implementable on unstructured meshes and they are high-order methods.

The main difficulty is to prove the stability of the bilinear forms arising from the Navier-Stokes convection term O_h (see definition in (3.3)) and the coupling term \mathcal{C}_h (see definition in (3.5)) on the discrete spaces.

To give the reader an idea of the main features of our DG method, let us compare it with other discontinuous Galerkin methods that have been used to approximate the Boussinesq system or related problems.

In a recent work [9], the authors proposed an analysis of a DG scheme for the Boussinesq system where the boundary conditions are of Dirichlet type for the velocity field and of mixed type for the temperature. The general case of a Lipschitz domain Ω is considered. Since the solution \mathbf{u} (respectively θ) belongs to $\mathbf{H}^1(\Omega)$ (respectively to $H^1(\Omega)$) and hence to $\mathbf{L}^6(\Omega)$ (respectively to $L^6(\Omega)$) by Sobolev embedding, they show the continuity of the nonlinear terms by applying an L^2 - L^4 - L^4 argument. To this end, they apply the discrete inequality derived in [17, 18] (see also [11]) in two and three dimensional bounded domains with Lipschitz boundary., which states that the \mathbf{L}^6 norm is controlled by the following DG norm denoted by $\|\cdot\|_h$:

$$\|\mathbf{v}_h\|_{\mathbf{L}^6(\Omega)} \leq C \|\mathbf{v}_h\|_h := C \left(\sum_{T \in \mathcal{T}_h} \|\nabla \mathbf{v}_h\|_{0,T}^2 + \sum_{e \in \mathcal{F}_h} \frac{\gamma}{h_e} \|[[\mathbf{v}_h]]\|_{0,e}^2 \right)^{1/2}. \quad (1.4)$$

This approach is not suitable for the problem that we propose to study. Indeed, in the case of a non-smooth domain and given the boundary conditions considered for the velocity field \mathbf{u} , the solution \mathbf{u} of the system (1.3) is only in $\mathbf{H}^{1/2}(\Omega)$ and hence in $\mathbf{L}^3(\Omega)$ by Sobolev embedding. Therefore, the previous argument can be again applied to show the continuity of the form \mathcal{C}_h in the heat equations but cannot be applied to show the continuity of the nonlinear form O_h in the Navier-Stokes equations. Additional regularity assumptions on the exact solution are therefore necessary.

Moreover, due to the boundary conditions considered in this work for the velocity, the DG energy norm for \mathbf{u} is different from that defined in (1.4). In [25, 26], a discrete functional analysis is established and the authors show a new discrete inequality analogous to (1.4) on discontinuous spaces provided that the boundary of the domain is sufficiently regular. More precisely, for $1 \leq p \leq 6$, they show that the L^p norm is controlled by the following DG norm:

$$\|\mathbf{v}_h\|_{\mathbf{L}^p(\Omega)}^2 \leq C \| \mathbf{v}_h \|_h^2 := C \sum_{T \in \mathcal{T}_h} \left(\|\operatorname{div} \mathbf{v}_h\|_{0,T}^2 + \|\operatorname{curl} \mathbf{v}_h\|_{0,T}^2 \right) + \sum_{e \in \mathcal{F}_h} \frac{\sigma}{h_e} \|[[\mathbf{v}_h]]_N\|_{0,e}^2 + \sum_{e \in \mathcal{F}_h} \frac{\sigma}{h_e} \|[[\mathbf{v}_h]]_T\|_{0,e}^2,$$

This new discrete inequality allows the application of an L^4 - L^4 - L^2 argument to show the continuity of the nonlinear forms associated with our DG scheme and then to prove the existence of a solution to the discrete problem.

The rest of the paper is structured as follows. In Section 2, we introduce and show the well-posedness of the continuous variational problem by applying the Leray-Schauder's theorem. A discontinuous Galerkin formulation based on the classical interior penalty (IP) symmetric method is presented in Section 3 where the existence and uniqueness of approximate solutions are proved. In Section 4, we state and prove the convergence and our *a priori* error estimates for velocity, the pressure and temperature in energy norms.

2 Analysis of the continuous problem

2.1 Preliminaries and notations

Let Ω be a bounded connected domain in \mathbb{R}^3 with a boundary Γ of class $\mathcal{C}^{1,1}$ or convex. For $p \in [1, +\infty]$, we denote by $L^p(\Omega)$ the usual Lebesgue space endowed with the norm $\|\cdot\|_{L^p(\Omega)}$ and $L_0^2(\Omega)$ is the space consisting of functions $q \in L^2(\Omega)$ that hold $\int_{\Omega} q = 0$. We adopt standard notation for the Sobolev spaces $H^s(\Omega)$ and $H_0^s(\Omega)$. In addition, according to the boundary conditions in (1.3d), and in view of deriving a weak formulation for (1.3), we introduce the following functional space:

$$\mathbf{H}_T^1(\Omega) = \{\mathbf{v} \in \mathbf{H}^1(\Omega); \quad \mathbf{v} \cdot \mathbf{n} = 0 \text{ on } \Gamma\} \quad (2.1)$$

We recall that the space $\mathbf{H}_T^1(\Omega)$ is continuously embedded in $\mathbf{H}^1(\Omega)$ if Ω is convex or the boundary of Ω is of class $\mathcal{C}^{1,1}$ (c.f. [16, Theorem 3.7] and [2, Theorem 3.4]). In addition we recall the following Poincaré inequalities, needed for proving the existence of a weak solutions: there exist $C_P > 0$ and $\tilde{C}_P > 0$ such that [16]

$$\|\phi\|_{H^1(\Omega)} \leq C_P \|\nabla \phi\|_{L^2(\Omega)}, \quad \forall \phi \in H_0^1(\Omega), \quad (2.2a)$$

$$\|\mathbf{v}\|_{\mathbf{H}^1(\Omega)} \leq \tilde{C}_P (\|\mathbf{curl} \mathbf{v}\|_{L^2(\Omega)} + \|\operatorname{div} \mathbf{v}\|_{L^2(\Omega)}), \quad \forall \mathbf{v} \in \mathbf{H}_T^1(\Omega). \quad (2.2b)$$

We also recall that the space $\mathbf{H}^1(\Omega)$ is compactly embedding within in $\mathbf{L}^q(\Omega)$ for any exponent $1 \leq q < 6$ and we have

$$\|\mathbf{v}\|_{\mathbf{L}^q(\Omega)} \leq \delta \|\mathbf{v}\|_{1,\Omega}, \quad (2.3)$$

where δ is a positive constant depending on the domain Ω .

Next, we introduce the following Banach space

$$\mathbf{H}^{3,\frac{3}{2}}(\mathbf{curl}, \Omega) = \{\mathbf{v} \in \mathbf{L}^3(\Omega); \quad \mathbf{curl} \mathbf{v} \in \mathbf{L}^{3/2}(\Omega)\} \quad (2.4)$$

provided with the norm

$$\|\mathbf{v}\|_{\mathbf{H}^{3,\frac{3}{2}}(\mathbf{curl}, \Omega)} = \|\mathbf{v}\|_{\mathbf{L}^3(\Omega)} + \|\mathbf{curl} \mathbf{v}\|_{\mathbf{L}^{3/2}(\Omega)}.$$

The space $\mathcal{D}(\bar{\Omega})$ is dense in $\mathbf{H}^{3,\frac{3}{2}}(\mathbf{curl}, \Omega)$. The proof of this density result is very much similar to (cf. [28, Proposition 1.0.2] and [2, Remark 5.4]). Moreover, we prove the following Green formula to define the tangential traces of functions which belong to $\mathbf{H}^{3,\frac{3}{2}}(\mathbf{curl}, \Omega)$.

Lemma 2.1 *The linear mapping $\gamma : \mathbf{v} \mapsto \mathbf{v} \times \mathbf{n}|_{\Gamma}$ defined on $\mathcal{D}(\bar{\Omega})$ can be extended to a linear continuous mapping*

$$\gamma : \mathbf{H}^{3,\frac{3}{2}}(\mathbf{curl}, \Omega) \longrightarrow \mathbf{W}^{-\frac{1}{3},3}(\Gamma).$$

Moreover, we have the Green formula: for any $\mathbf{v} \in \mathbf{H}^{3,\frac{3}{2}}(\mathbf{curl}, \Omega)$ and $\varphi \in \mathbf{W}^{1,3/2}(\Omega)$,

$$\int_{\Omega} \mathbf{curl} \mathbf{v} \cdot \varphi \, dx - \int_{\Omega} \mathbf{v} \cdot \mathbf{curl} \varphi \, dx = \langle \mathbf{v} \times \mathbf{n}, \varphi \rangle_{\mathbf{W}^{-\frac{1}{3},3}(\Gamma) \times \mathbf{W}^{\frac{1}{3},\frac{3}{2}}(\Gamma)}. \quad (2.5)$$

Proof. Let $\mathbf{v} \in \mathcal{D}(\bar{\Omega})$ and $\varphi \in \mathbf{W}^{1,3/2}(\Omega)$, then the Green Formula (2.5) obviously holds. Moreover, we can easily verify that

$$\left| \langle \mathbf{v} \times \mathbf{n}, \varphi \rangle_{\mathbf{W}^{-\frac{1}{3},3}(\Gamma) \times \mathbf{W}^{\frac{1}{3},\frac{3}{2}}(\Gamma)} \right| \leq C \|\mathbf{v}\|_{\mathbf{H}^{3,\frac{3}{2}}(\mathbf{curl}, \Omega)} \|\varphi\|_{\mathbf{W}^{1,3/2}(\Omega)}.$$

On the other hand, for every $\boldsymbol{\mu} \in \mathbf{W}^{\frac{1}{3}, \frac{3}{2}}(\Gamma)$, there exists a function $\boldsymbol{\varphi} \in \mathbf{W}^{1, \frac{3}{2}}(\Omega)$ such that $\boldsymbol{\varphi} = \boldsymbol{\mu}_\tau$ on Γ with the estimate

$$\|\boldsymbol{\varphi}\|_{\mathbf{W}^{1, \frac{3}{2}}(\Omega)} \leq C \|\boldsymbol{\mu}\|_{\mathbf{W}^{\frac{1}{3}, \frac{3}{2}}(\Gamma)},$$

where the subscript τ denotes the tangential component i.e. $\boldsymbol{\mu}_\tau = \boldsymbol{\mu} - (\boldsymbol{\mu} \cdot \mathbf{n})\mathbf{n}$ for any vector field $\boldsymbol{\mu}$. Consequently,

$$\begin{aligned} |\langle \mathbf{v} \times \mathbf{n}, \boldsymbol{\mu} \rangle_{\mathbf{W}^{-\frac{1}{3}, 3}(\Gamma) \times \mathbf{W}^{\frac{1}{3}, \frac{3}{2}}(\Gamma)}| &= |\langle \mathbf{v} \times \mathbf{n}, \boldsymbol{\mu}_\tau \rangle_{\mathbf{W}^{-\frac{1}{3}, 3}(\Gamma) \times \mathbf{W}^{\frac{1}{3}, \frac{3}{2}}(\Gamma)}| = |\langle \mathbf{v} \times \mathbf{n}, \boldsymbol{\varphi} \rangle_{\mathbf{W}^{-\frac{1}{3}, 3}(\Gamma) \times \mathbf{W}^{\frac{1}{3}, \frac{3}{2}}(\Gamma)}| \\ &\leq C \|\mathbf{v}\|_{\mathbf{H}^{3, \frac{3}{2}}(\mathbf{curl}, \Omega)} \|\boldsymbol{\varphi}\|_{\mathbf{W}^{1, \frac{3}{2}}(\Omega)} \\ &\leq C \|\mathbf{v}\|_{\mathbf{H}^{3, \frac{3}{2}}(\mathbf{curl}, \Omega)} \|\boldsymbol{\mu}\|_{\mathbf{W}^{\frac{1}{3}, \frac{3}{2}}(\Gamma)}, \end{aligned}$$

which implies that

$$\|\mathbf{v} \times \mathbf{n}\|_{\mathbf{W}^{-\frac{1}{3}, 3}(\Gamma)} \leq C \|\mathbf{v}\|_{\mathbf{H}^{3, \frac{3}{2}}(\mathbf{curl}, \Omega)}.$$

Thus the linear mapping $\gamma : \mathcal{D}(\overline{\Omega}) \longrightarrow \mathbf{W}^{-\frac{1}{3}, 3}(\Gamma)$ is continuous for the norm of $\mathbf{H}^{3, \frac{3}{2}}(\mathbf{curl}, \Omega)$. Since $\mathcal{D}(\overline{\Omega})$ is dense in $\mathbf{H}^{3, \frac{3}{2}}(\mathbf{curl}, \Omega)$, γ can be extended by continuity to a linear continuous mapping from $\mathbf{H}^{3, \frac{3}{2}}(\mathbf{curl}, \Omega)$ to $\mathbf{W}^{-\frac{1}{3}, 3}(\Gamma)$ and the Green Formula (2.5) holds for all $\mathbf{v} \in \mathbf{H}^{3, \frac{3}{2}}(\mathbf{curl}, \Omega)$ and for all $\boldsymbol{\varphi} \in \mathbf{W}^{1, \frac{3}{2}}(\Omega)$. \square

2.2 Weak Formulation

The weak formulation of (1.3) reads : Find $(\mathbf{u}, p, \theta) \in \mathbf{H}_T^1(\Omega) \times L_0^2(\Omega) \times H_0^1(\Omega)$ such that

$$A(\mathbf{u}, \mathbf{v}) + O(\mathbf{u}; \mathbf{u}, \mathbf{v}) + B(\mathbf{v}, p) = D(\theta, \mathbf{v}), \quad (2.6a)$$

$$B(\mathbf{u}, q) = 0 \quad (2.6b)$$

$$M(\theta, \psi) + \mathcal{C}(\mathbf{u}; \theta, \psi) = F(\psi), \quad (2.6c)$$

for all $(\mathbf{v}, q, \psi) \in \mathbf{H}_T^1(\Omega) \times L_0^2(\Omega) \times H_0^1(\Omega)$, where the bilinear forms are defined by

$$\begin{aligned} A(\mathbf{u}, \mathbf{v}) &= \nu \left(\int_{\Omega} \mathbf{curl} \mathbf{u} \cdot \mathbf{curl} \mathbf{v} \, d\mathbf{x} + \int_{\Omega} (\operatorname{div} \mathbf{u}) (\operatorname{div} \mathbf{v}) \, d\mathbf{x} \right), \\ M(\theta, \psi) &= \kappa \int_{\Omega} \nabla \theta \cdot \nabla \psi \, d\mathbf{x}, & D(\theta, \mathbf{v}) &= \int_{\Omega} \theta \mathbf{g} \cdot \mathbf{v} \, d\mathbf{x} \\ O(\mathbf{w}; \mathbf{u}, \mathbf{v}) &= \int_{\Omega} (\mathbf{curl} \mathbf{w} \times \mathbf{u}) \cdot \mathbf{v} \, d\mathbf{x}, & \mathcal{C}(\mathbf{u}; \theta, \psi) &= \int_{\Omega} (\mathbf{u} \cdot \nabla \theta) \psi \, d\mathbf{x}, \\ B(\mathbf{v}, q) &= - \int_{\Omega} (\operatorname{div} \mathbf{v}) q \, d\mathbf{x}, & F(\psi) &= \int_{\Omega} f \psi \, d\mathbf{x}. \end{aligned} \quad (2.7)$$

We describe a fixed point strategy that allows to solve the problem (2.6). First, we eliminate the pressure from the problem by restricting to the subspace

$$\mathbf{K} = \{\mathbf{v} \in \mathbf{H}_T^1(\Omega); \quad B(\mathbf{v}, q) = 0, \quad \forall q \in L_0^2(\Omega)\}$$

We then consider the equivalent problem: Find $(\mathbf{u}, \theta) \in \mathbf{K} \times H_0^1(\Omega)$, such that

$$A(\mathbf{u}, \mathbf{v}) + O(\mathbf{u}, \mathbf{u}, \mathbf{v}) = D(\theta, \mathbf{v}), \quad \forall \mathbf{v} \in \mathbf{K}, \quad (2.8a)$$

$$M(\theta, \psi) + \mathcal{C}(\mathbf{u}, \theta, \psi) = F(\psi), \quad \forall \psi \in H_0^1(\Omega). \quad (2.8b)$$

The bilinear form B is continuous in $\mathbf{H}_T^1(\Omega) \times L_0^2(\Omega)$ and satisfies the following inf-sup condition: there exists a constant $\beta > 0$ such that

$$\sup_{\mathbf{v} \in \mathbf{H}_T^1(\Omega)} \frac{B(\mathbf{v}, q)}{\|\mathbf{v}\|_{\mathbf{H}^1(\Omega)}} \geq \beta \|q\|_{L^2(\Omega)}, \quad (2.9)$$

which is a direct consequence of its analogue with $\mathbf{H}_T^1(\Omega)$ replaced by $\mathbf{H}_0^1(\Omega)$ (see [4, 5]).

As a consequence, it is easy to see that problems (2.6) and (2.8) are equivalent. In fact, we have the following standard result [16].

Lemma 2.2 *If $(\mathbf{u}, \theta) \in \mathbf{K} \times H_0^1(\Omega)$ is a solution of (2.8), then there exists $p \in L_0^2(\Omega)$ such that (\mathbf{u}, p, θ) is a solution of (2.6). Conversely, if $(\mathbf{u}, p, \theta) \in \mathbf{H}_T^1(\Omega) \times L_0^2(\Omega) \times H_0^1(\Omega)$ is a solution of (2.6), then $\mathbf{u} \in \mathbf{K}$ and $(\mathbf{u}, \theta) \in \mathbf{K} \times H_0^1(\Omega)$ is a solution of (2.8).*

We construct a map \mathcal{S} by linearizing the term D and the convection terms O and \mathcal{C} in problem (2.8) and show existence of a fixed point of \mathcal{S} . Define \mathcal{S} as follows:

$$\begin{aligned} \mathcal{S}: \mathbf{K} \times H_0^1(\Omega) &\rightarrow \mathbf{K} \times H_0^1(\Omega) \\ (\mathbf{w}, \phi) &\mapsto \mathcal{S}(\mathbf{w}, \phi) = (\mathbf{u}, \theta), \end{aligned} \quad (2.10)$$

where (\mathbf{u}, θ) satisfies the linearized problem: Find $(\mathbf{u}, \theta) \in \mathbf{K} \times H_0^1(\Omega)$ such that

$$\begin{aligned} A(\mathbf{u}, \mathbf{v}) + O(\mathbf{w}; \mathbf{u}, \mathbf{v}) &= D(\phi, \mathbf{v}), \quad \forall \mathbf{v} \in \mathbf{K}, \\ M(\theta, \psi) + \mathcal{C}(\mathbf{w}; \theta, \psi) &= F(\psi), \quad \forall \psi \in H_0^1(\Omega). \end{aligned} \quad (2.11)$$

Observe that, thanks to Lemma 2.2, a fixed point (\mathbf{u}, θ) of the map \mathcal{S} is the component of a solution (\mathbf{u}, p, θ) of problem (2.6). The well posedness of (2.6) will be addressed in Subsection 2.4 by applying the Leray-Schauder theorem. It requires some stability properties of the forms defined above.

2.3 Stability properties of the forms

In this subsection, we show some crucial stability properties of the forms that are used to prove the well posedness of the problem (2.6). First, we discuss the coercivity properties of the forms A , M , O and \mathcal{C} . We have the following result.

Proposition 2.1 *There exist positive constants α_A and α_M depending on Ω such that*

$$A(\mathbf{v}, \mathbf{v}) \geq \nu \alpha_A \|\mathbf{v}\|_{\mathbf{H}^1(\Omega)}^2, \quad \forall \mathbf{v} \in \mathbf{K}, \quad (2.12)$$

$$M(\psi, \psi) \geq \kappa \alpha_M \|\psi\|_{H^1(\Omega)}^2, \quad \forall \psi \in H_0^1(\Omega), \quad (2.13)$$

Furthermore, the following results hold:

(i) Let $\mathbf{w}, \mathbf{v} \in \mathbf{H}^1(\Omega)$. Then we have

$$O(\mathbf{w}; \mathbf{v}, \mathbf{v}) = 0. \quad (2.14)$$

(ii) Let $\mathbf{w} \in \mathbf{K}$ and $\phi \in H_0^1(\Omega)$. Then we have

$$\mathcal{C}(\mathbf{w}; \psi, \psi) = 0 \quad (2.15)$$

Proof. The coercivity of the forms A and M follows from the Poincaré-Friedrichs inequalities (2.2a) and (2.2b). The property in (2.14) is obvious. It follows from the definition of O and the fact that the vector $\mathbf{curl} \mathbf{w} \times \mathbf{v}$ is orthogonal to \mathbf{v} . The property in (2.15) is a consequence of the following well-known skew-symmetry property of the form \mathcal{C} with respect to the last two components:

$$\mathcal{C}(\mathbf{w}; \theta, \psi) = -\mathcal{C}(\mathbf{w}; \psi, \theta), \quad \forall \mathbf{w} \in \mathbf{K}, \forall (\theta, \psi) \in H_0^1(\Omega) \times H_0^1(\Omega).$$

□

We also need to study the continuity of the forms involved in the variational formulation (2.6). We have the following results where the proof is obtained by applying Cauchy-Schwarz's inequality to the different forms.

Proposition 2.2 *There exist positive constants C_A , C_M , C_B and C_F depending on Ω such that*

$$A(\mathbf{u}, \mathbf{v}) \leq \nu C_A \|\mathbf{u}\|_{\mathbf{H}^1(\Omega)} \|\mathbf{v}\|_{\mathbf{H}^1(\Omega)}, \quad (2.16)$$

$$M(\theta, \psi) \leq \kappa C_M \|\theta\|_{H^1(\Omega)} \|\psi\|_{H^1(\Omega)}, \quad (2.17)$$

$$B(q, \mathbf{v}) \leq C_B \|q\|_{L^2(\Omega)} \|\mathbf{v}\|_{\mathbf{H}^1(\Omega)}, \quad (2.18)$$

$$F(\psi) \leq C_F \|\psi\|_{L^2(\Omega)} \|\psi\|_{H^1(\Omega)}, \quad (2.19)$$

for all $\mathbf{u}, \mathbf{v} \in \mathbf{H}_T^1(\Omega)$, $\forall q \in L_0^2(\Omega)$ and $\theta, \psi \in H^1(\Omega)$.

The next results show that the nonlinear forms O , \mathcal{C} and D are continuous.

Proposition 2.3 *There exist positive constants C_o , C_c and C_d depending on Ω such that*

$$O(\mathbf{w}; \mathbf{u}, \mathbf{v}) \leq C_o \|\mathbf{w}\|_{\mathbf{H}^1(\Omega)} \|\mathbf{u}\|_{\mathbf{H}^1(\Omega)} \|\mathbf{v}\|_{\mathbf{H}^1(\Omega)} \quad (2.20)$$

$$\mathcal{C}(\mathbf{w}; \theta, \psi) \leq C_c \|\mathbf{w}\|_{\mathbf{H}^1(\Omega)} \|\theta\|_{H^1(\Omega)} \|\psi\|_{H^1(\Omega)}, \quad (2.21)$$

$$D(\theta, \mathbf{v}) \leq C_d \|\theta\|_{H^1(\Omega)} \|\mathbf{g}\|_{L^2(\Omega)} \|\mathbf{v}\|_{\mathbf{H}^1(\Omega)}, \quad (2.22)$$

for all $\mathbf{w}, \mathbf{u}, \mathbf{v} \in \mathbf{H}_T^1(\Omega)$ and $\theta, \psi \in H^1(\Omega)$.

Proof. Applying Hölder's inequality, we have

$$|O(\mathbf{w}; \mathbf{u}, \mathbf{v})| \leq \|\mathbf{curl} \mathbf{w}\|_{L^2(\Omega)} \|\mathbf{u}\|_{L^4(\Omega)} \|\mathbf{v}\|_{L^4(\Omega)}.$$

Estimate (2.20) follows from the compact imbedding (2.3) with $q = 4$. The proof of the continuity of \mathcal{C} and D uses essentially the same techniques as for the form O , so we skip the details. \square

2.4 A priori estimates and solvability

In this subsection, we prove the existence and uniqueness of solutions for the (2.6). We will apply the Leray-Schauder theorem, see [14, Theorem 11.3, p. 280]. For this, we must prove that \mathcal{S} is well-defined, a compact operator on $\mathbf{K} \times H_0^1(\Omega)$ and that the set

$$\mathcal{Z} = \{(\mathbf{u}, \theta) \in \mathbf{K} \times H_0^1(\Omega) : (\mathbf{u}, \theta) = \lambda \mathcal{S}(\mathbf{u}, \theta) \text{ for some } 0 \leq \lambda \leq 1\}$$

is bounded. For the convenience of the subsequent analysis, setting the following product norm on the space $\mathbf{K} \times H_0^1(\Omega)$:

$$\|(\mathbf{u}, \theta)\| = \left(\|\mathbf{u}\|_{\mathbf{H}^1(\Omega)}^2 + \|\theta\|_{H^1(\Omega)}^2 \right)^{1/2}.$$

The main result of this subsection is stated as follows.

Theorem 2.1 *Let $\mathbf{g} \in L^2(\Omega)$, $f \in L^2(\Omega)$. Then the problem (2.6) has at least one weak solution $(\mathbf{u}, p, \theta) \in \mathbf{H}_T^1(\Omega) \times L_0^2(\Omega) \times H_0^1(\Omega)$ satisfying*

$$\|(\mathbf{u}, \theta)\| \leq \kappa^{-1} \alpha_M^{-1} C_F \|f\|_{L^2(\Omega)} \left(1 + \nu^{-1} \alpha_A^{-1} C_D \|\mathbf{g}\|_{L^2(\Omega)} \right). \quad (2.23)$$

Moreover, if $\min(\nu \alpha_A, \kappa \nu_M) K_3 < 1$ with K_3 the constant given in (2.50), the solution is unique.

Since solving (2.6) is equivalent to finding a fixed point of the map \mathcal{S} defined in (2.10), we start by checking that the map \mathcal{S} is well-defined, i.e. that there exists a unique solution (\mathbf{u}, θ) to the linearized problem (2.11).

Lemma 2.3 *There exists a unique $(\mathbf{u}, \theta) \in \mathbf{K} \times H_0^1(\Omega)$ satisfying the linearized problem (2.11). In addition, we have the following bound*

$$\|(\mathbf{u}, \theta)\| \leq \alpha_A^{-1} (C_D \|\mathbf{g}\|_{L^2(\Omega)} \|(\mathbf{w}, \phi)\| + C_F \|f\|_{L^2(\Omega)}) \quad (2.24)$$

Proof. First, we write the mixed system (2.11) in the following equivalent compact form:

Find $(\mathbf{u}, \theta) \in \mathbf{K} \times H_0^1(\Omega)$ such that:

$$\mathcal{A}((\mathbf{w}, \phi); (\mathbf{u}, \theta), (\mathbf{v}, \psi)) = \mathcal{L}((\mathbf{w}, \phi), (\mathbf{v}, \psi)), \quad \forall (\mathbf{v}, \psi) \in \mathbf{K} \times H_0^1(\Omega), \quad (2.25)$$

where the forms \mathcal{A} and \mathcal{L} are defined as

$$\mathcal{A}((\mathbf{w}, \phi); (\mathbf{u}, \theta), (\mathbf{v}, \psi)) = A(\mathbf{u}, \mathbf{v}) + M(\theta, \psi) + O(\mathbf{w}; \mathbf{u}, \mathbf{v}) + \mathcal{C}(\mathbf{w}; \theta, \psi), \quad (2.26)$$

and

$$\mathcal{L}((\mathbf{w}, \phi), (\mathbf{v}, \psi)) = D(\phi, \mathbf{v}) + F(\psi). \quad (2.27)$$

It follows from Proposition 2.1 that

$$\mathcal{A}((\mathbf{w}, \phi); (\mathbf{u}, \theta), (\mathbf{u}, \theta)) \geq \nu \alpha_A \|\mathbf{u}\|_{\mathbf{H}^1(\Omega)}^2 + \kappa \alpha_M \|\theta\|_{H^1(\Omega)}^2 \geq \alpha_A \|(\mathbf{u}, \theta)\|^2, \quad (2.28)$$

where

$$\alpha_A = \min(\nu \alpha_A, \kappa \alpha_M). \quad (2.29)$$

Moreover, employing the continuity results in (2.16)-(2.17), (2.20)-(2.21) together with the inequality $(a+b) \leq 2^{1/2}(a^2+b^2)^{1/2}$, we can check that the trilinear form \mathcal{A} verifies the estimate:

$$\begin{aligned} \mathcal{A}((\mathbf{w}, \phi); (\mathbf{u}, \theta), (\mathbf{v}, \psi)) &\leq |A(\mathbf{u}, \mathbf{v})| + |M(\theta, \psi)| + |O(\mathbf{w}; \mathbf{u}, \mathbf{v})| + |\mathcal{C}(\mathbf{w}; \theta, \psi)|, \\ &\leq (\nu C_A + \kappa C_M + (C_o + C_c) \|\mathbf{w}\|_{\mathbf{H}^1(\Omega)}) (\|\mathbf{u}\|_{\mathbf{H}^1(\Omega)}^2 + \|\theta\|_{H^1(\Omega)}^2)^{1/2} (\|\mathbf{v}\|_{\mathbf{H}^1(\Omega)}^2 + \|\psi\|_{H^1(\Omega)}^2)^{1/2} \\ &\leq C_A \|(\mathbf{u}, \theta)\| \|(\mathbf{v}, \psi)\|, \end{aligned}$$

with $C_A = (\nu C_A + \kappa C_M + (C_o + C_c) \|\mathbf{w}\|_{\mathbf{H}^1(\Omega)})$. Thus, we showed that \mathcal{A} is coercive and continuous in $\mathbf{K} \times H_0^1(\Omega)$. In addition, thanks to (2.22) and (2.19), we have

$$\mathcal{L}((\mathbf{w}, \phi), (\mathbf{v}, \psi)) \leq C_D \|\phi\|_{H^1(\Omega)} \|\mathbf{g}\|_{L^2(\Omega)} \|\mathbf{v}\|_{\mathbf{H}^1(\Omega)} + C_F \|f\|_{L^2(\Omega)} \|\psi\|_{H^1(\Omega)} \leq C_c \|(\mathbf{v}, \psi)\|, \quad (2.30)$$

with $C_c = C_D \|\mathbf{g}\|_{L^2(\Omega)} \|(\mathbf{w}, \phi)\| + C_F \|f\|_{L^2(\Omega)}$. So, the form $\mathcal{L}((\mathbf{w}, \phi), \cdot)$ is an element of $(\mathbf{K} \times H_0^1(\Omega))'$. Therefore, by Lax-Milgram's theorem, there exists a unique $(\mathbf{u}, \theta) \in \mathbf{K} \times H_0^1(\Omega)$ solution of (2.25) and equivalently to (2.11). The estimate (2.24) follows by combining the estimates in (2.28) and (2.30). \square

Proof of Theorem 2.1. In order to prove the existence of the velocity \mathbf{u} and the temperature θ , we proceed in two steps.

Step 1 : Let us show that the operator \mathcal{S} is compact. Suppose $(\mathbf{w}_n, \phi_n) \in \mathbf{K} \times H_0^1(\Omega)$, $n \in \mathbb{N}$ such that $(\mathbf{w}_n, \phi_n) \rightharpoonup (\mathbf{w}, \phi)$ weakly in $\mathbf{K} \times H_0^1(\Omega)$. Define $(\mathbf{u}_n, \theta_n) = \mathcal{S}(\mathbf{w}_n, \phi_n)$ and $(\mathbf{u}, \theta) = \mathcal{S}(\mathbf{w}, \phi)$. We will show that $(\mathbf{u}_n, \theta_n) \rightarrow (\mathbf{u}, \theta)$ strongly in $\mathbf{K} \times H_0^1(\Omega)$.

We have $(\mathbf{u}_n - \mathbf{u}, \theta_n - \theta) \in \mathbf{K} \times H_0^1(\Omega)$ and satisfies the problem:

$$A(\mathbf{u}_n - \mathbf{u}, \mathbf{v}) + O(\mathbf{w}_n; \mathbf{u}_n, \mathbf{v}) - O(\mathbf{w}; \mathbf{u}, \mathbf{v}) = D(\phi_n - \phi, \mathbf{v}), \quad \forall \mathbf{v} \in \mathbf{K}, \quad (2.31a)$$

$$M(\theta_n - \theta, \psi) + \mathcal{C}(\mathbf{w}_n; \theta_n, \psi) - \mathcal{C}(\mathbf{w}; \theta, \psi) = 0, \quad \forall \psi \in H_0^1(\Omega). \quad (2.31b)$$

Taking $\mathbf{v} = \mathbf{u}_n - \mathbf{u}$ in (2.31a), we obtain

$$A(\mathbf{u}_n - \mathbf{u}, \mathbf{u}_n - \mathbf{u}) + O(\mathbf{w}_n; \mathbf{u}_n, \mathbf{u}_n - \mathbf{u}) - O(\mathbf{w}; \mathbf{u}, \mathbf{u}_n - \mathbf{u}) = D(\phi_n - \phi, \mathbf{u}_n - \mathbf{u}) \quad (2.32)$$

We can split up the nonlinear terms in the left hand side of (2.32) as

$$O(\mathbf{w}_n; \mathbf{u}_n, \mathbf{u}_n - \mathbf{u}) - O(\mathbf{w}; \mathbf{u}, \mathbf{u}_n - \mathbf{u}) = O(\mathbf{w}_n - \mathbf{w}; \mathbf{u}_n, \mathbf{u}_n - \mathbf{u}) - \underbrace{O(\mathbf{w}; \mathbf{u} - \mathbf{u}_n, \mathbf{u}_n - \mathbf{u})}_{=0}.$$

Applying the coercivity of A (c.f. (2.12)) and the continuity of D (c.f. (2.22)), we obtain

$$\nu \alpha_A \|\mathbf{u}_n - \mathbf{u}\|_{\mathbf{H}^1(\Omega)}^2 \leq O(\mathbf{w}_n - \mathbf{w}; \mathbf{u}_n, \mathbf{u}_n - \mathbf{u}) + D(\phi_n - \phi, \mathbf{u}_n - \mathbf{u}). \quad (2.33)$$

By definition, we have

$$\begin{aligned} & O(\mathbf{w}_n - \mathbf{w}; \mathbf{u}_n, \mathbf{u}_n - \mathbf{u}) \\ &= \int_{\Omega} (\mathbf{curl}(\mathbf{w}_n - \mathbf{w}) \times \mathbf{u}_n) \cdot (\mathbf{u}_n - \mathbf{u}) \, dx = \int_{\Omega} \mathbf{curl}(\mathbf{w}_n - \mathbf{w}) \cdot (\mathbf{u}_n \times (\mathbf{u}_n - \mathbf{u})) \, dx \end{aligned} \quad (2.34)$$

Since \mathbf{u}_n, \mathbf{u} belong to $\mathbf{H}^1(\Omega) \hookrightarrow \mathbf{L}^6(\Omega)$, we have $\mathbf{u}_n \times (\mathbf{u}_n - \mathbf{u}) \in \mathbf{L}^3(\Omega)$. Moreover, because $\operatorname{div} \mathbf{u}_n = \operatorname{div}(\mathbf{u}_n - \mathbf{u}) = 0$, we have

$$\mathbf{curl}(\mathbf{u}_n \times (\mathbf{u}_n - \mathbf{u})) = ((\mathbf{u}_n - \mathbf{u}) \cdot \nabla) \mathbf{u}_n - (\mathbf{u}_n \cdot \nabla)(\mathbf{u}_n - \mathbf{u}). \quad (2.35)$$

Since $\mathbf{u}_n, \mathbf{u} \in \mathbf{L}^6(\Omega)$ and $\nabla \mathbf{u}_n \in \mathbf{L}^2(\Omega)$, we have $((\mathbf{u}_n - \mathbf{u}) \cdot \nabla) \mathbf{u}_n \in \mathbf{L}^{3/2}(\Omega)$. Similarly, $(\mathbf{u}_n \cdot \nabla)(\mathbf{u}_n - \mathbf{u})$ belongs to $\mathbf{L}^{3/2}(\Omega)$. So, the two terms in the right hand side of the relation (2.35) belong to $\mathbf{L}^{3/2}(\Omega)$. We deduce that also $\mathbf{curl}(\mathbf{u}_n \times (\mathbf{u}_n - \mathbf{u}))$ belongs to $\mathbf{L}^{3/2}(\Omega)$. Then, $\mathbf{u}_n \times (\mathbf{u}_n - \mathbf{u})$ belongs to the space $\mathbf{H}^{3, \frac{3}{2}}(\mathbf{curl}, \Omega)$ defined in (2.4). Thanks to Lemma 2.1, the tangential trace of $\mathbf{u}_n \times (\mathbf{u}_n - \mathbf{u})$ is well-defined and belongs to $\mathbf{W}^{-\frac{1}{3}, 3}(\Gamma) \hookrightarrow \mathbf{H}^{-1/2}(\Gamma)$. On the other hand, we have

$$(\mathbf{u}_n \times (\mathbf{u}_n - \mathbf{u})) \times \mathbf{n} = (\mathbf{u}_n - \mathbf{u}) \underbrace{(\mathbf{u}_n \cdot \mathbf{n})}_{=0} - \mathbf{u}_n \underbrace{((\mathbf{u}_n - \mathbf{u}) \cdot \mathbf{n})}_{=0} = \mathbf{0}, \quad \text{on } \Gamma$$

Applying Green formula (2.5) with $\mathbf{v} = \mathbf{u}_n \times (\mathbf{u}_n - \mathbf{u}) \in \mathbf{H}^{3, \frac{3}{2}}(\mathbf{curl}, \Omega)$ and $\varphi = (\mathbf{w}_n - \mathbf{w}) \in \mathbf{H}^1(\Omega) \hookrightarrow \mathbf{W}^{1, \frac{3}{2}}(\Omega)$, we can rewrite the term O in (2.34) as

$$\begin{aligned} O(\mathbf{w}_n - \mathbf{w}; \mathbf{u}_n, \mathbf{u}_n - \mathbf{u}) &= \int_{\Omega} \mathbf{curl}(\mathbf{w}_n - \mathbf{w}) \cdot (\mathbf{u}_n \times (\mathbf{u}_n - \mathbf{u})) \, dx \\ &= \int_{\Omega} (\mathbf{w}_n - \mathbf{w}) \cdot \underbrace{\mathbf{curl}(\mathbf{u}_n \times (\mathbf{u}_n - \mathbf{u}))}_{=0} \, dx - \underbrace{\langle \mathbf{w}_n - \mathbf{w}, (\mathbf{u}_n \times (\mathbf{u}_n - \mathbf{u})) \times \mathbf{n} \rangle}_{\mathbf{W}^{-\frac{1}{3}, 3}(\Gamma) \times \mathbf{W}^{\frac{1}{3}, \frac{3}{2}}(\Gamma)}. \end{aligned}$$

Using again the relation (2.35), we obtain

$$O(\mathbf{w}_n - \mathbf{w}; \mathbf{u}_n, \mathbf{u}_n - \mathbf{u}) = \int_{\Omega} (\mathbf{w}_n - \mathbf{w}) \cdot ((\mathbf{u}_n - \mathbf{u}) \cdot \nabla) \mathbf{u}_n \, dx - \int_{\Omega} (\mathbf{w}_n - \mathbf{w}) \cdot (\mathbf{u}_n \cdot \nabla)(\mathbf{u}_n - \mathbf{u}) \, dx.$$

By Hölder inequality, we derive

$$\begin{aligned} & O(\mathbf{w}_n - \mathbf{w}; \mathbf{u}_n, \mathbf{u}_n - \mathbf{u}) \\ & \leq \|\mathbf{w}_n - \mathbf{w}\|_{\mathbf{L}^3(\Omega)} \|\mathbf{u}_n - \mathbf{u}\|_{\mathbf{L}^6(\Omega)} \|\nabla \mathbf{u}_n\|_{\mathbf{L}^2(\Omega)} + \|\mathbf{w}_n - \mathbf{w}\|_{\mathbf{L}^3(\Omega)} \|\mathbf{u}_n\|_{\mathbf{L}^6(\Omega)} \|\nabla(\mathbf{u}_n - \mathbf{u})\|_{\mathbf{L}^2(\Omega)}. \end{aligned}$$

Then, since $\mathbf{H}^1(\Omega)$ is continuously embedded in $\mathbf{L}^6(\Omega)$, we have

$$O(\mathbf{w}_n - \mathbf{w}; \mathbf{u}_n, \mathbf{u}_n - \mathbf{u}) \leq C \|\mathbf{w}_n - \mathbf{w}\|_{\mathbf{L}^3(\Omega)} \|\mathbf{u}_n\|_{\mathbf{H}^1(\Omega)} \|\mathbf{u}_n - \mathbf{u}\|_{\mathbf{H}^1(\Omega)}. \quad (2.36)$$

Similarly, we have

$$\begin{aligned} D(\phi_n - \phi, \mathbf{u}_n - \mathbf{u}) & \leq \|\phi_n - \phi\|_{\mathbf{L}^3(\Omega)} \|\mathbf{g}\|_{\mathbf{L}^2(\Omega)} \|\mathbf{u}_n - \mathbf{u}\|_{\mathbf{L}^6(\Omega)} \\ & \leq C \|\phi_n - \phi\|_{\mathbf{L}^3(\Omega)} \|\mathbf{g}\|_{\mathbf{L}^2(\Omega)} \|\mathbf{u}_n - \mathbf{u}\|_{\mathbf{H}^1(\Omega)} \end{aligned} \quad (2.37)$$

Combining the inequalities (2.36) and (2.37) into (2.33), we obtain

$$\nu\alpha_A \|\mathbf{u}_n - \mathbf{u}\|_{\mathbf{H}^1(\Omega)} \leq C \|\mathbf{w}_n - \mathbf{w}\|_{\mathbf{L}^3(\Omega)} \|\mathbf{u}_n\|_{\mathbf{H}^1(\Omega)} + C \|\phi_n - \phi\|_{L^3(\Omega)} \|\mathbf{g}\|_{L^2(\Omega)}. \quad (2.38)$$

Now, taking $\varphi = \theta_n - \theta$ in (2.31b), using the coercivity of M (c.g. (2.13)) together with Hölder inequality, we derive

$$\begin{aligned} \kappa\alpha_M \|\theta_n - \theta\|_{H^1(\Omega)}^2 &\leq \mathcal{C}(\mathbf{w}; \theta, \theta_n - \theta) - \mathcal{C}(\mathbf{w}_n; \theta_n, \theta_n - \theta) \\ &:= \mathcal{C}(\mathbf{w}_n - \mathbf{w}; \theta_n, \theta_n - \theta) - \underbrace{\mathcal{C}(\mathbf{w}; \theta_n - \theta, \theta_n - \theta)}_{=0} \\ &\leq \|\mathbf{w}_n - \mathbf{w}\|_{\mathbf{L}^3(\Omega)} \|\nabla\theta_n\|_{L^2(\Omega)} \|\theta_n - \theta\|_{L^6(\Omega)} \end{aligned}$$

Using again the continuous embedding of $H^1(\Omega)$ in $L^6(\Omega)$, we obtain

$$\kappa\alpha_M \|\theta_n - \theta\|_{H^1(\Omega)} \leq C \|\mathbf{w}_n - \mathbf{w}\|_{\mathbf{L}^3(\Omega)} \|\theta_n\|_{H^1(\Omega)} \quad (2.39)$$

Since $\mathbf{w}_n \rightharpoonup \mathbf{w}$ weakly in $\mathbf{H}^1(\Omega)$ and $\phi_n \rightharpoonup \phi$ weakly in $H^1(\Omega)$, therefore $\mathbf{w}_n \rightharpoonup \mathbf{w}$ strongly in $\mathbf{L}^3(\Omega)$ and $\phi_n \rightarrow \phi$ strongly in $L^3(\Omega)$. Moreover, we note that the sequence $\{(\mathbf{w}_n, \phi_n)\}_n$ is bounded. Since (\mathbf{u}_n, θ_n) and (\mathbf{u}, θ) satisfy (2.24), they are also bounded in the corresponding H^1 norm. By (2.38) and (2.39), we conclude that $(\mathbf{u}_n, \theta_n) \rightarrow (\mathbf{u}, \theta)$ strongly in $\mathbf{K} \times H^1(\Omega)$. Hence, we obtain compactness of the operator \mathcal{S} .

Step 2 : We show that there exists a constant $C_* > 0$ such that $\|(\mathbf{u}, \theta)\| \leq C_*$ for any $(\mathbf{u}, \theta) \in \mathbf{K} \times H_0^1(\Omega)$ and for any $\lambda \in [0, 1]$ such that $(\mathbf{u}, \theta) = \lambda \mathcal{S}(\mathbf{u}, \theta)$.

By the definition of \mathcal{S} , we have:

$$\begin{aligned} A(\mathbf{u}, \mathbf{v}) &= D(\lambda\theta, \mathbf{v}) - O(\lambda\mathbf{u}; \mathbf{u}, \mathbf{v}), \quad \forall \mathbf{v} \in \mathbf{K}, \\ M(\theta, \psi) &= F(\psi) - \mathcal{C}(\lambda\mathbf{u}; \theta, \psi), \quad \forall \psi \in H_0^1(\Omega). \end{aligned} \quad (2.40)$$

Choosing $(\mathbf{v}, \psi) = (\mathbf{u}, \theta)$ and using the properties (2.14) and (2.15), we obtain

$$A(\mathbf{u}, \mathbf{u}) = D(\lambda\theta, \mathbf{u}) \quad \text{and} \quad M(\theta, \theta) = F(\theta) \quad (2.41)$$

From the coercivity of A and M (c.f. (2.12) and (2.13)) and the continuity of D and F (c.f. (2.22) and (2.19)), we have immediately that

$$\|\mathbf{u}\|_{\mathbf{H}^1(\Omega)} \leq \lambda\nu^{-1}\alpha_A^{-1}C_D \|\theta\|_{H^1(\Omega)} \|\mathbf{g}\|_{L^2(\Omega)} \quad \text{and} \quad \|\theta\|_{H^1(\Omega)} \leq \kappa^{-1}\alpha_M^{-1}C_F \|f\|_{L^2(\Omega)}.$$

Then, using the fact that $\lambda \leq 1$, it follows

$$\|\mathbf{u}\|_{\mathbf{H}^1(\Omega)} \leq K_1(\nu, \kappa, \mathbf{g}, f) \quad \text{and} \quad \|\theta\|_{H^1(\Omega)} \leq K_2(\kappa, f), \quad (2.42)$$

where $K_1(\nu, \kappa, \mathbf{g}, f)$ and $K_2(\kappa, f)$ are the following positive constants independent of (\mathbf{u}, θ) and λ :

$$K_1(\nu, \kappa, \mathbf{g}, f) = \nu^{-1}\alpha_A^{-1}C_D K_2(\kappa, f) \|\mathbf{g}\|_{L^2(\Omega)} \quad \text{and} \quad K_2(\kappa, f) = \kappa^{-1}\alpha_M^{-1}C_F \|f\|_{L^2(\Omega)}. \quad (2.43)$$

It follows from (2.42) that $\|(\mathbf{u}, \theta)\| \leq C_*$ with $C_* = K_1(\nu, \kappa, \mathbf{g}, f) + K_2(\kappa, f)$ is a positive constant independent of (\mathbf{u}, θ) and λ . Finally, by Leray-Schauder fixed point theorem, there exists a fixed point $(\mathbf{u}, \theta) \in \mathbf{K} \times H_0^1(\Omega)$ for the operator \mathcal{S} which is a solution of (2.8). The estimate (2.23) follows directly from (2.42) and (2.43).

Now, we show the uniqueness of the solution of (2.6). Suppose that $(\mathbf{u}_1, \theta_1, p_1)$ and $(\mathbf{u}_2, \theta_2, p_2)$ are two solutions of (2.6). We set $\mathbf{u} = \mathbf{u}_1 - \mathbf{u}_2$, $\theta = \theta_1 - \theta_2$, $p = p_1 - p_2$ and we want to prove that

$\mathbf{u} = \mathbf{0}$, $\theta = 0$ and $p = 0$. Since (\mathbf{u}_1, θ_1) and (\mathbf{u}_2, θ_2) are solutions of (2.8), substituting (\mathbf{u}_1, θ_1) and (\mathbf{u}_2, θ_2) in (2.8) and subtracting corresponding equations, we obtain

$$A(\mathbf{u}, \mathbf{v}) = -O(\mathbf{u}; \mathbf{u}_1, \mathbf{v}) + O(\mathbf{u}_2; \mathbf{u}, \mathbf{v}) + D(\theta, \mathbf{v}), \quad \forall \mathbf{v} \in \mathbf{K}, \quad (2.44a)$$

$$M(\theta, \psi) = \mathcal{C}(\mathbf{u}; \theta_2, \psi) - \mathcal{C}(\mathbf{u}_2; \theta, \psi), \quad \forall \psi \in H_0^1(\Omega). \quad (2.44b)$$

Choosing $\mathbf{v} = \mathbf{u}$ in (2.44a) and $\psi = \theta$ in (2.44b), summing up the two relations, we obtain :

$$A(\mathbf{u}, \mathbf{u}) + M(\theta, \theta) = -O(\mathbf{u}; \mathbf{u}_1, \mathbf{u}) + \mathcal{C}(\mathbf{u}; \theta_2, \theta) + D(\theta, \mathbf{u}).$$

Applying Proposition (2.1), we obtain

$$\min(\nu\alpha_A, \kappa\nu_M)^{-1} (\|\mathbf{u}\|_{\mathbf{H}^1(\Omega)}^2 + \|\theta\|_{H^1(\Omega)}^2) \leq |O(\mathbf{u}; \mathbf{u}_1, \mathbf{u})| + |\mathcal{C}(\mathbf{u}; \theta_2, \theta)| + |D(\theta, \mathbf{u})| \quad (2.45)$$

Let us bound the nonlinear terms on the right hand side of (2.45). Using the continuity of the form O from (2.20) and the estimate (2.42) for \mathbf{u}_1 , we obtain:

$$\begin{aligned} |O(\mathbf{u}; \mathbf{u}_1, \mathbf{u})| &\leq C_o \|\mathbf{u}_1\|_{\mathbf{H}^1(\Omega)} \|\mathbf{u}\|_{\mathbf{H}^1(\Omega)}^2 \\ &\leq C_o K_1(\nu, \kappa, \mathbf{g}, f) \|\mathbf{u}\|_{\mathbf{H}^1(\Omega)}^2. \end{aligned} \quad (2.46)$$

After using the continuity of the form \mathcal{C} from (2.21), the Hölder inequality and the estimate (2.42) for θ_2 , we derive :

$$\begin{aligned} |\mathcal{C}(\mathbf{u}; \theta_2, \theta)| &\leq C_c \|\mathbf{u}\|_{\mathbf{H}^1(\Omega)} \|\theta_2\|_{H^1(\Omega)} \|\theta\|_{H^1(\Omega)} \\ &\leq \frac{1}{2} C_c K_2(\kappa, f) (\|\mathbf{u}\|_{\mathbf{H}^1(\Omega)}^2 + \|\theta\|_{H^1(\Omega)}^2) \end{aligned} \quad (2.47)$$

Similarly, using the continuity of the form D from (2.22) and the Hölder inequality, we obtain

$$\begin{aligned} |D(\theta, \mathbf{u})| &\leq C_D \|\theta\|_{H^1(\Omega)} \|\mathbf{g}\|_{L^2(\Omega)} \|\mathbf{u}\|_{\mathbf{H}^1(\Omega)} \\ &\leq \frac{1}{2} C_D \|\mathbf{g}\|_{L^2(\Omega)} (\|\mathbf{u}\|_{\mathbf{H}^1(\Omega)}^2 + \|\theta\|_{H^1(\Omega)}^2) \end{aligned} \quad (2.48)$$

Collecting the above inequalities into (2.45), we derive

$$\begin{aligned} &\min(\nu\alpha_A, \kappa\nu_M)^{-1} (\|\mathbf{u}\|_{\mathbf{H}^1(\Omega)}^2 + \|\theta\|_{H^1(\Omega)}^2) \\ &\leq \max(C_o \|\mathbf{u}_1\|_{\mathbf{H}^1(\Omega)}, \frac{1}{2} C_c K_2(\kappa, f), \frac{1}{2} C_D \|\mathbf{g}\|_{L^2(\Omega)}) (\|\mathbf{u}\|_{\mathbf{H}^1(\Omega)}^2 + \|\theta\|_{H^1(\Omega)}^2) \end{aligned} \quad (2.49)$$

Setting

$$K_3 = \max(C_o K_1(\nu, \kappa, \mathbf{g}, f), \frac{1}{2} C_c K_2(\kappa, f), \frac{1}{2} C_D \|\mathbf{g}\|_{L^2(\Omega)}), \quad (2.50)$$

this implies that if $\min(\nu\alpha_A, \kappa\nu_M) K_3 < 1$, we have $\mathbf{u} = \mathbf{0}$ and $\theta = 0$.

Next, since $(\mathbf{u}_1, \theta_1, p_1)$ and $(\mathbf{u}_2, \theta_2, p_2)$ are two solutions of (2.6), it follows that

$$B(\mathbf{v}, p_1 - p_2) = D(\theta, \mathbf{v}) - A(\mathbf{u}, \mathbf{v}) - O(\mathbf{u}; \mathbf{u}_1, \mathbf{v}) + O(\mathbf{u}_2; \mathbf{u}, \mathbf{v}) = 0.$$

We then conclude by using the inf-sup condition in (2.9) that $p_1 - p_2 = 0$. This completes the proof.

3 The DG finite element approximation

In this section, we introduce a mixed DG approximation for the Boussinesq system (1.3). We provide the solvability and stability of the discrete scheme. To this end, let us introduce some notations. We assume the domain Ω is discretized by a discrete family of conforming meshes \mathcal{T}_h made of tetrahedra. The index h is indicative of the mesh size h which is defined as $h = \max_{T \in \mathcal{T}_h} h_T$, where h_T is the diameter of T . The family is supposed to be regular in Ciarlet's sense [7], i.e. there exists $\varsigma > 0$ independent of h such that the ratio

$$\frac{h_T}{\rho_T} \leq \varsigma, \quad \forall T \in \mathcal{T}_h, \quad (3.1)$$

where ρ_T is the diameter of the inscribed ball in T . We shall use the assumption (3.1) throughout this work. Let us denote by \mathcal{F}_h^I the set of internal faces and by \mathcal{F}_h^Γ the set of external faces on Γ . We set $\mathcal{F}_h = \mathcal{F}_h^I \cup \mathcal{F}_h^\Gamma$. We denote by h_e the diameter of each face e . Let T^+ and T^- be two adjacent elements of \mathcal{T}_h and let \mathbf{n}^+ (respectively \mathbf{n}^-) be the outward unit normal vector on ∂T^+ (respectively ∂T^-). For a vector field \mathbf{u} , we denote by \mathbf{u}^\pm the trace of \mathbf{u} from the interior of T^\pm . We define jumps

$$[[\mathbf{v}]]_T := \mathbf{n}^+ \times \mathbf{v}^+ + \mathbf{n}^- \times \mathbf{v}^-, \quad [[\mathbf{v}]]_N := \mathbf{v}^+ \cdot \mathbf{n}^+ + \mathbf{v}^- \cdot \mathbf{n}^-, \quad [q] := q^+ \mathbf{n}^+ + q^- \mathbf{n}^-, \quad \llbracket \mathbf{v} \rrbracket = \mathbf{v}^+ - \mathbf{v}^-,$$

and averages

$$\{\!\{ \mathbf{v} \}\!\} := \frac{1}{2}(\mathbf{v}^+ + \mathbf{v}^-), \quad \{\!\{ q \}\!\} := \frac{1}{2}(q^+ + q^-),$$

and adopt the convention that for boundary faces $e \in \mathcal{F}_h^\Gamma$, we set $[[\mathbf{v}]]_T = \mathbf{v} \times \mathbf{n}$, $[[\mathbf{v}]]_N = \mathbf{v} \cdot \mathbf{n}$, $[q] = q\mathbf{n}$, $\{\!\{ \mathbf{v} \}\!\} = \mathbf{v}$ and $\{\!\{ q \}\!\} = q$. Let $\mathcal{P}_k(T)$ denotes the space of polynomials of total degree at most k on T with $k = 1, 2$ or 3 . The corresponding vector-valued function space is denoted by $\mathcal{P}_k(T)$.

3.1 Defining discrete problem

Now, we introduce the following finite element spaces which respectively approximate \mathbf{u} , θ and p :

$$\begin{aligned} \mathbf{X}_h &:= \{ \mathbf{v}_h \in \mathbf{L}^2(\Omega); \mathbf{v}_h|_T \in \mathcal{P}_k(T), \forall T \in \mathcal{T}_h \}, \\ Z_h &:= \{ \psi_h \in L^2(\Omega); \psi_h|_T \in \mathcal{P}_k(T), \forall T \in \mathcal{T}_h \}, \\ Q_h &:= \{ q_h \in L_0^2(\Omega); q_h|_T \in \mathcal{P}_{k-1}(T), \forall T \in \mathcal{T}_h \}. \end{aligned}$$

We denote by \mathbf{W}_h the product space $\mathbf{X}_h \times Z_h$. The norm $\|\cdot\|_{\mathbf{L}^2(\mathcal{T}_h)}$ is defined by

$$\|\cdot\|_{\mathbf{L}^2(\mathcal{T}_h)} = \sum_{T \in \mathcal{T}_h} \|\cdot\|_{0,T}, \quad \text{for any } T \in \mathcal{T}_h,$$

with $\|\cdot\|_{0,T} = \|\cdot\|_{\mathbf{L}^2(T)}$. Similarly, we use the notation $\|\cdot\|_{0,e} = \|\cdot\|_{\mathbf{L}^2(e)}$ for any $e \in \mathcal{F}_h$.

The mixed DG scheme reads: Find $((\mathbf{u}_h, \theta_h), p_h) \in \mathbf{W}_h \times Q_h$ such that

$$A_h(\mathbf{u}_h, \mathbf{v}_h) + O_h(\mathbf{u}_h; \mathbf{u}_h, \mathbf{v}_h) + B_h(\mathbf{v}_h, p_h) = D_h(\theta_h, \mathbf{v}_h), \quad (3.2a)$$

$$B_h(\mathbf{u}_h, q_h) = 0, \quad (3.2b)$$

$$M_h(\theta_h, \psi_h) + C_h(\mathbf{u}_h; \theta_h, \psi_h) = F_h(\psi_h), \quad (3.2c)$$

for all $(\mathbf{v}_h, \psi_h) \in \mathbf{W}_h$ and $q_h \in Q_h$.

The bilinear form A_h is defined by

$$\begin{aligned}
A_h(\mathbf{u}_h, \mathbf{v}_h) &:= \nu \sum_{T \in \mathcal{T}_h} \int_T \mathbf{curl} \mathbf{u}_h \cdot \mathbf{curl} \mathbf{v}_h \, d\mathbf{x} + \nu \sum_{T \in \mathcal{T}_h} \int_T (\operatorname{div} \mathbf{u}_h)(\operatorname{div} \mathbf{v}_h) \, d\mathbf{x} \\
&- \nu \sum_{e \in \mathcal{F}_h^I} \left(\int_e \{\{\mathbf{curl} \mathbf{u}_h\}\} \cdot \llbracket \mathbf{v}_h \rrbracket_T \, ds + \int_e \{\{\mathbf{curl} \mathbf{v}_h\}\} \cdot \llbracket \mathbf{u}_h \rrbracket_T \, ds \right) \\
&- \nu \sum_{e \in \mathcal{F}_h} \left(\int_e \{\{\operatorname{div} \mathbf{u}_h\}\} \llbracket \mathbf{v}_h \rrbracket_N \, ds + \int_e \{\{\operatorname{div} \mathbf{v}_h\}\} \llbracket \mathbf{u}_h \rrbracket_N \, ds \right) \\
&+ \nu \sum_{e \in \mathcal{F}_h^I} \frac{\sigma}{h_e} \int_e \llbracket \mathbf{u}_h \rrbracket_T \cdot \llbracket \mathbf{v}_h \rrbracket_T \, ds + \nu \sum_{e \in \mathcal{F}_h} \frac{\sigma}{h_e} \int_e \llbracket \mathbf{u}_h \rrbracket_N \llbracket \mathbf{v}_h \rrbracket_N \, ds
\end{aligned}$$

with $\sigma > 0$ a stabilization parameter that will be chosen large enough. The two last terms in the definition of A_h involving the tangential and normal jumps of the discrete vector fields across the edges are necessary to ensure the coercivity of the bilinear form A_h .

We define the convective term in the Navier-Stokes equations with :

$$O_h(\mathbf{w}_h; \mathbf{u}_h, \mathbf{v}_h) := \sum_{T \in \mathcal{T}_h} \int_T (\mathbf{curl} \mathbf{w}_h \times \mathbf{u}_h) \cdot \mathbf{v}_h \, d\mathbf{x} \quad (3.3)$$

The divergence constraint on the velocity is represented by B_h :

$$B_h(\mathbf{v}_h, q_h) := - \sum_{T \in \mathcal{T}_h} \int_T (\operatorname{div} \mathbf{v}_h) q_h \, d\mathbf{x} + \sum_{e \in \mathcal{F}_h} \int_e \{\{q_h\}\} \llbracket \mathbf{v}_h \rrbracket_N \, ds. \quad (3.4)$$

The coupling form D_h is defined by

$$D_h(\theta_h, \mathbf{v}_h) = \sum_{T \in \mathcal{T}_h} \int_T (\theta_h \mathbf{g}) \cdot \mathbf{v}_h$$

The bilinear form M_h is defined by:

$$\begin{aligned}
M_h(\theta_h, \psi_h) &:= \kappa \sum_{T \in \mathcal{T}_h} \int_T \nabla \theta_h \cdot \nabla \psi_h \, d\mathbf{x} - \kappa \sum_{e \in \mathcal{F}_h} \left(\int_e \{\{\nabla \theta_h\}\} \cdot \llbracket \psi_h \rrbracket + \sum_{e \in \mathcal{F}_h} \int_e \{\{\nabla \psi_h\}\} \cdot \llbracket \theta_h \rrbracket \right) \\
&+ \sum_{e \in \mathcal{F}_h} \frac{\kappa \gamma}{h_e} \int_e \llbracket \theta_h \rrbracket \cdot \llbracket \psi_h \rrbracket \, ds
\end{aligned}$$

with $\gamma > 0$ is a stabilization parameter that will be chosen large enough to ensure the coercivity of the bilinear form M_h .

We use the upwinding of Lesaint-Raviart [17] to discretize the convection term $\mathbf{u} \cdot \nabla \theta$. So, the coupling form C_h using upwind fluxes is defined by :

$$\begin{aligned}
C_h(\mathbf{w}_h; \theta_h, \psi_h) &:= \sum_{T \in \mathcal{T}_h} \left(\int_T (\mathbf{w}_h \cdot \nabla \theta_h) \psi_h \, d\mathbf{x} + \int_{\partial T_-} | \{\{\mathbf{w}_h\}\} \cdot \mathbf{n}_T | (\theta_h^{int} - \theta_h^{ext}) \psi_h^{int} \, ds \right), \\
&+ \frac{1}{2} \sum_{T \in \mathcal{T}_h} \int_T (\operatorname{div} \mathbf{w}_h) \theta_h \cdot \psi_h \, d\mathbf{x} - \frac{1}{2} \sum_{e \in \mathcal{F}_h} \int_e \llbracket \mathbf{w}_h \rrbracket_N \{\{\theta_h \cdot \psi_h\}\} \, ds,
\end{aligned} \quad (3.5)$$

where θ_h^{int} , ψ_h^{int} (respectively θ_h^{ext}) refers to the trace of θ_h and ψ_h (respectively of θ_h) on a side of

T taken from the interior of T (respectively taken from the exterior of T on that side). ∂T_- denotes the inflow boundary of T defined by

$$\partial T_- = \{\mathbf{x} \in \partial T : \{\{\mathbf{u}\}\} \cdot \mathbf{n} < 0\}.$$

Finally, the form F_h is defined by

$$F_h(\psi_h) = \int_{\Omega} f \psi_h \, d\mathbf{x}.$$

3.2 Preliminary results

We need to introduce the following semi-norms

$$|\mathbf{v}_h|_{1,h}^2 := \sum_{T \in \mathcal{T}_h} \|\operatorname{div} \mathbf{v}_h\|_{0,T}^2 + \sum_{T \in \mathcal{T}_h} \|\operatorname{curl} \mathbf{v}_h\|_{0,T}^2, \quad \forall \mathbf{v}_h \in \mathbf{X}_h.$$

and

$$\begin{aligned} \|\mathbf{v}_h\|^2 &:= |\mathbf{v}_h|_{1,h}^2 + \sum_{e \in \mathcal{F}_h} \frac{\sigma}{h_e} \|[\![\mathbf{v}_h]\!]_N\|_{0,e}^2 + \sum_{e \in \mathcal{F}_h^I} \frac{\sigma}{h_e} \|[\![\mathbf{v}_h]\!]_T\|_{0,e}^2, \quad \forall \mathbf{v}_h \in \mathbf{X}_h. \\ \|\psi_h\|_h^2 &:= \sum_{T \in \mathcal{T}_h} \|\nabla \psi_h\|_{0,T}^2 + \sum_{e \in \mathcal{F}_h} \frac{\gamma}{h_e} \|[\![\psi_h]\!]_{0,e}\|_{0,e}^2, \quad \forall \psi_h \in Z_h. \\ \|q_h\|_{Q_h}^2 &:= \|q_h\|_{0,\Omega}^2, \quad \forall q_h \in Q_h. \end{aligned}$$

The proof of the following Lemma follows along the same lines as Lemma 10.2.1 in [28]. We carry out the details for the sake of completeness.

Lemma 3.1 *For σ and γ large enough, there exists positive constants α_{A_h} , α_{M_h} independent of h such that:*

$$A_h(\mathbf{u}_h, \mathbf{u}_h) \geq \alpha_{A_h} \nu \|\mathbf{u}_h\|^2, \quad \forall \mathbf{u}_h \in \mathbf{X}_h, \quad (3.6a)$$

$$M_h(\theta_h, \theta_h) \geq \alpha_{M_h} \kappa \|\theta_h\|_h^2, \quad \forall \theta_h \in Z_h. \quad (3.6b)$$

Proof. For the proof of (3.6a), we use similar arguments in [25]. Let $\mathbf{u}_h \in \mathbf{X}_h$, we have:

$$\begin{aligned} A_h(\mathbf{u}_h, \mathbf{u}_h) &= \nu \sum_{T \in \mathcal{T}_h} (\|\operatorname{curl} \mathbf{u}_h\|_{0,T}^2 + \|\operatorname{div} \mathbf{u}_h\|_{0,T}^2) \\ &\quad - 2\nu \sum_{e \in \mathcal{F}_h^I} \int_e \{\{\operatorname{curl} \mathbf{u}_h\}\} \cdot [\![\mathbf{u}_h]\!]_T \, ds - 2\nu \sum_{e \in \mathcal{F}_h} \int_e \{\{\operatorname{div} \mathbf{u}_h\}\} [\![\mathbf{u}_h]\!]_N \, ds \\ &\quad + \nu \sum_{e \in \mathcal{F}_h^I} \frac{\sigma}{h_e} \|[\![\mathbf{u}_h]\!]_T\|_{0,e}^2 + \nu \sum_{e \in \mathcal{F}_h} \frac{\sigma}{h_e} \|[\![\mathbf{u}_h]\!]_N\|_{0,e}^2. \end{aligned} \quad (3.7)$$

Using the Cauchy-Schwarz inequality, we have:

$$2\nu \sum_{e \in \mathcal{F}_h^I} \int_e \{\{\operatorname{curl} \mathbf{u}_h\}\} \cdot [\![\mathbf{u}_h]\!]_T \, ds \leq 2C_1 \nu \left(\sum_{T \in \mathcal{T}_h} \|\operatorname{curl} \mathbf{u}_h\|_{0,T}^2 \right)^{1/2} \left(\sum_{e \in \mathcal{F}_h^I} h_e^{-1} \|[\![\mathbf{u}_h]\!]_T\|_{0,e}^2 \right)^{1/2}$$

$$\leq 2C_1\nu\|\mathbf{u}_h\|\left(\sum_{e\in\mathcal{F}_h^I}h_e^{-1}\|\llbracket\mathbf{u}_h\rrbracket_T\|_{0,e}^2\right)^{\frac{1}{2}}.$$

In the same way, we get

$$2\nu\sum_{e\in\mathcal{F}_h}\int_e\{\{\operatorname{div}\mathbf{u}_h\}\}\llbracket\mathbf{u}_h\rrbracket_N ds\leq 2C_2\nu\|\mathbf{u}_h\|\left(\sum_{e\in\mathcal{F}_h}h_e^{-1}\|\llbracket\mathbf{u}_h\rrbracket_N\|_{0,e}^2\right)^{\frac{1}{2}},$$

where C_1 and C_2 are a positive constants independent of h .

Applying now Young's inequality, we obtain

$$A_h(\mathbf{u}_h, \mathbf{u}_h) \geq \nu\left(1 - \frac{C}{\sigma}\right)\|\mathbf{u}_h\|^2,$$

with $C = C_1 + C_2$. Therefore, the estimate (3.6a) follows by assuming that $\sigma > C$.

For the proof of (3.6b), we refer the reader to [8, 17]

□

We will need the following inf-sup condition on B_h , where the proof can be found in [25, 28].

Lemma 3.2 *There exists $\beta > 0$ only depending on Ω such that :*

$$\inf_{q_h\in Q_h}\sup_{\mathbf{v}_h\in\mathbf{X}_h}\frac{B_h(\mathbf{v}_h, q_h)}{\|\mathbf{v}_h\|\|q_h\|_{Q_h}}\geq\beta. \quad (3.8)$$

Lemma 3.3 *Let $\mathbf{u}_h, \mathbf{v}_h \in X_h, \theta_h, \psi_h \in Z_h$ and $p_h \in L_0^2(\Omega)$. Then, we have :*

$$|A_h(\mathbf{u}_h, \mathbf{v}_h)| \leq C_{A_h}\nu\|\mathbf{u}_h\|\|\mathbf{v}_h\|, \quad (3.9a)$$

$$|M_h(\theta_h, \psi_h)| \leq C_{M_h}\kappa\|\theta_h\|_h\|\psi_h\|_h, \quad (3.9b)$$

$$|B_h(\mathbf{v}_h, p_h)| \leq C_{B_h}\|\mathbf{v}_h\|\|p_h\|_{0,\Omega}, \quad (3.9c)$$

$$|F_h(\psi_h)| \leq C_{F_h}\|f\|_{L^2(\Omega)}\|\psi_h\|_h, \quad (3.9d)$$

where $C_{A_h}, C_{M_h}, C_{B_h}$ and C_{F_h} are positive constants independent of h .

Proof. The proof of the continuity properties (3.9b), (3.9c) can be found in [8, 17, 23] and the continuity of A_h and F_h follows from the Cauchy-Schwarz inequality has been proved in [25]. □

Next, we recall the following discrete Sobolev inequality for discontinuous finite element spaces (see [17, Lemma 3.1]) :

$$\forall\psi_h\in Z_h, \quad \|\psi_h\|_{L^6(\Omega)}\leq C\|\psi_h\|_h, \quad (3.10)$$

where the constant $C > 0$ is independent of h . This inequality is not still valid when the norm $\|\cdot\|_h$ is replaced by $\|\cdot\|$ without supposing more regularity on the boundary Γ . When it is Lipschitz polyhedral, we have the following discrete Poincaré-Friedrichs inequality (see [31, Lemma 3.1])

$$\forall\mathbf{v}_h\in\mathbf{X}_h, \quad \|\mathbf{v}_h\|_{L^2(\Omega)}\leq C\|\mathbf{v}_h\|. \quad (3.11)$$

When the boundary Γ is of class $\mathcal{C}^{2,1}$, an extension of the previous inequality is proved in [26, Lemma 3.4.2] for the L^p norm with $p \in (1, 6]$:

$$\forall\mathbf{v}_h\in\mathbf{X}_h, \quad \|\mathbf{v}_h\|_{L^p(\Omega)}\leq C\|\mathbf{v}_h\|. \quad (3.12)$$

The discrete Sobolev inequality (3.12) plays an important role in the stability of our DG scheme. Indeed, with $p = 4$, this inequality allows to apply an $L^4 - L^2 - L^4$ to bound the terms on T in the nonlinear forms O_h and \mathcal{C}_h . So, starting now, we shall make the additional smoothness assumptions on Ω . Indeed, we suppose that the domain Ω has a boundary of class $\mathcal{C}^{2,1}$.

Lemma 3.4 *We have*

$$\forall \theta_h \in Z_h, \forall \mathbf{u}_h \in \mathbf{X}_h \quad |D_h(\theta_h, \mathbf{u}_h)| \leq C_{D_h} \|g\|_{0,\Omega} \|\theta_h\|_h \|\mathbf{u}_h\|, \quad (3.13a)$$

$$\forall \mathbf{w}_h, \mathbf{u}_h, \mathbf{v}_h \in \mathbf{X}_h, \quad |O_h(\mathbf{w}_h; \mathbf{u}_h, \mathbf{v}_h)| \leq C_{O_h} \|\mathbf{w}_h\| \|\mathbf{u}_h\| \|\mathbf{v}_h\| \quad (3.13b)$$

$$\forall \mathbf{w}_h \in \mathbf{X}_h, \forall \theta_h, \psi_h \in Z_h, \quad |C_h(\mathbf{w}_h; \theta_h, \psi_h)| \leq C_{C_h} \|\mathbf{w}_h\| \|\theta_h\|_h \|\psi_h\|_h \quad (3.13c)$$

where C_{D_h} , C_{O_h} and C_{C_h} are positive constants independent of h .

Proof. Using Hölder's inequality, we can easily obtain

$$|D_h(\theta_h, \mathbf{v}_h)| \leq \|g\|_{0,\Omega} \|\theta_h\|_{L^6(\Omega)} \|\mathbf{v}_h\|_{L^3(\Omega)}. \quad (3.14)$$

Thanks to (3.10) and to (3.12) with $p = 3$, we have (3.13a).

Applying Cauchy-Schwarz inequality, we obtain

$$|O_h(\mathbf{w}_h; \mathbf{u}_h, \mathbf{v}_h)| = \left| \sum_{T \in \mathcal{T}_h} \int_T (\mathbf{curl} \mathbf{w}_h \times \mathbf{u}_h) \cdot \mathbf{v}_h \, dx \right| \leq 2 \|\mathbf{curl} \mathbf{w}_h\|_{L^2(\mathcal{T}_h)} \|\mathbf{u}_h\|_{L^3(\Omega)} \|\mathbf{v}_h\|_{L^6(\Omega)}.$$

By virtue of (3.12), the estimate (3.13b) follows immediately.

Now, applying the Sobolev embedding (3.12) with $p = 4$ and the trace inequalities (see for instance [8, Proposition 4.2]), we get (3.13c). \square

We define the space

$$\mathbf{K}_h = \{\mathbf{v}_h \in \mathbf{X}_h; \quad B_h(\mathbf{u}_h, q_h) = 0, \quad \forall q_h \in Q_h\}$$

and the discrete energy norm on $\mathbf{K}_h \times Z_h$:

$$\|(\mathbf{u}_h, \theta_h)\|_h = \left(\|\mathbf{u}_h\|^2 + \|\theta_h\|_h^2 \right)^{1/2}.$$

It is well-known (see, e.g., [17], [18]) that

$$C_h(\mathbf{w}_h; \theta_h, \theta_h) := \frac{1}{2} \sum_{T \in \mathcal{T}_h} \int_{\partial T^-} |\{\{\mathbf{w}_h\}\} \cdot \mathbf{n}_T| \|\theta_h^{int} - \theta_h^{ext}\|^2 \, ds + \frac{1}{2} \int_{\Gamma_+} |\mathbf{w}_h \cdot \mathbf{n}_T| \|\theta_h\|^2 \, ds \geq 0. \quad (3.15)$$

Moreover, since the vector $\mathbf{curl} \mathbf{w}_h \times \mathbf{v}_h$ is orthogonal to \mathbf{v}_h , it is clear that for any $\mathbf{w}_h, \mathbf{v}_h$ in \mathbf{X}_h :

$$O_h(\mathbf{w}_h; \mathbf{v}_h, \mathbf{v}_h) = \sum_{T \in \mathcal{T}_h} \int_T (\mathbf{curl} \mathbf{w}_h \times \mathbf{v}_h) \cdot \mathbf{v}_h \, dx = 0, \quad (3.16)$$

To establish the well posedness of the DG scheme, we first eliminate the pressure from the problem by restricting ourselves to the space \mathbf{K}_h . So, we consider the following problem: Find $(\mathbf{u}_h, \theta_h) \in \mathbf{K}_h \times Z_h$ such that

$$A_h(\mathbf{u}_h, \mathbf{v}_h) + O_h(\mathbf{u}_h; \mathbf{u}_h, \mathbf{v}_h) = D_h(\theta_h, \mathbf{v}_h), \quad \forall \mathbf{v}_h \in \mathbf{K}_h, \quad (3.17a)$$

$$M_h(\theta_h, \psi_h) + C_h(\mathbf{u}_h; \theta_h, \psi_h) = F_h(\psi_h), \quad \forall \psi_h \in Z_h. \quad (3.17b)$$

We define the operator \mathcal{S}_h by:

$$\begin{aligned} \mathcal{S}_h: \mathbf{K}_h \times Z_h &\rightarrow \mathbf{K}_h \times Z_h \\ (\mathbf{w}_h, \phi_h) &\mapsto \mathcal{S}_h(\mathbf{w}_h, \phi_h) = (\mathbf{u}_h, \theta_h), \end{aligned}$$

where (\mathbf{u}_h, θ_h) is the solution of the linearized problem: Find $(\mathbf{u}_h, \theta_h) \in \mathbf{K}_h \times Z_h$ such that

$$A_h(\mathbf{u}_h, \mathbf{v}_h) + O_h(\mathbf{w}_h; \mathbf{u}_h, \mathbf{v}_h) = D_h(\phi_h, \mathbf{v}_h), \quad \forall \mathbf{v}_h \in \mathbf{K}_h, \quad (3.18a)$$

$$M_h(\theta_h, \psi_h) + \mathcal{C}_h(\mathbf{w}_h; \theta_h, \psi_h) = F_h(\psi_h), \quad \forall \psi_h \in Z_h. \quad (3.18b)$$

Then, the problem (3.17a)-(3.17b) can be rewritten equivalently as the following fixed-point problem:

$$\text{Find } (\mathbf{u}_h, \theta_h) \in \mathbf{K}_h \times Z_h \text{ such that } \mathcal{S}_h(\mathbf{w}_h, \phi_h) = (\mathbf{u}_h, \theta_h). \quad (3.19)$$

3.3 Solvability of the fixed-point problem

In this subsection, we proceed analogously to Subsection 2.4 and prove the well-posedness of problem (3.17) by means of a fixed point argument. We will apply Brouwer's fixed point theorem (c.f. [6, Theorem 9.9-2]) instead of Schauder's theorem for the existence and the uniqueness of (\mathbf{u}_h, θ_h) . The existence and uniqueness of p_h follow from the discrete inf-sup condition for the incompressibility form B_h . The classical Brouwer's fixed point theorem is stated as follows: let W be a nonempty compact convex subset of a finite-dimensional normed space, and let $S : W \rightarrow W$ be a contraction from W into itself. Then S has a unique fixed point in W .

We begin by the following result, where we show that the operator \mathcal{S}_h is defined correctly.

Lemma 3.5 *Assuming the stabilization parameters σ and γ sufficiently large, there exists a unique solution $(\mathbf{u}_h, \theta_h) \in \mathbf{K}_h \times Z_h$ for the linearized problem (3.18). Moreover, we have the following estimates:*

$$\| \mathbf{u}_h \| \leq \alpha_{A_h}^{-1} \nu^{-1} C_{D_h} \| \phi_h \|_h \| \mathbf{g} \|_{L^2(\Omega)} \quad \text{and} \quad \| \theta_h \|_h \leq \alpha_{M_h}^{-1} \kappa^{-1} C_{F_h} \| f \|_{L^2(\Omega)}. \quad (3.20)$$

Proof. Since (3.18a)-(3.18b) consists of a linear system, it suffices to establish the uniqueness. Assuming that the data are homogeneous $f = 0$ and $\mathbf{g} = \mathbf{0}$, we can choose $(\mathbf{v}_h, \psi_h) = (\mathbf{u}_h, \theta_h)$ as test functions. This leads to

$$\alpha_{A_h} \nu \| \mathbf{u}_h \|^2 + \alpha_{M_h} \kappa \| \theta_h \|_h^2 = 0,$$

implying that $\mathbf{u}_h = \mathbf{0}$ and $\theta = 0$. The estimates in (3.20) follow as a consequence of the coercivity of A_h and M_h in (3.6) together with the continuity of D_h and F_h in (3.13a) and (3.9d). \square

Theorem 3.1 *Assume that*

$$M := \max \left(\sqrt{2} \left(\frac{C_{O_h} C_1(\nu, \kappa, f, \mathbf{g})}{\alpha_{A_h} \nu} + \frac{C_{C_h} C_2(\kappa, f)}{\alpha_{M_h} \kappa} \right), \sqrt{2} \frac{C_{D_h}}{\alpha_{A_h} \nu} \| \mathbf{g} \|_{L^2(\Omega)} \right) < 1 \quad (3.21)$$

Then, the problem (3.17) has a unique solution $(\mathbf{u}_h, \theta_h) \in \mathbf{K}_h \times Z_h$ satisfying

$$\nu \| \mathbf{u}_h \|^2 + \kappa \| \theta_h \|_h^2 \leq \alpha_{M_h}^{-2} C_{F_h}^2 \| f \|_{L^2(\Omega)}^2 \left(\kappa^{-2} \alpha_{A_h}^{-2} C_{D_h}^2 \| \mathbf{g} \|_{L^2(\Omega)}^2 + 1 \right) \quad (3.22)$$

Proof. The well-posedness of (3.17) follows by using the Brouwer's fixed point theorem and showing that operator \mathcal{S}_h has a unique fixed-point. Setting $(\mathbf{v}_h, \psi_h) = (\mathbf{u}_h, \theta_h)$ in (3.17) and applying the coercivity of the forms A_h and M_h , the continuity of the form D_h and F_h , we obtain that

$$\| \mathbf{u}_h \| \leq \alpha_{A_h}^{-1} \nu^{-1} C_{D_h} \| \theta_h \|_h \| \mathbf{g} \|_{L^2(\Omega)} \quad \text{and} \quad \| \theta_h \|_h \leq \alpha_{M_h}^{-1} \kappa^{-1} C_{F_h} \| f \|_{L^2(\Omega)}$$

and then,

$$\| \mathbf{u}_h \| \leq C_1(\nu, \kappa, f, \mathbf{g}) \quad \text{and} \quad \| \theta_h \|_h \leq C_2(\kappa, f), \quad (3.23)$$

where

$$C_1(\nu, \kappa, f, \mathbf{g}) = \frac{C_{F_h} C_{D_h}}{\nu \kappa \alpha_{A_h} \alpha_{M_h}} \| \mathbf{g} \|_{L^2(\Omega)} \| f \|_{L^2(\Omega)} \quad \text{and} \quad C_2(\kappa, f) = \frac{C_{F_h}}{\kappa \alpha_{M_h}} \| f \|_{L^2(\Omega)}. \quad (3.24)$$

Inspired by this, define the compact and convex subset B_R of $\mathbf{K}_h \times Z_h$:

$$B_R = \left\{ (\mathbf{u}_h, \theta_h) \in \mathbf{K}_h \times Z_h : \| (\mathbf{u}_h, \theta_h) \|_h \leq R \right\},$$

where $R = \alpha_{M_h}^{-1} \kappa^{-1} C_{F_h} \| f \|_{L^2(\Omega)} (\alpha_{A_h}^{-1} \nu^{-1} C_{D_h} \| \mathbf{g} \|_{L^2(\Omega)} + 1)$. Let us check that \mathcal{S}_h maps B_R into itself. For a given $(\mathbf{w}_h, \phi_h) \in B_R$, we set $(\mathbf{v}_h, \psi_h) = \mathcal{S}(\mathbf{w}_h, \phi_h)$. Thanks to the estimate (3.20), (\mathbf{v}_h, ψ_h) satisfies

$$\| \mathbf{v}_h \| \leq \alpha_{A_h}^{-1} \nu^{-1} C_{D_h} \| \phi_h \|_h \| \mathbf{g} \|_{L^2(\Omega)} \quad \text{and} \quad \| \psi_h \|_h \leq \alpha_{M_h}^{-1} \kappa^{-1} C_{F_h} \| f \|_{L^2(\Omega)}. \quad (3.25)$$

Combining (3.25) with the fact that $(\mathbf{w}_h, \phi_h) \in B_R$, we obtain that (\mathbf{v}_h, ψ_h) belongs also to B_R . Now, we show that the operator \mathcal{S}_h is a contraction on B_R . To that end, let $(\mathbf{u}_h^1, \theta_h^1), (\mathbf{u}_h^2, \theta_h^2) \in B_R$ and $(\mathbf{u}_h^1, \theta_h^1) = \mathcal{S}(\mathbf{w}_1, \phi_1), (\mathbf{u}_h^2, \theta_h^2) = \mathcal{S}(\mathbf{w}_2, \phi_2)$. Setting $\mathbf{u}_h := \mathbf{u}_h^1 - \mathbf{u}_h^2, \theta_h := \theta_h^1 - \theta_h^2$, by definition, we deduce that

$$\begin{aligned} & A_h(\mathbf{u}_h, \mathbf{v}_h) + M_h(\theta_h, \phi_h) + O_h(\mathbf{w}_1; \mathbf{u}_h, \mathbf{v}_h) + \mathcal{C}_h(\mathbf{w}_1; \theta, \psi_h) \\ &= -O_h(\mathbf{w}_1 - \mathbf{w}_2; \mathbf{u}_h^2, \mathbf{v}_h) - \mathcal{C}_h(\mathbf{w}_1 - \mathbf{w}_2; \theta_h^2, \psi_h) + D_h(\phi_1 - \phi_2, \mathbf{v}_h). \end{aligned}$$

Taking $(\mathbf{v}_h, \psi_h) = (\mathbf{u}_h, \theta_h)$, using (3.6) and (3.13), we obtain

$$\begin{aligned} \| \mathbf{u}_h \| \|^2 + \| \theta_h \|_h^2 &\leq \alpha_{A_h}^{-1} \nu^{-1} C_{O_h} \| \mathbf{w}_1 - \mathbf{w}_2 \| \| \mathbf{u}_h^2 \| \| \mathbf{u}_h \| + \alpha_{M_h}^{-1} \kappa^{-1} C_{c_h} \| \mathbf{w}_1 - \mathbf{w}_2 \| \| \theta_h^2 \|_h \| \theta_h \|_h \\ &+ \alpha_{A_h}^{-1} \nu^{-1} C_{D_h} \| \mathbf{g} \|_{L^2(\Omega)} \| \phi_1 - \phi_2 \|_h \| \mathbf{u}_h \| \end{aligned}$$

Applying Young's inequality and using the fact that $(\mathbf{u}_h^2, \theta_h^2) \in B_R$, we derive that

$$\begin{aligned} \| \mathbf{u}_h \| \|^2 + \| \theta_h \|_h^2 &\leq 2 \left(\alpha_{A_h}^{-2} \nu^{-2} C_{O_h}^2 C_1^2(\nu, \kappa, f, \mathbf{g}) + \alpha_{M_h}^{-2} \kappa^{-2} C_{c_h}^2 C_2^2(\kappa, f) \right) \| \mathbf{w}_1 - \mathbf{w}_2 \| \|^2 \\ &+ 2 \alpha_{A_h}^{-2} \nu^{-2} C_{D_h}^2 \| \mathbf{g} \|_{L^2(\Omega)}^2 \| \phi_1 - \phi_2 \|_h^2, \end{aligned}$$

and then

$$\| (\mathbf{u}_h, \theta_h) \|_h \leq M \| (\mathbf{w}_1, \phi_1) - (\mathbf{w}_2, \phi_2) \|_h,$$

with

$$M = \max \left(\sqrt{2} (\alpha_{A_h}^{-1} \nu^{-1} C_{O_h} C_1(\nu, \kappa, f, \mathbf{g}) + \alpha_{M_h}^{-1} \kappa^{-1} C_{c_h} C_2(\kappa, f)), \sqrt{2} \alpha_{A_h}^{-1} \nu^{-1} C_{D_h} \| \mathbf{g} \|_{L^2(\Omega)} \right). \quad (3.26)$$

So, if $M < 1$ that is, if the smallness condition (3.21) is satisfied, the mapping \mathcal{S}_h is a contraction. Consequently, an application of Brower's fixed point theorem shows that \mathcal{S}_h has a unique fixed point in B_R , which is the solution of problem (3.17). Besides, the stability bound for (\mathbf{u}_h, θ_h) follows immediately. \square

Remark 3.1 We note that the hypothesis (3.21) is not necessary to get the existence of solution (\mathbf{u}_h, θ_h) . Indeed, We can use only the fact that \mathcal{S}_h is Lipschitz continuous on $\mathbf{K}_h \times Z_h$.

Now, in order to recovering the pressure, we have the following Corollary.

Corollary 3.1 *Let (\mathbf{u}_h, θ_h) the solution of the problem (3.17) given by Theorem 3.1. Then, there exists a unique $p_h \in Q_h$ such that $((\mathbf{u}_h, \theta_h), p_h) \in \mathbf{X}_h \times Z_h \times Q_h$ is the solution of (3.2). Moreover, we have the following estimate:*

$$\|p_h\|_{0,\Omega} \leq C_3(\nu, \kappa, f, \mathbf{g}) \quad (3.27)$$

where

$$C_3(\nu, \kappa, f, \mathbf{g}) = \beta^{-1} C_{A_h} C_1(\nu, \kappa, f, \mathbf{g}) + \beta^{-1} C_{O_h} C_1^2(\nu, \kappa, f, \mathbf{g}) + \beta^{-1} C_{D_h} C_2(\kappa, f) \|\mathbf{g}\|_{L^2(\Omega)} \quad (3.28)$$

and $C_1(\nu, \kappa, f, \mathbf{g})$, $C_2(\kappa, f)$ are the constants in (3.23).

Proof. Analogously to the continuous case (see Lemma (2.2)), due to the inf-sup condition (3.8) and the continuity properties of A_h , O_h and D_h , here we also obtain that both (3.2) and (3.17) are equivalent. Indeed, the pressure is uniquely solvable by the following problem

$$B_h(\mathbf{v}_h, p_h) = -A_h(\mathbf{u}_h, \mathbf{v}_h) - O_h(\mathbf{u}_h; \mathbf{u}_h, \mathbf{v}_h) + D_h(\theta_h, \mathbf{v}_h). \quad (3.29)$$

Then, it suffices to prove the estimate (3.27) to conclude the proof. To do that, using the inf sup-condition (3.8) and the continuity of the forms A_h , O_h and D_h , we obtain

$$\begin{aligned} \beta \|p_h\|_{Q_h} &\leq \sup_{\mathbf{v}_h \in \mathbf{X}_h} \frac{B_h(\mathbf{v}_h, p_h)}{\|\mathbf{v}_h\|} \\ &= \sup_{\mathbf{v}_h \in \mathbf{X}_h} \left\{ \frac{-A_h(\mathbf{u}_h, \mathbf{v}_h) - O_h(\mathbf{u}_h; \mathbf{u}_h, \mathbf{v}_h) + D_h(\theta_h, \mathbf{v}_h)}{\|\mathbf{v}_h\|} \right\} \\ &\leq C_{A_h} \|\mathbf{u}_h\| + C_{O_h} \|\mathbf{u}_h\|^2 + C_{D_h} \|\mathbf{g}\|_{L^2(\Omega)} \|\theta_h\|_h \end{aligned}$$

Recalling that $(\mathbf{u}_h, \theta_h) \in B_R$ and satisfies (3.23), then we obtain the estimate (3.27) from the latter estimate which concludes the proof. \square

4 Error analysis

Let us begin by introducing an approximation result for the space \mathbf{X}_h (see [15]). For $k = 1, 2, 3$, there exists a continuous interpolation operator I_h defined from $\mathbf{H}^1(\Omega)$ to \mathbf{X}_h such that, for all $T \in \mathcal{T}_h$ and $e \in \mathcal{F}_h$:

$$\forall \mathbf{v} \in \mathbf{H}^1(\Omega), \quad \forall q_h \in \mathcal{P}_{k-1}(T), \quad \int_T q_h \operatorname{div}(I_h(\mathbf{v}) - \mathbf{v}) \, dx = 0, \quad (4.1)$$

$$\forall \mathbf{v} \in \mathbf{H}_T^1(\Omega), \quad \forall e \in \mathcal{F}_h, \quad \forall q_h \in \mathcal{P}_{k-1}(e), \quad \int_e q_h \llbracket I_h(\mathbf{v}) \rrbracket \, ds = 0. \quad (4.2)$$

Moreover, for $s \in [1, k+1]$ the following interpolation estimate holds:

$$\forall \mathbf{v} \in \mathbf{H}^s(\Omega), \quad \|I_h(\mathbf{v}) - \mathbf{v}\|_{1,T} \leq Ch_T^{s-1} \|\mathbf{v}\|_{s,\Delta_T}, \quad (4.3)$$

where Δ_T is a suitable macro-element containing T .

We use the L^2 -projection of degree $k-1$ onto Q_h (respectively of degree k onto Z_h) to approximate the pressure p (respectively the temperature θ). So there exists approximationz $\Pi_Q p \in Q_h$ and $\Pi_Z \theta \in Z_h$ (see [17]), defined on each $T \in \mathcal{T}_h$ by

$$\forall q \in \mathcal{P}_{k-1}(T), \quad \int_T q(p - \Pi_Q p) \, dx = 0. \quad (4.4a)$$

$$\forall \psi \in \mathcal{P}_k(T), \quad \int_T \psi(\theta - \Pi_Z \theta) \, dx = 0. \quad (4.4b)$$

and satisfy the following approximations properties for every integer $s \in [0, k]$:

$$\|p - \Pi_Q p\|_{0,T} \leq Ch_T^s \|p\|_{s,T}, \quad \forall p \in H^s(\Omega) \cap L_0^2(\Omega). \quad (4.5)$$

Theorem 4.1 *Let $(\mathbf{u}, \theta, p) \in \mathbf{H}^{k+1}(\Omega) \times H^{k+1}(\Omega) \times H^k(\Omega)$ be a solution of the continuous problem (1.3). Let $(\mathbf{u}_h, \theta_h, p_h)$ be the solution in $\mathbf{X}_h \times Q_h \times \mathbf{C}_h$ of the DG problem (3.2). We assume that*

$$\frac{C_{O_h} K_1(\nu, \kappa, \mathbf{g}, f)}{\nu \alpha_{A_h}} + \frac{C_{D_h} \|\mathbf{g}\|_{0,\Omega}}{\nu \alpha_{A_h} \kappa \alpha_{M_h}} \leq \frac{1}{2}. \quad (4.6)$$

Then, there exists positive constant $C > 0$, independent of h , such that, the following estimates hold true:

$$\|\mathbf{u} - \mathbf{u}_h\| + \|\theta - \theta_h\|_h \leq Ch^k \left(\|\mathbf{u}\|_{k+1,\Omega} + \|\theta\|_{k+1,\Omega} + \|p\|_{k,\Omega} \right) \quad (4.7)$$

$$\|p - p_h\|_{0,\Omega} \leq Ch^k \left(\|\mathbf{u}\|_{k+1,\Omega} + \|\theta\|_{k+1,\Omega} + \|p\|_{k,\Omega} \right) \quad (4.8)$$

Proof. We denote the corresponding errors by

$$\mathbf{e}_u := \mathbf{u} - \mathbf{u}_h, \quad e_\theta := \theta - \theta_h, \quad e_p := p - p_h.$$

We decompose these errors into

$$\mathbf{e}_u = \boldsymbol{\eta}_u + \boldsymbol{\chi}_u, \quad e_\theta = \eta_\theta + \chi_\theta, \quad e_p = \eta_p + \chi_p, \quad (4.9)$$

with

$$\begin{aligned} \boldsymbol{\eta}_u &:= \mathbf{u} - I_h \mathbf{u}, & \boldsymbol{\chi}_u &:= I_h \mathbf{u} - \mathbf{u}_h \\ \eta_\theta &:= \theta - \Pi_Z \theta, & \chi_\theta &:= \Pi_Z \theta - \theta_h \\ \eta_p &:= p - \Pi_Q p, & \chi_p &:= \Pi_Z p - p_h \end{aligned}$$

From the approximation properties of operators I_h , Π_Q and Π_Z (see (4.3), (4.4a) and (4.4b) respectively) combined with inverse inequality, it can be readily seen that

$$\|\boldsymbol{\eta}_u\| \leq Ch^k \|\mathbf{u}\|_{k+1,\Omega} + \|\boldsymbol{\chi}_u\|, \quad (4.10a)$$

$$\|\eta_\theta\|_h \leq Ch^k \|\theta\|_{k+1,\Omega} + \|\chi_\theta\|_h, \quad (4.10b)$$

$$\|\eta_p\|_{0,\Omega} \leq Ch^k \|p\|_{k,\Omega} + \|\chi_p\|_{0,\Omega}, \quad (4.10c)$$

To estimate the error it is therefore sufficient to estimate the terms $\|\boldsymbol{\chi}_u\|$, $\|\chi_\theta\|_h$ and $\|\chi_p\|_{0,\Omega}$.

We begin by proving the error on (\mathbf{u}, θ) . We note that the solution (\mathbf{u}, p, θ) of the continuous problem (1.3) satisfies

$$\begin{aligned} A_h(\mathbf{u}, \mathbf{v}_h) + O_h(\mathbf{u}; \mathbf{u}, \mathbf{v}_h) + B_h(\mathbf{v}_h, p) &= D_h(\theta, \mathbf{v}_h), \\ B_h(\mathbf{u}, q_h) &= 0, \\ M_h(\theta, \psi_h) + C_h(\mathbf{u}; \theta, \psi_h) &= F_h(\psi_h), \end{aligned}$$

for all $(\mathbf{v}_h, q_h, \psi_h) \in \mathbf{X}_h \times Q_h \times Z_h$. Subtracting the above equations from the discrete formulation (3.2), we obtain the error equations

$$A_h(\mathbf{e}_u, \mathbf{v}_h) + O_h(\mathbf{u}; \mathbf{u}, \mathbf{v}_h) - O_h(\mathbf{u}_h; \mathbf{u}_h, \mathbf{v}_h) + B_h(\mathbf{v}_h, e_p) = D_h(e_\theta, \mathbf{v}_h), \quad (4.11a)$$

$$B_h(\mathbf{e}_u, q_h) = 0, \quad (4.11b)$$

$$M_h(e_\theta, \psi_h) + C_h(\mathbf{u}; \theta, \psi_h) - C_h(\mathbf{u}_h; \theta_h, \psi_h) = 0, \quad (4.11c)$$

for all $(\mathbf{v}_h, q_h, \psi_h) \in \mathbf{X}_h \times Q_h \times Z_h$, which gives using (4.9) and (4.11a) with $\mathbf{v}_h = \boldsymbol{\chi}_u$

$$A_h(\boldsymbol{\chi}_u, \boldsymbol{\chi}_u) + O_h(\mathbf{u}; \mathbf{u}, \boldsymbol{\chi}_u) - O_h(\mathbf{u}_h; \mathbf{u}_h, \boldsymbol{\chi}_u) + B_h(\boldsymbol{\chi}_u, e_p) = D_h(e_\theta, \boldsymbol{\chi}_u) - A_h(\boldsymbol{\eta}_u, \boldsymbol{\chi}_u).$$

Using again the decomposition (4.9), we have

$$\begin{aligned} O_h(\mathbf{u}; \mathbf{u}, \boldsymbol{\chi}_u) - O_h(\mathbf{u}_h; \mathbf{u}_h, \boldsymbol{\chi}_u) &= O_h(\mathbf{e}_u; \mathbf{u}, \boldsymbol{\chi}_u) + O_h(\mathbf{u}_h; \mathbf{e}_u, \boldsymbol{\chi}_u) \\ &= O_h(\boldsymbol{\eta}_u; \mathbf{u}, \boldsymbol{\chi}_u) + O_h(\boldsymbol{\chi}_u; \mathbf{u}, \boldsymbol{\chi}_u) + O_h(\mathbf{u}_h; \boldsymbol{\eta}_u, \boldsymbol{\chi}_u) + \underbrace{O_h(\mathbf{u}_h; \boldsymbol{\chi}_u, \boldsymbol{\chi}_u)}_{=0}, \end{aligned}$$

Observe that from the definition of I_h in (4.1)-(4.2), we have $B_h(\boldsymbol{\chi}_u, \chi_p) = 0$ and then

$$B_h(\boldsymbol{\chi}_u, e_p) = B_h(\boldsymbol{\chi}_u, \eta_p) + \underbrace{B_h(\boldsymbol{\chi}_u, \chi_p)}_{=0}$$

Hence, we get

$$\begin{aligned} A_h(\boldsymbol{\chi}_u, \boldsymbol{\chi}_u) &= D_h(e_\theta, \boldsymbol{\chi}_u) - A_h(\boldsymbol{\eta}_u, \boldsymbol{\chi}_u) - B_h(\boldsymbol{\chi}_u, \eta_p) - O_h(\boldsymbol{\eta}_u; \mathbf{u}, \boldsymbol{\chi}_u) \\ &\quad - O_h(\boldsymbol{\chi}_u; \mathbf{u}, \boldsymbol{\chi}_u) - O_h(\mathbf{u}_h; \boldsymbol{\eta}_u, \boldsymbol{\chi}_u). \end{aligned}$$

Using Lemmas 3.1, Lemma 3.3 and Lemma 3.4, we have

$$\begin{aligned} \nu \alpha_{A_h} \|\boldsymbol{\chi}_u\|^2 &\leq C_{D_h} \|\mathbf{g}\|_{0,\Omega} \|e_\theta\|_h \|\boldsymbol{\chi}_u\| + \nu C_{A_h} \|\boldsymbol{\eta}_u\| \|\boldsymbol{\chi}_u\| + C_{B_h} \|\eta_p\|_{0,\Omega} \|\boldsymbol{\chi}_u\| + C_{O_h} \|\boldsymbol{\eta}_u\| \|\mathbf{u}\| \|\boldsymbol{\chi}_u\| \\ &\quad + C_{O_h} \|\mathbf{u}\| \|\boldsymbol{\chi}_u\|^2 + C_{O_h} \|\mathbf{u}_h\| \|\boldsymbol{\eta}_u\| \|\boldsymbol{\chi}_u\|. \end{aligned}$$

Now, we recall that thanks to the *a priori* estimates (2.42) and (3.23), we have

$$\|\mathbf{u}\|_{\mathbf{H}^1(\Omega)} \leq K_1(\nu, \kappa, \mathbf{g}, f) \quad \text{and} \quad \|\mathbf{u}_h\| \leq C_1(\nu, \kappa, \mathbf{g}, f),$$

which implies

$$\begin{aligned} \left(\nu \alpha_{A_h} - C_{O_h} K_1(\nu, \kappa, \mathbf{g}, f) \right) \|\boldsymbol{\chi}_u\| &\leq C_{D_h} \|\mathbf{g}\|_{0,\Omega} \|\chi_\theta\|_h + C_{D_h} \|\mathbf{g}\|_{0,\Omega} \|\eta_p\|_{0,\Omega} + \nu C_{A_h} \|\boldsymbol{\eta}_u\| \\ &\quad + C_{B_h} \|\eta_p\|_{0,\Omega} + C_{O_h} (K_1(\nu, \kappa, \mathbf{g}, f) + C_1(\nu, \kappa, \mathbf{g}, f)) \|\boldsymbol{\eta}_u\|. \end{aligned}$$

So, we have

$$\left(\nu \alpha_{A_h} - C_{O_h} K_1(\nu, \kappa, \mathbf{g}, f) \right) \|\boldsymbol{\chi}_u\| \leq C_{D_h} \|\mathbf{g}\|_{0,\Omega} \|\chi_\theta\|_h + C_* \quad (4.12)$$

with $C_* = C_{D_h} \|\mathbf{g}\|_{0,\Omega} \|\eta_p\|_{0,\Omega} + \nu C_{A_h} \|\boldsymbol{\eta}_u\| + C_{B_h} \|\eta_p\|_{0,\Omega} + C_{O_h} (K_1(\nu, \kappa, \mathbf{g}, f) + C_1(\nu, \kappa, \mathbf{g}, f)) \|\boldsymbol{\eta}_u\|$. To estimate $\|\chi_\theta\|_h$, we use (4.11c) with $\psi_h = \chi_\theta$

$$M_h(e_\theta, \chi_\theta) + C_h(\mathbf{u}, \theta, \chi_\theta) - C_h(\mathbf{u}_h, \theta_h, \chi_\theta) = 0,$$

which gives using the error decompositions (4.9) and the positivity of the form C_h (see (3.15)):

$$M_h(\chi_\theta, \chi_\theta) + \underbrace{C_h(\mathbf{u}_h; \chi_\theta, \chi_\theta)}_{\geq 0} = -M_h(\eta_\theta, \chi_\theta) - C_h(\boldsymbol{\eta}_u; \theta, \chi_\theta) - C_h(\boldsymbol{\chi}_u; \theta, \chi_\theta) - C_h(\mathbf{u}_h; \eta_\theta, \chi_\theta).$$

Using again the *a priori* estimate for \mathbf{u}_h in (3.23) and that for θ : (see (2.42)):

$$\|\theta\|_{\mathbf{H}^1(\Omega)} \leq K_2(\kappa, f),$$

together with the continuity of the forms M_h and C_h (see (3.9b) and (3.13c)), we obtain:

$$\begin{aligned} \kappa \alpha_{M_h} \|\chi_\theta\|_h &\leq C_{M_h} \|\eta_\theta\|_h + C_{C_h} \|\boldsymbol{\eta}_u\| \|\theta\|_h + C_{C_h} \|\boldsymbol{\chi}_u\| \|\theta\|_h + C_{C_h} \|\mathbf{u}_h\| \|\eta_\theta\|_h \\ &\leq C_{M_h} \|\eta_\theta\|_h + C_{C_h} K_2(\kappa, f) (\|\boldsymbol{\eta}_u\| + \|\boldsymbol{\chi}_u\|) + C_{C_h} C_1(\nu, \kappa, \mathbf{g}, f) \|\eta_\theta\|_h \\ &\leq C_{C_h} K_2(\kappa, f) \|\boldsymbol{\chi}_u\| + \tilde{C}_*, \end{aligned} \quad (4.13)$$

with

$$\tilde{C}_* = C_{M_h} \|\eta_\theta\|_h + C_{C_h} K_2(\kappa, f) \|\boldsymbol{\eta}_u\| + C_{C_h} C_1(\nu, \kappa, \mathbf{g}, f) \|\eta_\theta\|_h.$$

Combining the estimates (4.12) and (4.13), we obtain

$$\left(\nu \alpha_A - C_{O_h} K_1(\nu, \kappa, \mathbf{g}, f) - \frac{C_{D_h} \|\mathbf{g}\|_{0,\Omega}}{\kappa \alpha_{M_h}} \right) \|\boldsymbol{\chi}_u\| \leq \frac{C_{D_h} \|\mathbf{g}\|_{0,\Omega}}{\kappa \alpha_{M_h}} \tilde{C}_* + C_*,$$

which gives by using assumption (4.6)

$$\frac{1}{2} \nu \alpha_A \|\boldsymbol{\chi}_u\| \leq \frac{C_{D_h} \|\mathbf{g}\|_{0,\Omega}}{\kappa \alpha_{M_h}} \tilde{C}_* + C_*. \quad (4.14)$$

Replacing (4.14) in (4.13) gives

$$\kappa \alpha_{M_h} \|\chi_\theta\|_h \leq \frac{2C_{C_h} K_2(\kappa, f)}{\nu \alpha_A} \left(\frac{C_{D_h} \|\mathbf{g}\|_{0,\Omega}}{\kappa \alpha_{M_h}} \tilde{C}_* + C_* \right) + \tilde{C}_* \quad (4.15)$$

The energy-norm error estimate for the velocity \mathbf{u}_h and the temperature θ_h in (4.7) now follows by the bounds in (4.14), (4.15), (4.10a) and (4.10b).

To prove the error estimate on the pressure in (4.8), we use the inf-sup condition (3.8), the continuity property of B_h (3.9c) and the fact that $\chi_p = \eta_p - e_p$ to write

$$\begin{aligned} \beta \|\chi_p\|_{0,\Omega} &\leq \sup_{\mathbf{v}_h \in \mathbf{X}_h} \frac{B_h(\mathbf{v}_h, \chi_p)}{\|\mathbf{v}_h\|} \\ &\leq C_{B_h} \|\eta_p\|_{0,\Omega} + \sup_{\mathbf{v}_h \in \mathbf{X}_h} \frac{B_h(\mathbf{v}_h, -e_p)}{\|\mathbf{v}_h\|} \end{aligned} \quad (4.16)$$

To bound the term $B_h(\mathbf{v}_h, -e_p)$, we first rewrite equation (4.11a), adding and subtracting suitable terms to obtain:

$$\begin{aligned} B_h(\mathbf{v}_h, -e_p) &= A_h(\mathbf{e}_u, \mathbf{v}_h) + O_h(\mathbf{u}; \mathbf{u}, \mathbf{v}_h) - O_h(\mathbf{u}_h; \mathbf{u}_h, \mathbf{v}_h) - D_h(e_\theta, \mathbf{v}_h) \\ &= A_h(\mathbf{e}_u, \mathbf{v}_h) + O_h(\mathbf{e}_u; \mathbf{u}, \mathbf{v}_h) + O_h(\mathbf{u}_h; \mathbf{e}_u, \mathbf{v}_h) - D_h(e_\theta, \mathbf{v}_h) \end{aligned}$$

From the continuity properties of A_h , O_h and D_h (see (3.9a), (3.13b) and (3.13a)), we have

$$|B_h(\mathbf{v}_h, -e_p)| \leq \left(C_{A_h} + C_{O_h} \|\mathbf{u}\|_{1,\Omega} + C_{O_h} \|\mathbf{u}_h\| \right) \|\mathbf{e}_u\| \|\mathbf{v}_h\| + C_{D_h} \|\mathbf{g}\|_{0,\Omega} \|e_\theta\|_h \|\mathbf{v}_h\|$$

By replacing this last bound into (4.16) and using the *a priori* estimate for \mathbf{u} and \mathbf{u}_h , we get

$$\beta \|\chi_p\|_{0,\Omega} \leq C_{B_h} \|\eta_p\|_{0,\Omega} + \left(C_{A_h} + C_{O_h} K_1(\nu, \kappa, \mathbf{g}, f) + C_{O_h} C_1(\nu, \kappa, \mathbf{g}, f) \right) \|\mathbf{e}_u\| + C_{D_h} \|\mathbf{g}\|_{0,\Omega} \|e_\theta\|_h$$

Using estimates (4.14) and (4.15) together with (4.10) implies the desired estimate (4.8) for the error on the pressure. \square

5 Conclusion

This article presents a study of a mixed DG scheme for Boussinesq problem with Navier-type boundary condition for the velocity. We have introduced the continuous formulation of the problem, applying a fixed-point approach to analyse the well-posedness of the associated problem. We have also introduced a discontinuous Galerkin scheme and used the Brouwer theorem to prove the existence of a solution. We have utilized recent result concerning a Sobolev embedding from the broken DG norm to the $L^6(\Omega)$ norm, which requires some additional regularity conditions on the boundary $\partial\Omega$. For nonsmooth domains, such as polygonal or polyhedral domains, the main difficulty caused by the Navier-type boundary condition is that the solution is only $H^{1/2}(\Omega)$ which is embedded in $L^3(\Omega)$. Using Holder's inequality, this regularity is not sufficient to prove the continuity of the trilinear term. With standard regularity assumption on the exact solution, we proved that the numerical solution converges to the exact solution optimally for all unknowns in the energy norm. To the best of our knowledge, it is the first analysis dedicated to DG methods for nonlinear MHD problems. Ongoing work is addressing the issues associated with the implementation of this mixed DG method.

CRedit authorship contribution statement

Afaf Bouharguane: Methodology, Validation, Formal analysis, Writing - review & editing.

Nour Seloula: Conceptualization, Methodology, Validation, Formal analysis, Writing - original draft, Writing - review & editing

Declaration of Competing Interest

The author declares that there is no conflict of interest.

Data availability

No data was used for the research described in the article.

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