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Characterisation of the pressure term in the incompressible Navier–Stokes equations on the whole space

Pedro Gabriel Fernández-Dalgo^{*†}, Pierre Gilles Lemarié–Rieusset^{‡§}

Abstract

We characterise the pressure term in the incompressible 2D and 3D Navier–Stokes equations for solutions defined on the whole space.

Keywords : Navier–Stokes equations, pressure term, Leray projection, extended Galilean invariance, suitable solutions

AMS classification : 35Q30, 76D05.

Introduction

In the context of the Cauchy initial value problem for Navier–Stokes equations on \mathbb{R}^d (with $d = 2$ or $d = 3$)

$$\begin{cases} \partial_t \mathbf{u} = \Delta \mathbf{u} - (\mathbf{u} \cdot \nabla) \mathbf{u} - \nabla p + \nabla \cdot \mathbb{F} \\ \nabla \cdot \mathbf{u} = 0, & \mathbf{u}(0, \cdot) = \mathbf{u}_0 \end{cases}$$

an important problem is to propose a formula for the gradient of the pressure, which is an auxiliary unknown (usually interpreted as a Lagrange multiplier for the constraint of incompressibility).

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As we shall not assume differentiability of \mathbf{u} in our computations, it is better to write the equations as

$$(NS) \begin{cases} \partial_t \mathbf{u} = \Delta \mathbf{u} - \nabla \cdot (\mathbf{u} \otimes \mathbf{u}) - \nabla p + \nabla \cdot \mathbb{F} \\ \nabla \cdot \mathbf{u} = 0, & \mathbf{u}(0, \cdot) = \mathbf{u}_0 \end{cases}$$

Taking the Laplacian of equations (NS), since we have for a vector field \mathbf{w} the identity

$$-\Delta \mathbf{w} = \nabla \wedge (\nabla \wedge \mathbf{w}) - \nabla (\nabla \cdot \mathbf{w})$$

we get the equations

$$\partial_t \Delta \mathbf{u} = \Delta^2 \mathbf{u} + \nabla \wedge (\nabla \wedge (\nabla \cdot (\mathbf{u} \otimes \mathbf{u} - \mathbb{F})))$$

and

$$0 = -\Delta \nabla p - \nabla (\nabla \cdot (\nabla \cdot (\mathbf{u} \otimes \mathbf{u} - \mathbb{F}))) = -\Delta \nabla p - \nabla \left(\sum_{1 \leq i, j \leq d} \partial_i \partial_j (u_i u_j - F_{i,j}) \right).$$

Thus, the rotational-free unknown ∇p obeys a Poisson equation. If G_d is the fundamental solution of the operator $-\Delta$:

$$G_2 = \frac{1}{2\pi} \ln\left(\frac{1}{|x|}\right), \quad G_3 = \frac{1}{4\pi|x|}$$

(which satisfies $-\Delta G_d = \delta$), we *formally* have

$$\nabla p = G_d * \nabla \left(\sum_{1 \leq i, j \leq d} \partial_i \partial_j (u_i u_j - F_{i,j}) \right) + H \quad (1)$$

with $\Delta H = 0$. In the litterature, one usually finds the assumption that ∇p vanishes at infinity and this is read as $H = 0$. Equivalently, this is read as

$$\partial_t \mathbf{u} = G_d * \nabla \wedge (\nabla \wedge \partial_t \mathbf{u});$$

the operator

$$\mathbb{P} = G_d * \nabla \wedge (\nabla \wedge \cdot)$$

is called the Leray projection operator and the decomposition (*when justified*)

$$\mathbf{w} = \mathbb{P} \mathbf{w} + G_d * \nabla (\nabla \cdot \mathbf{w})$$

the Hodge decomposition of the vector field \mathbf{w} .

Hence, an important issue when dealing with the Navier–Stokes equations is to study whether in formula (1) the first half of the right-hand term is well-defined, and if so which values the second half (the harmonic part H) may have.

In order to give some meaning to the formal convolution $G_d * \nabla \partial_i \partial_j (u_i u_j)$ or to $(\nabla \partial_i \partial_j G_d) * (u_i u_j)$, we should require u_i to be locally $L_t^2 L_x^2$ (in order to define $u_i u_j$ as a distribution) and to have small increase at infinity, since the distribution $\nabla \partial_i \partial_j G$ has small decay at infinity (it belongs to $L^1 \cap L^\infty$ far from the origin and is $O(|x|^{-(d+1)})$). Thus, we will focus on solutions \mathbf{u} that belong to $L^2((0, T), L^2(\mathbb{R}^d, w_{d+1} dx))$ where

$$w_\gamma(x) = (1 + |x|)^{-\gamma}.$$

We shall recall various examples (from recent or older literature) of solutions belonging to the space $L^2((0, T), L^2(\mathbb{R}^d, w_\gamma dx))$ (with $\gamma \in \{d, d+1\}$). As $F_{i,j}$ plays a role similar to $u_i u_j$, we shall assume that $\mathbb{F} \in L^1((0, T), L^1(\mathbb{R}^d, w_\gamma dx))$.

1 Main results.

First, we precise the meaning of ∇p in equations (NS) :

Lemma 1.1 *Consider the dimension $d \in \{2, 3\}$ and $\gamma \geq 0$. Let $0 < T < +\infty$. Let \mathbb{F} be a tensor $\mathbb{F}(t, x) = (F_{i,j}(t, x))_{1 \leq i, j \leq d}$ such that \mathbb{F} belongs to $L^1((0, T), L^1(\mathbb{R}^d, w_\gamma dx))$, and let \mathbf{u} be a vector field $\mathbf{u}(t, x) = (u_i(t, x))_{1 \leq i \leq d}$ such that \mathbf{u} belongs to $L^2((0, T), L^2(\mathbb{R}^d, w_\gamma dx))$ and $\nabla \cdot \mathbf{u} = 0$. Define the distribution S by*

$$\mathbf{S} = \Delta \mathbf{u} - \nabla \cdot (\mathbf{u} \otimes \mathbf{u} - \mathbb{F}) - \partial_t \mathbf{u}.$$

Then the following assertions are equivalent :

(A) S is curl-free : $\nabla \wedge \mathbf{S} = 0$.

(B) There exists a distribution $p \in \mathcal{D}'((0, T) \times \mathbb{R}^d)$ such that $S = \nabla p$.

Theorem 1 *Consider the dimension $d \in \{2, 3\}$. Let $0 < T < +\infty$. Let \mathbb{F} be a tensor $\mathbb{F}(t, x) = (F_{i,j}(t, x))_{1 \leq i, j \leq d}$ such that \mathbb{F} belongs to $L^1((0, T), L^1(\mathbb{R}^d, w_{d+1} dx))$. Let \mathbf{u} be a solution of the following problem*

$$\begin{cases} \partial_t \mathbf{u} = \Delta \mathbf{u} - \nabla \cdot (\mathbf{u} \otimes \mathbf{u}) - \mathbf{S} + \nabla \cdot \mathbb{F} \\ \nabla \cdot \mathbf{u} = 0, \quad \nabla \wedge \mathbf{S} = 0, \end{cases} \quad (2)$$

such that : \mathbf{u} belongs to $L^2((0, T), L^2_{w_{d+1}}(\mathbb{R}^d))$, and \mathbf{S} belongs to $\mathcal{D}'((0, T) \times \mathbb{R}^d)$.

Let us choose $\varphi \in \mathcal{D}(\mathbb{R}^d)$ such that $\varphi(x) = 1$ on a neighborhood of 0 and define

$$A_{i,j,\varphi} = (1 - \varphi)\partial_i\partial_j G_d.$$

Then, there exists $g(t) \in L^1((0, T))$ such that

$$\mathbf{S} = \nabla p_\varphi + \partial_t g$$

with

$$\begin{aligned} p_\varphi &= \sum_{i,j} (\varphi\partial_i\partial_j G_d) * (u_i u_j - F_{i,j}) \\ &\quad + \sum_{i,j} \int (A_{i,j,\varphi}(x-y) - A_{i,j,\varphi}(-y))(u_i(t,y)u_j(t,y) - F_{i,j}(t,y)) dy. \end{aligned}$$

Moreover,

- ∇p_φ does not depend on the choice of φ : if we change φ in ψ , then

$$p_\varphi(t, x) - p_\psi(t, x) = \sum_{i,j} \int (A_{i,j,\psi}(-y) - A_{i,j,\varphi}(-y))(u_i(t,y)u_j(t,y) - F_{i,j}(t,y)) dy.$$

- ∇p_φ is the unique solution of the Poisson problem

$$\Delta \mathbf{w} = -\nabla(\nabla \cdot (\nabla \cdot (\mathbf{u} \otimes \mathbf{u} - \mathbb{F}))$$

with

$$\lim_{\tau \rightarrow +\infty} e^{\tau\Delta} \mathbf{w} = 0 \text{ in } \mathcal{D}'.$$

- if \mathbb{F} belongs more precisely to $L^1((0, T), L_{w_d}^1(\mathbb{R}^d))$ and \mathbf{u} belongs to $L^2((0, T), L_{w_d}^2(\mathbb{R}^d))$, then $g = 0$ and $\nabla p_\varphi = \nabla p_0$ where

$$p_0 = \sum_{i,j} (\varphi\partial_i\partial_j G_d) * (u_i u_j - F_{i,j}) + \sum_{i,j} ((1 - \varphi)\partial_i\partial_j G_d) * (u_i u_j - F_{i,j}).$$

(p_0 does not actually depend on φ and could have been defined as $p_0 = \sum_{i,j} (\partial_i\partial_j G_d) * (u_i u_j - F_{i,j})$.)

When $\mathbb{F} = 0$, the case $g \neq 0$ can easily be reduced to a change of referential, due to the extended Galilean invariance of the Navier–Stokes equations :

Theorem 2 Consider the dimension $d \in \{2, 3\}$. Let $0 < T < +\infty$. Let \mathbf{u} be a solution of the following problem

$$\begin{cases} \partial_t \mathbf{u} = \Delta \mathbf{u} - \nabla \cdot (\mathbf{u} \otimes \mathbf{u}) - \mathbf{S} \\ \nabla \cdot \mathbf{u} = 0, \quad \nabla \wedge \mathbf{S} = 0, \quad \mathbf{u}(0, x) = \mathbf{u}_0(x) \end{cases} \quad (3)$$

such that : \mathbf{u} belongs to $L^2((0, T), L^2_{w_{d+1}}(\mathbb{R}^d))$, and \mathbf{S} belongs to $\mathcal{D}'((0, T) \times \mathbb{R}^d)$.

Let us choose $\varphi \in \mathcal{D}(\mathbb{R}^d)$ such that $\varphi(x) = 1$ on a neighborhood of 0 and define

$$A_{i,j,\varphi} = (1 - \varphi) \partial_i \partial_j G_d.$$

We decompose \mathbf{S} into

$$\mathbf{S} = \nabla p_\varphi + \partial_i g$$

with

$$\begin{aligned} p_\varphi &= \sum_{i,j} (\varphi \partial_i \partial_j G_d) * (u_i u_j) \\ &+ \sum_{i,j} \int (A_{i,j,\varphi}(x - y) - A_{i,j,\varphi}(-y)) (u_i(t, y) u_j(t, y)) dy \end{aligned}$$

and

$$g(t) \in L^1((0, T)).$$

Let us define

$$E(t) = \int_0^t g(\lambda) d\lambda$$

and

$$\mathbf{w}(t, x) = \mathbf{u}(t, x - E(t)) + g(t).$$

Then, \mathbf{w} is a solution of the Navier–Stokes problem

$$\begin{cases} \partial_t \mathbf{w} = \Delta \mathbf{w} - \nabla \cdot (\mathbf{w} \otimes \mathbf{w}) - \nabla q_\varphi \\ \nabla \cdot \mathbf{w} = 0, \quad \mathbf{w}(0, x) = \mathbf{u}_0(x) \\ q_\varphi = \sum_{i,j} (\varphi \partial_i \partial_j G_d) * (w_i w_j) + \sum_{i,j} \int (A_{i,j,\varphi}(x - y) - A_{i,j,\varphi}(-y)) (w_i(t, y) w_j(t, y)) dy \end{cases} \quad (4)$$

2 Curl-free vector fields.

In this section we prove Lemma 1.1 with simple arguments :

Proof. We take a partition of unity on $(0, T)$

$$\sum_{j \in \mathbb{Z}} \omega_j = 1$$

with ω_j supported in $(2^{j-2}T, 2^jT)$ for $j < 0$, in $(T/4, 3T/4)$ for $j = 0$ and in $(T - 2^{-j}T, T - 2^{-(j+2)}T)$ for $j > 1$. We define

$$V_j = -\omega_j \mathbf{u} + \int_0^t \omega_j \Delta \mathbf{u} - \omega_j \nabla \cdot (\mathbf{u} \otimes \mathbf{u} - \mathbb{F}) + (\partial_t \omega_j) \mathbf{u} ds.$$

Then V_j is a sum of the form $A + \Delta B + \nabla \cdot C + D$ with A, B, C and D in $L^1((0, T), L^1(\mathbb{R}^d, w_{d+1} dx))$; thus, by Fubini's theorem, we may see it as a time-dependent tempered distribution. Moreover, $\partial_t V_j = \omega_j \mathbf{S}$, V_j is equal to 0 for t in a neighbourhood of 0, and $\nabla \wedge V_j = 0$. Moreover, $\mathbf{S} = \sum_{j \in \mathbb{Z}} \partial_t V_j$.

We choose $\Phi \in \mathcal{S}(\mathbb{R}^d)$ such that the Fourier transform of Φ is compactly supported and is equal to 1 in the neighbourhood of 0. Then $\Phi * V_j$ is well-defined and $\nabla \wedge (\Phi * V_j) = 0$. We define

$$X_j = \Phi * V_j \text{ and } Y_j = V_j - X_j.$$

We have

$$Y_j = \nabla \left(\frac{1}{\Delta} \nabla \cdot Y_j \right)$$

and (due to Poincaré's lemma)

$$X_j = \nabla \left(\int_0^1 x \cdot X_j(t, \lambda x) d\lambda \right)$$

We find $\mathbf{S} = \nabla p$ with

$$p = \partial_t \sum_{j \in \mathbb{Z}} \left(\int_0^1 x \cdot X_j(t, \lambda x) d\lambda + \frac{1}{\Delta} \nabla \cdot Y_j \right).$$

◇

3 The Poisson problem $-\Delta U = \partial_k \partial_i \partial_j h$

We first consider a simple Poisson problem :

Proposition 3.1 *Let $h \in L^1(\mathbb{R}^d, (1 + |x|)^{-(d+1)} dx)$ then*

$$U = U_1 + U_2 = (\partial_k(\varphi \partial_i \partial_j G_d)) * h + \partial_k((1 - \varphi) \partial_i \partial_j G_d) * h.$$

is a distribution such that U_2 belongs to $L^1(\mathbb{R}^d, (1 + |x|)^{-(d+1)} dx)$ and U is a solution of the problem

$$-\Delta U = \partial_k \partial_i \partial_j h. \quad (5)$$

More precisely, U is the unique solution in \mathcal{S}' such that $\lim_{\tau \rightarrow 0} e^{\tau \Delta} U = 0$ in \mathcal{S}' .

Proof. We may write $\partial_j G_d$ as

$$\partial_j G_d = - \int_0^{+\infty} \partial_j W_t dt$$

where $W_t(x)$ is the heat kernel $W_t(x) = (4\pi t)^{-\frac{d}{2}} e^{-\frac{|x|^2}{4t}}$, so that on $\mathbb{R}^d \setminus \{0\}$, we have

$$\partial_j G_d = c_d \frac{x_j}{|x|^d} \text{ with } c_d = \frac{1}{2(4\pi)^{d/2}} \int_0^{+\infty} e^{-\frac{1}{4u}} \frac{du}{u^{\frac{d+2}{2}}}$$

The first part defining U , $U_1 = (\partial_k(\varphi \partial_i \partial_j G_d)) * h$, is well defined, since $\partial_k(\varphi \partial_i \partial_j G_d)$ is a compactly supported distribution. To control U_2 , we write

$$\begin{aligned} & \int \int \frac{1}{(1 + |x|)^{d+1}} |\partial_k(1 - \varphi) \partial_i \partial_j G_d(x - y)| |h(y)| dy dx \\ & \leq \int \int \frac{1}{(1 + |x|)^{d+1}} \frac{C}{(1 + |x - y|)^{d+1}} |h(y)| dy dx \\ & \leq C' \int \frac{1}{(1 + |y|)^{d+1}} |h(y)| dy \end{aligned}$$

since

$$\begin{aligned} & \int \frac{1}{(1 + |x|)^{d+1}} \frac{1}{(1 + |x - y|)^{d+1}} dx \\ & \leq \int_{|x| > \frac{|y|}{2}} \frac{1}{(1 + |x|)^{d+1}} \frac{1}{(1 + |x - y|)^{d+1}} dx + \int_{|x - y| > \frac{|y|}{2}} \frac{1}{(1 + |x|)^{d+1}} \frac{1}{(1 + |x - y|)^{d+1}} dx \\ & \leq \frac{2^{d+1}}{(1 + |y|)^{d+1}} \int \frac{1}{(1 + |x - y|)^{d+1}} dx + \frac{2^{d+1}}{(1 + |y|)^{d+1}} \int \frac{1}{(1 + |x|)^{d+1}} dx \\ & \leq C \frac{1}{(1 + |y|)^{d+1}}. \end{aligned}$$

Now that we know that U is well defined, we may compute $-\Delta U$. $-\Delta U_1$ is equal to

$$(-\Delta \partial_k(\varphi \partial_i \partial_j G_d)) * h = \partial_k(\varphi \partial_i \partial_j h) - \partial_k((\Delta \varphi) \partial_i \partial_j G_d) * h - 2 \sum_{1 \leq l \leq d} \partial_k((\partial_l \varphi) \partial_l \partial_i \partial_j G_d) * h.$$

For computing $-\Delta U_2$, we see that we can differentiate under the integration sign and find

$$-\Delta U_2 = \partial_k((1 - \varphi) \partial_i \partial_j h) + \partial_k((\Delta \varphi) \partial_i \partial_j G_d) * h + 2 \sum_{1 \leq l \leq d} \partial_k((\partial_l \varphi) \partial_l \partial_i \partial_j G_d) * h.$$

Thus, U is a solution of the Poisson problem.

Computing $e^{\tau \Delta} U$, we find that

$$e^{\tau \Delta} U = (e^{\tau \Delta} \partial_k \partial_i \partial_j G_d) * h$$

and thus

$$|e^{\tau \Delta} U(x)| \leq C \int \frac{1}{(\sqrt{\tau} + |x - y|)^{d+1}} |h(y)| dy.$$

By the dominated convergence theorem, we get that $\lim_{\tau \rightarrow 0} e^{\tau \Delta} U = 0$ in $L^1(\mathbb{R}^d, (1 + |x|)^{-(d+1)} dx)$. If V is another solution of the same Poisson problem with $V \in \mathcal{S}'$ and $\lim_{\tau \rightarrow 0} e^{\tau \Delta} V = 0$ in \mathcal{S}' , then $\Delta(U - V) = 0$ and $U - V \in \mathcal{S}'$, so that $U - V$ is a polynomial; with the assumption that $\lim_{\tau \rightarrow 0} e^{\tau \Delta}(U - V) = 0$, we find that this polynomial is equal to 0. \diamond

If we have better integrability on h , then of course we have better integrability of U_2 . For instance, we have :

Proposition 3.2 *Let $h \in L^1(\mathbb{R}^d, (1 + |x|)^{-d} dx)$ then*

$$U_2 = \partial_k((1 - \varphi) \partial_i \partial_j G_d) * h.$$

belongs to $L^1(\mathbb{R}^d, (1 + |x|)^{-d})$.

Proof.

We write

$$\begin{aligned} & \int \int \frac{1}{(1 + |x|)^d} |\partial_k((1 - \varphi) \partial_i \partial_j G_d(x - y))| |h(y)| dy dx \\ & \leq C \int \int \frac{1}{(1 + |x|)^d} \frac{1}{(1 + |x - y|)^{d+1}} |h(y)| dy dx. \end{aligned}$$

For $|y| < 1$, we have

$$\int \frac{1}{(1+|x|)^{d+1}} \frac{1}{(1+|x-y|)^{d+1}} dx \leq \int \frac{1}{(1+|x|)^{d+1}} dx \leq C$$

and for $|y| > 1$, as the real number $\int_{|x| < \frac{1}{2}} \frac{1}{|x|^{d-1}} \frac{1}{|x-\frac{y}{|y|}|^2} dx$ is finite and does not depend on y , we can write

$$\begin{aligned} & \int \frac{1}{(1+|x|)^d} \frac{1}{(1+|x-y|)^{d+1}} dx \\ & \leq \int_{|x| > \frac{|y|}{2}} \frac{1}{(1+|x|)^d} \frac{1}{(1+|x-y|)^{d+1}} dx + \int_{|x| < \frac{|y|}{2}} \frac{1}{(1+|x|)^d} \frac{1}{(1+|x-y|)^{d+1}} dx \\ & \leq \frac{2^d}{(1+|y|)^d} \int \frac{1}{(1+|x-y|)^{d+1}} dx + \frac{2^{d-1}}{(1+|y|)^{d-1}} \int_{|x| < \frac{|y|}{2}} \frac{1}{|x|^{d-1}} \frac{1}{|x-y|^2} dx \\ & \leq C \frac{1}{(1+|y|)^d} + C \frac{1}{(1+|y|)^{d-1}} \frac{1}{|y|} \int_{|x| < \frac{1}{2}} \frac{1}{|x|^{d-1}} \frac{1}{|x-\frac{y}{|y|}|^2} dx \\ & \leq C' \frac{1}{(1+|y|)^d}. \end{aligned}$$

This concludes the proof. \diamond

4 The Poisson problem $-\Delta V = \partial_i \partial_j h$

Proposition 4.1 *Let $h \in L^1((1+|x|)^{-d-1} dx)$ and $A_\varphi = (1-\varphi)\partial_i \partial_j G_d$ then*

$$V = V_1 + V_2 = (\varphi \partial_i \partial_j G_d) * h + \int (A_\varphi(x-y) - A_\varphi(-y)) h(y) dy$$

is a distribution such that V_2 belongs to $L^1((1+|x|)^{-\gamma})$, for $\gamma > d+1$, and V is a solution of the problem

$$-\Delta V = \partial_i \partial_j h. \quad (6)$$

Proof. We know that V_1 is well defined since $\varphi \partial_i \partial_j G_d$ is a supported compactly distribution, and we will verify that V_2 is well defined.

We have

$$\begin{aligned} & \int \int \frac{1}{(1+|x|)^\gamma} |A_\varphi(x-y) - A_\varphi(-y)| dx \\ & \leq C \|A_\varphi\|_{L^\infty} \int \frac{1}{(1+|x|)^\gamma} dx \end{aligned}$$

For $|y| > 1$, we have by the mean value inequality

$$\int_{|x| < \frac{|y|}{2}} \frac{1}{(1 + |x|)^\gamma} |A_\varphi(x - y) - A_\varphi(-y)| dx \leq C \frac{1}{|y|^{d+1}} \int_{|x| < \frac{|y|}{2}} \frac{|x|}{(1 + |x|)^\gamma} dx$$

and we can control the other part as follows

$$\int_{|x| > \frac{|y|}{2}} \frac{1}{(1 + |x|)^\gamma} |A_\varphi(-y)| dx \leq C \frac{1}{|y|^d} \int_{|x| > \frac{|y|}{2}} \frac{1}{(|x|)^\gamma} \leq C \frac{1}{|y|^\gamma}$$

and for $\varepsilon > 0$ such that $\gamma - \varepsilon \geq d + 1$, we have

$$\begin{aligned} \int_{|x| > \frac{|y|}{2}} \frac{1}{(1 + |x|)^\gamma} |A_\varphi(x - y)| dx &\leq C \int_{|x| > \frac{|y|}{2}} \frac{1}{|x|^\gamma} \frac{1}{(1 + |x - y|)^d} dx \\ &\leq C \int_{|x| > \frac{|y|}{2}} \frac{1}{|x|^\gamma} \frac{1}{|x - y|^{d-\varepsilon}} dx \\ &\leq C \frac{1}{|y|^{d+1}} \int_{|x| > \frac{|y|}{2}} \frac{1}{|x|^\gamma} \frac{1}{|x - \frac{y}{|y|}|^{d-\varepsilon}} dx \\ &\leq C' \frac{1}{|y|^d}. \end{aligned}$$

◇

5 Proof of Theorems 1 and 2.

We may now prove Theorem 1 :

Proof. Taking the divergence of

$$\partial_t \mathbf{u} = \Delta \mathbf{u} - \nabla \cdot (\mathbf{u} \otimes \mathbf{u}) - \mathbf{S} + \nabla \cdot \mathbb{F},$$

we obtain

$$-\sum_{i,j} \partial_i \partial_j (u_i u_j) + \sum_{i,j} \partial_i \partial_j F_{i,j} - \nabla \cdot \mathbf{S} = 0$$

and

$$-\Delta \mathbf{S} = \nabla \cdot \left(\sum_{i,j} \partial_i \partial_j (u_i u_j - F_{i,j}) \right).$$

We write $h_{i,j} = u_i u_j - F_{i,j}$, and $A_\varphi = (1 - \varphi) \partial_i \partial_j G_d$. By Proposition 4.1, we can define

$$p_\varphi = \sum_{i,j} (\varphi \partial_i \partial_j G_d) * h_{i,j} + \sum_{i,j} \int (A_{i,j,\varphi}(x - y) - A_{i,j,\varphi}(-y)) h_{i,j}(y) dy$$

and

$$U = U_1 + U_2 = \nabla \sum_{i,j} (\varphi \partial_i \partial_j G_d) * h_{i,j} + \nabla \sum_{i,j} ((1 - \varphi) \partial_i \partial_j G_d) * h_{i,j} = \nabla p_\varphi.$$

Let $\tilde{U} = \mathbf{S} - U$. First, we remark that $\Delta U = \Delta \mathbf{S}$ so that $\Delta \tilde{U} = 0$, hence \tilde{U} is harmonic in the space variable.

On the other hand, for a test function $\alpha \in \mathcal{D}(\mathbb{R})$ such that $\alpha(t) = 0$ for all $|t| \geq \varepsilon$, and a test function $\beta \in \mathcal{D}(\mathbb{R}^3)$, and for $t \in (\varepsilon, T - \varepsilon)$, we have

$$\begin{aligned} \tilde{U}(t) *_{t,x} (\alpha \otimes \beta) &= (\mathbf{u} * (-\partial_t \alpha \otimes \beta + \alpha \otimes \Delta \beta) + (-\mathbf{u} \otimes \mathbf{u} + \mathbb{F}) \cdot * (\alpha \otimes \nabla \beta))(t, \cdot) \\ &\quad - \sum_{i,j} ((h_{ij}) * (\nabla(\varphi \partial_i \partial_j G_d) * (\alpha \otimes \beta)))(t, \cdot) - (U_2 * (\alpha \otimes \beta))(t, \cdot). \end{aligned}$$

By Proposition 3.1, we conclude that $\tilde{U} * (\alpha \otimes \beta)(t, \cdot)$ belongs to the space $L^1(\mathbb{R}^d, (1 + |x|^{-d-1}))$. Thus, it is a tempered distribution; as it is harmonic, it must be polynomial. The integrability in $L^1(\mathbb{R}^d, (1 + |x|^{-d-1}))$ implies that this polynomial is constant.

If \mathbb{F} belongs more precisely to $L^1((0, T), L^1_{w_d}(\mathbb{R}^d))$ and \mathbf{u} belongs to $L^2((0, T), L^2_{w_d}(\mathbb{R}^d))$, we find that this polynomial belongs to $L^1(\mathbb{R}^d, w_d dx)$, hence is equal to 0.

Then, using the identity approximation $\Phi_\varepsilon = \frac{1}{\varepsilon^4} \alpha(\frac{t}{\varepsilon}) \beta(\frac{x}{\varepsilon})$ and letting ε go to 0, we obtain a similar result for \tilde{U} . Thus $\mathbf{S} = \nabla p_\varphi + f(t)$, with $f(t) = 0$ if \mathbb{F} belongs to $L^1((0, T), L^1_{w_d}(\mathbb{R}^d))$ and \mathbf{u} belongs to $L^2((0, T), L^2_{w_d}(\mathbb{R}^d))$.

As f does not depend on x , we may take a function $\beta \in \mathcal{D}(\mathbb{R}^d)$ with $\int \beta dx = 1$ and write $f = f *_{x} \beta$; we find that

$$f(t) = \partial_t (\mathbf{u}_0 * \beta - \mathbf{u} * \beta) + \int_0^t \mathbf{u} * \Delta \beta - (\mathbf{u} \otimes \mathbf{u} - \mathbb{F}) \cdot * \nabla \beta - p_\varphi * \nabla \beta ds = \partial_t g.$$

As $\partial_t \partial_j g = \partial_j f = 0$ and $\partial_j g(0, \cdot) = 0$, we find that g depends only on t ; moreover, the formula giving g proves that $g \in L^1((0, T))$. \diamond

The proof of Theorem 2 is classical and the result is known as the extended Galilean invariance of the Navier–Stokes equations :

Proof. Let us suppose that

$$\partial_t \mathbf{u} = \Delta \mathbf{u} - (\mathbf{u} \cdot \nabla) \mathbf{u} - \nabla p_\varphi - \frac{d}{dt} g(t),$$

with $g \in L^1((0, T))$. We define

$$E(t) = \int_0^t g(\lambda) d\lambda \text{ and } \mathbf{w} = \mathbf{u}(t, x - E(t)) + g(t).$$

We have

$$\begin{aligned}
\partial_t \mathbf{w} &= \partial_t \mathbf{u}(t, x - E(t)) - g(t) \cdot \nabla \mathbf{u}(t, x - E(t)) + \frac{d}{dt} g(t) \\
&= \Delta \mathbf{u}(t, x - E(t)) - [(\mathbf{u} \cdot \nabla) \mathbf{u}](t, x - E(t)) - \nabla p_\varphi(t, x - E(t)) - \frac{d}{dt} g(t) \\
&\quad - g(t) \cdot \nabla \mathbf{u}(t, x - E(t)) + \frac{d}{dt} g(t) \\
&= \Delta \mathbf{w} - (\mathbf{w} \cdot \nabla) \mathbf{w} - \nabla p_\varphi(t, x - E(t)).
\end{aligned}$$

If we define $q_\varphi(t, x) = p_\varphi(t, x - E(t))$, we find that we have

$$q_\varphi = \sum_{i,j} (\varphi \partial_i \partial_j G_d) * (w_i w_j) + \sum_{i,j} \int (A_{i,j,\varphi}(x-y) - A_{i,j,\varphi}(-y)) (w_i(t, y) w_j(t, y)) dy.$$

The theorem is proved. \diamond

6 Applications

A consequence of Proposition 3.1 is that we may define the Leray projection operator on the divergence of tensors that belong to $L^1((0, T), L^1(\mathbb{R}^d, w_{d+1} dx))$:

Definition 6.1 *Let $\mathbb{H} \in L^1((0, T), L^1(\mathbb{R}^d, w_{d+1} dx))$ and $\mathbf{w} = \nabla \cdot \mathbb{H}$. The Leray projection $\mathbb{P}(\mathbf{w})$ of \mathbf{w} on solenoidal vector fields is defined by*

$$\mathbb{P}\mathbf{w} = \mathbf{w} - \nabla p_\varphi$$

where ∇p_φ is the unique solution of

$$-\Delta \nabla p = \nabla(\nabla \cdot \mathbf{w})$$

such that

$$\lim_{\tau \rightarrow +\infty} e^{\tau \Delta} \nabla p = 0.$$

A special form of the Navier–Stokes equations is then given by

$$(MNS) \quad \partial_t \mathbf{u} = \Delta \mathbf{u} - \mathbb{P} \nabla \cdot (\mathbf{u} \otimes \mathbf{u} - \mathbb{F}), \quad \mathbf{u}(0, \cdot) = \mathbf{u}_0.$$

This leads to the integro-differential equation

$$u = e^{t\Delta} \mathbf{u}_0 - \int_0^t e^{(t-s)\Delta} \mathbb{P} \nabla \cdot (\mathbf{u} \otimes \mathbf{u} - \mathbb{F}) ds.$$

The kernel of the convolution operator $e^{(t-s)\Delta}\mathbb{P}\nabla\cdot$ is called the Oseen kernel; its study is the core of the method of mild solutions of Kato and Fujita [12]. Thus, we will call equations (MNS) a mild formulation of the Navier–Stokes equations.

The mild formulation together with the local Leray energy inequality has been as well a key tool for extending Leray’s theory of weak solutions in L^2 to the setting of weak solutions with infinite energy. We may propose a general definition of suitable Leray-type weak solutions :

Definition 6.2 (Suitable Leray-type solution)

Let $\mathbb{F} \in L^2((0, T), L^2(\mathbb{R}^d, \frac{1}{(1+|x|)^{d+1}}))$ and $\mathbf{u}_0 \in L^2(\mathbb{R}^d, \frac{1}{(1+|x|)^{d+1}})$ with $\nabla \cdot \mathbf{u}_0 = 0$. We consider the Navier–Stokes problem on $(0, T) \times \mathbb{R}^d$:

$$\begin{aligned} \partial_t \mathbf{u} &= \Delta \mathbf{u} - \mathbb{P}(\mathbf{u} \otimes \mathbf{u} - \mathbb{F}), \\ \nabla \cdot \mathbf{u} &= 0, \quad \mathbf{u}(0, \cdot) = \mathbf{u}_0. \end{aligned}$$

A suitable Leray-type solution \mathbf{u} of the Navier–Stokes equations is a vector field \mathbf{u} defined on $(0, T) \times \mathbb{R}^d$ such that :

- \mathbf{u} is locally $L_t^2 H_x^1$ on $(0, T) \times \mathbb{R}^d$
- $\sup_{0 < t < T} \int |\mathbf{u}(t, x)|^2 \frac{1}{(1+|x|)^{d+1}} dx < +\infty$
- $\iint_{(0, T) \times \mathbb{R}^d} |\nabla \otimes \mathbf{u}(t, x)|^2 \frac{1}{(1+|x|)^{d+1}} dx dt < +\infty$
- the application $t \in [0, T) \mapsto \int \mathbf{u}(t, x) \cdot \mathbf{w}(x) dx$ is continuous for every smooth compactly supported vector field \mathbf{w}
- for every compact subset K of \mathbb{R}^d , $\lim_{t \rightarrow 0} \int_K |\mathbf{u}(t, x) - \mathbf{u}_0(x)|^2 dx = 0$.
- defining p_φ as (the) solution of $-\Delta p_\varphi = \sum_{i,j} \partial_i \partial_j (u_i u_j - F_{i,j})$ given by Proposition 4.1, \mathbf{u} is suitable in the sense of Caffarelli, Kohn and Nirenberg : there exists a non-negative locally bounded Borel measure μ on $(0, T) \times \mathbb{R}^d$ such that

$$\partial_t \left(\frac{|\mathbf{u}|^2}{2} \right) = \Delta \left(\frac{|\mathbf{u}|^2}{2} \right) - |\nabla \otimes \mathbf{u}|^2 - \nabla \cdot \left(\left(\frac{|\mathbf{u}|^2}{2} + p_\varphi \right) \mathbf{u} \right) + \mathbf{u} \cdot (\nabla \cdot \mathbb{F}) - \mu$$

Remarks :

- a) With those hypotheses, p_φ belongs locally to $L_{t,x}^{3/2}$ and \mathbf{u} belongs locally to $L_{t,x}^3$ so that the distribution $(\frac{|\mathbf{u}|^2}{2} + p_\varphi)\mathbf{u}$ is well-defined.
- b) Suitability is a local assumption. It has been introduced by Caffarelli, Kohn and Nirenberg in 1982 [6] to get estimates on partial regularity for

weak Leray solutions. If we consider a solution of the Navier–Stokes equations on a small domain with no specifications on the behaviour of \mathbf{u} at the boundary, the estimates on the pressure (and the Leray projection operator) are no longer available. However, Wolf described in 2017 [21] a local decomposition of the pressure into a term similar to the Leray projection of $\nabla \cdot (\mathbf{u} \otimes \mathbf{u})$ and a harmonic term; he could generalize the notion of suitability to this new description of the pressure. On the equivalence of various notions of suitability, see the paper by Chamorro, Lemarié-Rieusset and Mayoufi [8].

c) The relationship between the system (NS) and its mild formulation (MNS) described in Theorem 1 has been described by Furioli, Lemarié-Rieusset and Terraneo in 2000 [13, 16] in the context of uniformly locally square integrable solutions. See the paper by Dubois [11], as well.

We list here a few examples to be found in the litterature :

1. Solutions in L^2 : in 1934, Leray [18] studied the Navier–Stokes problem (NS) with an initial data $\mathbf{u}_0 \in L^2$ and a forcing tensor $\mathbb{F} \in L_t^2 L_x^2$. He then obtained a solution $\mathbf{u} \in L^\infty L^2 \cap L^2 \dot{H}^1$. Remark that this solution is automatically a solution of the mild formulation of the Navier–Stokes equations (MNS). Leray’s construction by mollification provides suitable solutions.
2. Solutions in L_{uloc}^2 : in 1999, Lemarié-Rieusset [15, 16] studied the Navier–Stokes problem (MNS) with an initial data $\mathbf{u}_0 \in L_{\text{uloc}}^2$ (and, later in [17], a forcing tensor $\mathbb{F} \in (L_t^2 L_x^2)_{\text{uloc}}$). He obtained (local in time) existence of a suitable solution \mathbf{u} on a small strip $(0, T_0) \times \mathbb{R}^d$ such that

$$\sup_{x_0 \in \mathbb{R}^d} \sup_{0 < t < T_0} \int_{B(x_0, 1)} |\mathbf{u}(t, x)|^2 dx < +\infty$$

and

$$\sup_{x_0 \in \mathbb{R}^d} \int_0^{T_0} \int_{B(x_0, 1)} |\nabla \otimes \mathbf{u}(t, x)|^2 dx < +\infty.$$

Remark that we have $\mathbf{u} \in L^2((0, T_0), L^2(\mathbb{R}^d, \frac{1}{(1+|x|)^{d+1}} dx))$ but \mathbf{u} does not belong to $L^2((0, T_0), L^2(\mathbb{R}^d, \frac{1}{(1+|x|)^d} dx))$; thus, in this setting, problems (NS) and (MNS) are not equivalent.

Various reformulations of local Leray solutions in L_{uloc}^2 have been provided, such as Kikuchi and Seregin in 2007 [14] or Bradshaw and Tsai in 2019 [4]. The formulas proposed for the pressure, however, are actually equivalent, as they all imply that \mathbf{u} is solution to the (MNS) problem.

In the case of dimension $d = 2$, Basson [1] proved in 2006 that the solution \mathbf{u} is indeed global (i.e. $T_0 = T$) and that, moreover, the solution is unique.

3. Solutions in a weighted Lebesgue space : in 2019, Fernández-Dalgo and Lemarié–Rieusset [9] considered data $\mathbf{u}_0 \in L^2(\mathbb{R}^3, w_\gamma dx)$ and $\mathbb{F} \in L^2((0, +\infty), L^2(\mathbb{R}^3, w_\gamma dx))$ with $0 < \gamma \leq 2$. They proved (global in time) existence of a suitable solution \mathbf{u} such that, for all $T_0 < +\infty$,

$$\sup_{0 < t < T_0} \int |\mathbf{u}(t, x)|^2 w_\gamma(x) dx < +\infty$$

and

$$\int_0^{T_0} \int |\nabla \otimes \mathbf{u}(t, x)|^2 w_\gamma(x), dx < +\infty.$$

[Of course, for such solutions, (NS) and (MNS) are equivalent.] They showed that, for $\frac{4}{3} < \gamma \leq 2$, this frame of work is well adapted to the study of discretely self-similar solutions with locally L^2 initial value, providing a new proof of the results of Chae and Wolf in 2018 [7] and of Bradshaw and Tsai in 2019 [3].

4. Homogeneous Statistical Solutions : in 1977, Vishik and Fursikov [19] considered the (MNS) problem with a random initial value $\mathbf{u}_0(\omega)$. The statistics of the initial distributions were supposed to be invariant though translation of the arguments of \mathbf{u}_0 : for every Borel subset B of $L^2_{\text{loc}}(\mathbb{R}^3)$ and every $x_0 \in \mathbb{R}^3$,

$$Pr(\mathbf{u}_0(\cdot - x_0) \in A) = Pr(\mathbf{u}_0 \in A).$$

Another assumption was that \mathbf{u}_0 has a bounded mean energy density :

$$e_0 = \mathbb{E} \left(\frac{\int_{|x| \leq 1} |\mathbf{u}_0|^2 dx}{\int_{|x| \leq 1} dx} \right) < +\infty.$$

Then

$$Pr(\mathbf{u}_0 \in L^2 \text{ and } u \neq 0) = 0$$

while, for any $\epsilon > 0$,

$$Pr\left(\int |\mathbf{u}_0|^2 \frac{1}{(1+|x|)^{3+\epsilon}} dx < +\infty\right) = 1.$$

In [20], they constructed a solution $\mathbf{u}(t, x, \omega)$ that solved the Navier–Stokes equation for almost every initial value $\mathbf{u}_0(\omega)$, and the solution belonged almost surely to $L_t^\infty L_x^2(\frac{1}{(1+|x|)^{3+\epsilon}} dx)$ with $\nabla \otimes \mathbf{u} \in L_t^2 L_x^2(\frac{1}{(1+|x|)^{3+\epsilon}} dx)$.

In 2006, Basson [2] gave a precise description of the pressure in those equations (which is equivalent to our description through the Leray projection operator) and proved the suitability of the solutions.

7 The space B_γ^2 .

Instead of dealing with weighted Lebesgue spaces, one may deal with a kind of local Morrey space, the space B_γ^2 .

Definition 7.1 For $\gamma \geq 0$, define $w_\gamma(x) = \frac{1}{(1+|x|)^\gamma}$ and $L_{w_\gamma}^p = L^p(\mathbb{R}^d, w_\gamma(x) dx)$.

For $1 \leq p < +\infty$, we denote B_γ^p the Banach space of all functions $u \in L_{w_\gamma}^p$ such that :

$$\|u\|_{B_\gamma^p} = \sup_{R \geq 1} \left(\frac{1}{R^\gamma} \int_{B(0,R)} |u|^p dx \right)^{1/p} < +\infty.$$

Similarly, $B_\gamma^p L^p(0, T)$ is the Banach space of all functions $u \in (L_t^p L_x^p)_{\text{loc}}$ such that

$$\|u\|_{B_\gamma^p L^p(0,T)} = \sup \left(\frac{1}{R^\gamma} \int_0^T \int |u|^p \right)^{\frac{1}{p}} dx ds.$$

Lemma 7.1 Let $\gamma \geq 0$ and $\gamma < \delta < +\infty$, we have the continuous embedding $L_{w_\gamma}^p \hookrightarrow B_{\gamma,0}^p \hookrightarrow B_\gamma^p \hookrightarrow L_{w_\delta}^p$, where $B_{\gamma,0}^p \subset B_\gamma^p$ is the subspace of all functions $u \in B_\gamma^p$ such that $\lim_{R \rightarrow +\infty} \frac{1}{R^\gamma} \int_{B(0,R)} |u(x)|^p dx = 0$.

Proof. Let $u \in L_{w_\gamma}^p$. We verify easily that $\|u\|_{B_\gamma^p} \leq 2^{\gamma/p} \|u\|_{L_{w_\gamma}^p}$ and we see that

$$\frac{1}{R^\gamma} \int_{|x| \leq R} |u|^p dx = \int_{|x| \leq R} \frac{|u|^p}{(1+|x|)^\gamma} \frac{(1+|x|)^\gamma}{R^\gamma} dx$$

converges to zero when $R \rightarrow +\infty$ by dominated convergence, so $L_{w_\gamma}^p \hookrightarrow B_{\gamma,0}^p$. To demonstrate the other part, we estimate

$$\begin{aligned} \int \frac{|u|^p}{(1+|x|)^\delta} dx &= \int_{|x| \leq 1} \frac{|u|^p}{(1+|x|)^\delta} dx + \sum_{n \in \mathbb{N}} \int_{2^{n-1} \leq |x| \leq 2^n} \frac{|u|^p}{(1+|x|)^\delta} dx \\ &\leq \int_{|x| \leq 1} |u|^p dx + \sum_{n \in \mathbb{N}} \frac{1}{(1+2^{n-1})^\delta} \int_{2^{n-1} \leq |x| \leq 2^n} |u|^p dx \\ &\leq \int_{|x| \leq 1} |u|^p dx + c \sum_{n \in \mathbb{N}} \frac{1}{2^{\delta n}} \int_{2^{n-1} \leq |x| \leq 2^n} |u|^p dx \\ &\leq (1 + c \sum_{n \in \mathbb{N}} \frac{1}{2^{(\delta-\gamma)n}}) \sup_{R \geq 1} \frac{1}{R^\gamma} \int_{|x| \leq R} |u|^p dx, \end{aligned}$$

thus, $B_\gamma^p \subset L_{w_\delta}^p$. ◇

Remark : Similarly, for all $\delta > \gamma$, $B_\gamma^p L^p(0, T) \subset L^p((0, T), L_{w_\delta}^p)$.

Proposition 7.1 *The space B_γ^p can be obtained by interpolation,*

$$B_\gamma^p = [L^p, L_{w_\delta}^p]_{\frac{\gamma}{\delta}, \infty}$$

for all $0 < \gamma < \delta < \infty$, and the norms

$$\|\cdot\|_{B_\gamma^p} \quad \text{and} \quad \|\cdot\|_{[L^p, L_{w_\delta}^p]_{\frac{\gamma}{\delta}, \infty}}$$

are equivalent.

Proof. Let $f \in B_\gamma^p$. For $A < 1$, we write $f_0 = 0$ and $f_1 = f$, then we have $f = f_0 + f_1$ and $\|f_1\|_{L_{w_\delta}^p} \leq CA^{\frac{\gamma}{\delta}-1} \|f\|_{B_\gamma^p}$.

For $A > 1$, we let $R = A^{\frac{\delta}{\gamma}} > 1$. We write $f_0 = f\mathbf{1}_{|x| \leq R}$ and $f_1 = f\mathbf{1}_{|x| > R}$, then

$$\|f_0\|_p \leq C \|f\|_{B_\gamma^p} R^{\frac{\gamma}{p}} = CA^{\frac{\gamma}{\delta}} \|f\|_{B_\gamma^p}$$

and

$$\begin{aligned} \|f_1\|_p^p &= \sum_{n \in \mathbb{N}} \int_{2^{n-1}R \leq |x| \leq 2^n R} \frac{|u|^p}{(1+|x|)^\delta} dx \\ &\leq CR^{\gamma-\delta} \sum_{n \in \mathbb{N}} \frac{1}{2^{(\delta-\gamma)n}} \|f\|_{B_\gamma^p}^p \\ &= CA^{(\frac{\gamma}{\delta}-1)p} \|f\|_{B_\gamma^p}^p \end{aligned}$$

Thus, $B_\gamma^p \hookrightarrow [L^p, L_{w_\delta}^p]_{\frac{\gamma}{\delta}, \infty}$.

Let $f \in [L^p, L_{w_\delta}^p]_{\frac{\gamma}{\delta}, \infty}$, then there exist $c > 0$ such that for all $A > 0$, there exist $f_0 \in L^p$ and $f_1 \in L_{w_\delta}^p$ so that $f = f_0 + f_1$,

$$\|f_0\|_p \leq cA^{\frac{\gamma}{\delta}} \quad \text{and} \quad \|f_1\|_{L_{w_\delta}^p} \leq cA^{\frac{\gamma}{\delta}-1}.$$

For $j \in \mathbb{N}$ we take $A = 2^{\frac{j\delta}{p}}$, then

$$\begin{aligned}
& \frac{1}{2^{j\gamma}} \int_{|x| < 2^j} |f|^p dx \\
& \leq C \left(\frac{1}{2^{j\gamma}} \int_{|x| < 2^j} |f_0|^p dx + \frac{1}{2^{j\gamma}} \int_{|x| < 2^j} |f_1|^p dx \right) \\
& \leq C \left(\frac{1}{2^{j\gamma}} \|f_0\|_p^p + \frac{C}{2^{j\gamma}} \int_{|x| \leq 1} \frac{|f_1|^p}{(1+|x|)^\delta} dx + C \sum_{k=1}^j \frac{2^{k\delta}}{2^{j\gamma}} \int_{2^{k-1} < |x| < 2^k} \frac{|f_1|^p}{(1+|x|)^\delta} dx \right) \\
& \leq C \left(\frac{1}{2^{j\gamma}} \|f_0\|_p^p + C' 2^{j(\delta-\gamma)} \|f_1\|_{L_{w_\delta}^p}^p \right) \\
& \leq C''
\end{aligned}$$

which implies $\sup_{j \in \mathbb{N}} \frac{1}{2^{j\gamma}} \int_{|x| < 2^j} |f|^p dx < +\infty$, so $\sup_{R \geq 1} \frac{1}{R^\gamma} \int_{|x| < R} |f|^p dx < +\infty$. \diamond

Thus, we can see that the local Morrey spaces B_γ^p are very close to the weighted Lebesgue spaces $L_{w_\gamma}^p$. Indeed, the methods and results of Fernández-Dalgo and Lemarié-Rieusset [9] can be easily extended to the setting of local Morrey spaces in dimension $d = 2$ or $d = 3$: considering data $\mathbf{u}_0 \in B_\gamma^2(\mathbb{R}^d)$ and $\mathbb{F} \in (B_\gamma^2 L^2)(0, T)(\mathbb{R}^d)$ with $0 < \gamma \leq 2$, one gets (local in time) existence of a suitable solution \mathbf{u} for the (MNS) system on a small strip $(0, T_0) \times \mathbb{R}^d$ such that $\mathbf{u} \in L^\infty((0, T_0), B_\gamma^2)$ and $\nabla \otimes \mathbf{u} \in (B_\gamma^2 L^2)(0, T_0)$.

The case of $\gamma = 2$ deserves some comments. In the case $d = 3$, the results is slightly more general than the results in [9], as the class B_2^2 is larger than the space $L_{w_2}^2$. Equations in B_2^2 have been very recently discussed by Bradshaw, Kukavica and Tsai [5]. The case $d = 2$ is more intricate. Indeed, while the Leray projection operator is bounded on $B_2^2(\mathbb{R}^3)$ (by interpolation with L^2 and $L_{w_\delta}^2$ with $2 < \delta < 3$, the Riesz transforms being bounded on $L_{w_\delta}^2$ by the theory of Muckenhoupt weights), this is no longer the fact on $B_2^2(\mathbb{R}^2)$. Thus, one must be careful in the handling of the pressure. This has been done by Basson in his Ph. D. thesis in 2006 [1].

Local Morrey spaces B_d^2 occur naturally in the setting of homogeneous statistical solutions. By using an ergodicity argument, Dostoglou [10] proved in 2001 that, under the assumptions of Vishik and Fursikov [19], we have

$$Pr(\mathbf{u}_0(\cdot, \omega) \in B_d^2(\mathbb{R}^d)) = 1.$$

Thus, the solutions of Vishik and Fursikov live in a smaller space than $L_{w_{d+\epsilon}}^2$.

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