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1 **HIGH ORDER HOMOGENIZATION OF THE STOKES SYSTEM IN**  
2 **A PERIODIC POROUS MEDIUM\***

3 FLORIAN FEPPON<sup>†</sup>

4 **Abstract.** We derive high order homogenized models for the incompressible Stokes system in  
5 a cubic domain filled with periodic obstacles. These models have the potential to unify the three  
6 classical limit problems (namely the “unchanged” Stokes system, the Brinkman model, and the  
7 Darcy’s law) corresponding to various asymptotic regimes of the ratio  $\eta \equiv a_\varepsilon/\varepsilon$  between the radius  
8  $a_\varepsilon$  of the holes and the size  $\varepsilon$  of the periodic cell. What is more, a novel, rather surprising feature  
9 of our higher order effective equations is the occurrence of odd order differential operators when the  
10 obstacles are not symmetric. Our derivation relies on the method of two-scale power series expansions  
11 and on the existence of a “criminal” ansatz, which allows to reconstruct the oscillating velocity and  
12 pressure  $(\mathbf{u}_\varepsilon, p_\varepsilon)$  as a linear combination of the derivatives of their formal average  $(\mathbf{u}_\varepsilon^*, p_\varepsilon^*)$  weighted  
13 by suitable corrector tensors. The formal average  $(\mathbf{u}_\varepsilon^*, p_\varepsilon^*)$  is itself the solution to a formal, infinite  
14 order homogenized equation, whose truncation at any finite order is in general ill-posed. Inspired  
15 by the variational truncation method of [53, 27], we derive, for any  $K \in \mathbb{N}$ , a well-posed model of  
16 order  $2K + 2$  which yields approximations of the original solutions with an error of order  $O(\varepsilon^{K+3})$   
17 in the  $L^2$  norm. Furthermore, the error improves up to the order  $O(\varepsilon^{2K+4})$  if a slight modification  
18 of this model remains well-posed. Finally, we find asymptotics of all homogenized tensors in the low  
19 volume fraction limit  $\eta \rightarrow 0$  and in dimension  $d \geq 3$ . This allows us to obtain that our effective  
20 equations converge coefficient-wise to either of the Brinkman or Darcy regimes which arise when  $\eta$   
21 is respectively equivalent, or greater than the critical scaling  $\eta_{\text{crit}} \sim \varepsilon^{2/(d-2)}$ .

22 **Key words.** Homogenization, higher order models, porous media, Stokes system, strange term.

23 **AMS subject classifications.** 35B27, 76M50, 35J30

24 **1. Introduction.** This article is concerned with the high order homogenization  
25 of the Stokes system in a periodic porous medium. Let  $D := (0, L)^d$  be a  $d$ -dimensional  
26 box filled with periodic obstacles  $\omega_\varepsilon := \varepsilon(\mathbb{Z}^d + \eta T) \cap D$  obtained by rescaling and  
27 repeating periodically a unit hole  $T$  (the setting is illustrated on [Figure 1](#)). The  
28 parameter  $\varepsilon$  denotes the size of the periodic cell, it is equal to  $\varepsilon := L/N$  where  $N \in \mathbb{N}$   
29 is a large integer and  $L$  is the length of the box. The parameter  $\eta$  is the scaling ratio  
30 between the radius  $a_\varepsilon := \eta\varepsilon$  of the obstacles and the length  $\varepsilon$  of the cells. The total  
31 fluid domain is denoted by  $D_\varepsilon := D \setminus \overline{\omega_\varepsilon}$  and it is assumed to be connected.  $P = (0, 1)^d$   
32 is the unit cell and  $Y = P \setminus \eta T$  denotes its fluid component.

33 We consider  $(\mathbf{u}_\varepsilon, p_\varepsilon) \in H^1(D_\varepsilon, \mathbb{R}^d) \times L^2(D_\varepsilon)/\mathbb{R}$  the solution to the Stokes system

$$34 \quad (1.1) \quad \begin{cases} -\Delta \mathbf{u}_\varepsilon + \nabla p_\varepsilon = \mathbf{f} & \text{in } D_\varepsilon \\ \operatorname{div}(\mathbf{u}_\varepsilon) = 0 \\ \mathbf{u}_\varepsilon = 0 & \text{on } \partial\omega_\varepsilon \\ \mathbf{u}_\varepsilon & \text{is } D\text{-periodic,} \end{cases}$$

35 where  $\mathbf{f} \in C_{\text{per}}^\infty(D, \mathbb{R}^d)$  (and all its derivatives) is a smooth,  $D$ -periodic right hand-  
36 side. The goal of this paper is to derive high order effective models for (1.1); i.e. a  
37 family of well-posed partial differential equations posed in the homogeneous domain

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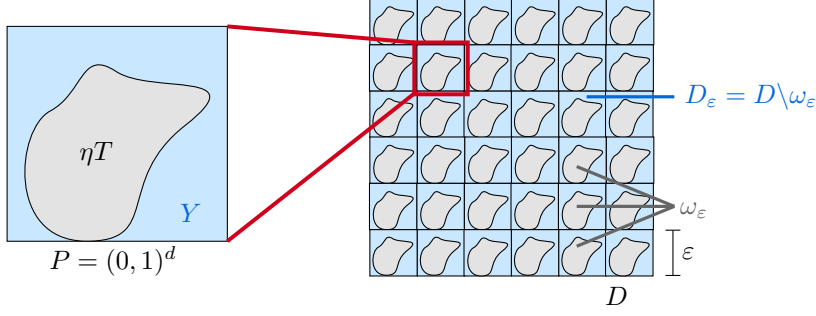


FIG. 1. The perforated domain  $D_\varepsilon = D \setminus \omega_\varepsilon$  and the unit cell  $Y = P \setminus (\eta T)$ .

38  $D$  (without the holes) and whose solutions approximate the macroscopic behavior of  
 39  $(\mathbf{u}_\varepsilon, p_\varepsilon)$  at any desired order of accuracy in  $\varepsilon$  as  $\varepsilon \rightarrow 0$ .

40 The literature [52, 47, 29, 5, 7, 4, 8] describes the occurrence of different asymp-  
 41 totic regimes depending on how the size  $a_\varepsilon = \eta\varepsilon$  of the holes compares to the critical  
 42 size  $\sigma_\varepsilon := \varepsilon^{d/(d-2)}$  in dimension  $d \geq 3$  (if  $d = 2$ , then these regimes depend on  
 43 how  $\log(a_\varepsilon)$  compares to  $-\varepsilon^{-2}$ , see [7]). In loose mathematical terms, these can be  
 44 summarized as follows (see e.g. [5, 7] for the precise statements):

- 45 • if  $a_\varepsilon = o(\sigma_\varepsilon)$ , then the holes have no effect and  $(\mathbf{u}_\varepsilon, p_\varepsilon)$  converges as  $\varepsilon \rightarrow 0$   
 46 to the solution  $(\mathbf{u}, p)$  of the Stokes equation in the homogeneous domain  $D$ :

$$47 \quad (1.2) \quad \begin{cases} -\Delta \mathbf{u} + \nabla p = \mathbf{f} & \text{in } D \\ \operatorname{div}(\mathbf{u}) = 0 \\ \mathbf{u} \text{ is } D\text{-periodic.} \end{cases}$$

- 48 • if  $a_\varepsilon = c\sigma_\varepsilon$  for a constant  $c > 0$ , then  $(\mathbf{u}_\varepsilon, p_\varepsilon)$  converges as  $\varepsilon \rightarrow 0$  to the  
 49 solution  $(\mathbf{u}, p)$  of the Brinkman equation

$$50 \quad (1.3) \quad \begin{cases} -\Delta \mathbf{u} + cF\mathbf{u} + \nabla p = \mathbf{f} & \text{in } D \\ \operatorname{div}(\mathbf{u}) = 0 \\ \mathbf{u} \text{ is } D\text{-periodic,} \end{cases}$$

51 where the so-called *strange term*  $cF\mathbf{u}$  involves a symmetric positive definite  
 52  $d \times d$  matrix  $F$  which can be computed by means of an exterior problem in  
 53  $\mathbb{R}^d \setminus T$  (see [4] and section 5).

- 54 • if  $\sigma_\varepsilon = o(a_\varepsilon)$  and  $a_\varepsilon = \eta\varepsilon$  with  $\eta \rightarrow 0$  as  $\varepsilon \rightarrow 0$ , then the holes are “large”  
 55 and  $(a_\varepsilon^{d-2}\varepsilon^{-d}\mathbf{u}_\varepsilon, p_\varepsilon)$  converges to the solution  $(\mathbf{u}, p)$  of the Darcy problem

$$56 \quad (1.4) \quad \begin{cases} F\mathbf{u} + \nabla p = \mathbf{f} & \text{in } D \\ \operatorname{div}(\mathbf{u}) = 0 & \text{in } D \\ \mathbf{u} \text{ is } D\text{-periodic,} \end{cases}$$

57 where  $F$  is the same symmetric positive definite  $d \times d$  matrix as in (1.3).

- 58 • if  $a_\varepsilon = \eta\varepsilon$  with the ratio  $\eta$  fixed, then  $(\varepsilon^{-2}\mathbf{u}_\varepsilon, p_\varepsilon)$  converges to the solution  
 59  $(\mathbf{u}, p)$  of the Darcy problem

$$60 \quad (1.5) \quad \begin{cases} M^0\mathbf{u} + \nabla p = \mathbf{f} & \text{in } D \\ \operatorname{div}(\mathbf{u}) = 0 & \text{in } D \\ \mathbf{u} \text{ is } D\text{-periodic,} \end{cases}$$

61 where  $M^0$  is another positive symmetric  $d \times d$  matrix (which depends on  $\eta$ ).  
 62 Furthermore  $M^0/|\log(\eta)| \rightarrow F$  if  $d = 2$ , and  $M^0/\eta^{d-2} \rightarrow F$  (if  $d \geq 3$ ) when  
 63  $\eta \rightarrow 0$ , so that there is a continuous transition from (1.5) to (1.4), see [6].

64 One of the long-term motivations driving this work is the need to lay down theo-  
 65 retical material that would allow to optimize the design of fluid systems by homog-  
 66 enization methods similar to those available in the context of mechanical structures  
 67 [21, 20, 10, 50, 14]. To date, the Brinkman [24, 25, 30] and the Darcy models [56, 51]  
 68 are commonly used by topology optimization algorithms in order to conveniently in-  
 69 terpolate the physics of the fluid at intermediate “gray” regions featuring locally a  
 70 mixture of fluid and solid. However, the above conclusions imply that these models  
 71 are consistent only in specific ranges of obstacle sizes  $a_\varepsilon$ : the Brinkman model (1.3)  
 72 is relevant when there are none or tiny obstacles, while the Darcy models (1.4) and  
 73 (1.5) should be used at locations where the obstacles are large enough. The arising  
 74 of these different regimes (1.2)–(1.5) is consequently a major obstacle towards the de-  
 75 velopment of ‘de-homogenization’ methods [14, 37, 50, 39, 40] for the optimal design  
 76 of fluid systems, which would enable to interpret “gray” designs as locally periodic  
 77 “black and white” microstructures (featuring for instance many small tubes or thin  
 78 plates).

79 It turns out that there is a continuous transition between these regimes which  
 80 can be captured by higher order homogenized equations, which is the object of the  
 81 present article. These higher order models are obtained by adding corrective terms  
 82 scaled by increasing powers of  $\varepsilon$  to the Darcy equation (1.5); they yield more accurate  
 83 approximations of  $(\mathbf{u}_\varepsilon, p_\varepsilon)$  when  $\varepsilon$  is “not so small”. For a desired order  $K \in \mathbb{N}$ , the  
 84 homogenized model of order  $2K + 2$  reads

$$85 \quad (1.6) \quad \begin{cases} \sum_{k=0}^{2K+2} \varepsilon^{k-2} \mathbb{D}_K^k \cdot \nabla^k \mathbf{v}_{\varepsilon, K}^* + \nabla q_{\varepsilon, K}^* = \mathbf{f}, \\ \operatorname{div}(\mathbf{v}_{\varepsilon, K}^*) = 0, \\ \mathbf{v}_{\varepsilon, K}^* \text{ is } D\text{-periodic,} \end{cases}$$

86 where  $(\mathbf{v}_{\varepsilon, K}^*, q_{\varepsilon, K}^*)$  is a high order homogenized approximation of  $(\mathbf{u}_\varepsilon, p_\varepsilon)$ . The coeffi-  
 87 cient  $\mathbb{D}_K^k$  is a  $k$ -th order *matrix valued* tensor which can be computed by a procedure  
 88 involving the resolution of cell problems; it makes  $\mathbb{D}_K^k \cdot \nabla^k$  a differential operator of  
 89 order  $k$  (the notation is defined in section 2 below). Finally, the high order equation  
 90 (1.6) encompasses at least the Brinkman and the Darcy regimes in the sense that it  
 91 converges coefficient-wise to either of (1.3) and (1.4) for the corresponding asymptotic  
 92 regime of the scaling  $\eta$  (see Remarks 5.6 and 5.7) (the analysis of the subcritical case  
 93 leading to the Stokes regime (1.2) requires more sophisticated arguments which are  
 94 to be investigated in future works).

95 A rather striking feature of (1.6) is the arising of *odd* order differential operators  
 96 despite the symmetry of the Laplace operator  $-\Delta$  (these vanish, however, in case  
 97 the obstacle  $\eta T$  is symmetric with respect to the cell axes; see Corollary 3.16). This  
 98 fact is closely related to the vectorial nature of the Stokes system (1.1): the tensors  
 99  $\mathbb{D}_K^k$  are symmetric and antisymmetric valued matrices for respectively even and odd  
 100 values of  $k$ . This property ensures that  $\mathbb{D}_K^k \cdot \nabla^k$  is a symmetric operator for any  
 101  $0 \leq k \leq 2K + 2$  (see Remark 3.12). To our knowledge, such terms have so far not  
 102 been proposed in the literature seeking similar higher order corrections for the Stokes  
 103 system, although these have been observed in other vectorial contexts [27, 28, 53].  
 104 Most of the available works have focused on situations with low regularity for  $\mathbf{f}$ ,  $T$

105 and  $D$  (see [52, 5]), where the homogenization process can be justified only for the  
 106 approximation at the leading order in  $\varepsilon$ . Error bounds for higher order approximations  
 107 of  $(\mathbf{u}_\varepsilon, p_\varepsilon)$  (namely for the truncation of the ansatz (1.7) below) have been obtained  
 108 in [46, 26], without relating these to effective models. A few additional works have  
 109 sought corrector terms from physical modelling considerations [35, 18, 17], without  
 110 considering odd order operators.

111 Our derivation is inspired from the works [19, 53, 15]; it is based on (non-standard)  
 112 two-scale asymptotic expansions and formal operations on related power series which  
 113 give rise to several families of tensors and homogenized equations at any order. We  
 114 extend our previous works [34, 33] where we investigated the cases of the perforated  
 115 Poisson problem and of the perforated elasticity system. Expectedly, the major dif-  
 116 ficulty in extending the analysis to (1.6) is the treatment of the pressure variable  $p_\varepsilon$   
 117 and of the incompressibility constraint  $\operatorname{div}(\mathbf{u}_\varepsilon) = 0$ . Note that the  $D$ -periodicity  
 118 assumption on  $\mathbf{f}$  and  $\mathbf{u}_\varepsilon$  is made in order to eliminate additional difficulties related  
 119 to the arising of boundary layers (see [43, 22, 23, 11]).

120 The starting point of the method of two-scale expansions is to postulate an ansatz  
 121 for the velocity and pressure solution  $(\mathbf{u}_\varepsilon, p_\varepsilon)$ :

$$122 \quad (1.7) \quad \mathbf{u}_\varepsilon(x) = \sum_{i=0}^{+\infty} \varepsilon^{i+2} \mathbf{u}_i(x, x/\varepsilon), \quad p_\varepsilon(x) = \sum_{i=0}^{+\infty} \varepsilon^i (p_i^*(x) + \varepsilon p_i(x, x/\varepsilon)), \quad x \in D_\varepsilon,$$

where the functions  $\mathbf{u}_i(x, y)$  and  $p_i(x, y)$  are  $P$ -periodic with respect to  $y \in P$ , and  
 $D$ -periodic with respect to  $x \in D$ . In (1.7), the oscillating function  $p_i(x, y)$  is required  
 to be of zero average with respect to  $y$ :

$$\int_Y p_i(x, y) dy = 0, \quad \forall i \geq 0.$$

123 The aim of the homogenization process is to obtain effective equations for the formal  
 124 “infinite order” homogenized averages  $\mathbf{u}_\varepsilon^*$  and  $p_\varepsilon^*$  defined by

$$125 \quad (1.8) \quad \mathbf{u}_\varepsilon^*(x) := \sum_{i=0}^{+\infty} \varepsilon^{i+2} \int_Y \mathbf{u}_i(x, y) dy, \quad p_\varepsilon^*(x) := \sum_{i=0}^{+\infty} \varepsilon^i p_i^*(x), \quad x \in D.$$

126 In Proposition 3.7 below, we obtain that  $(\mathbf{u}_\varepsilon^*, p_\varepsilon^*)$  solves the following formal “infinite-  
 127 order” homogenized equation,

$$128 \quad (1.9) \quad \begin{cases} \sum_{k=0}^{+\infty} \varepsilon^{k-2} M^k \cdot \nabla^k \mathbf{u}_\varepsilon^* + \nabla p_\varepsilon^* = \mathbf{f}, \\ \operatorname{div}(\mathbf{u}_\varepsilon^*) = 0, \\ \mathbf{u}_\varepsilon^* \text{ is } D\text{-periodic,} \end{cases}$$

129 which involves a family of constant matrix-valued tensors  $(M^k)_{k \in \mathbb{N}}$ . Classically, trun-  
 130 cating directly (1.9) yields, in general, an ill-posed model [12]. Several methods have  
 131 been proposed to address this issue in order to obtain nonetheless well-posed higher  
 132 order equations [16, 13, 1, 2, 15]. In our case, we adapt an idea from [53], whereby  
 133 the coefficients  $\mathbb{D}_K^k$  are obtained thanks to a minimization principle (described in sec-  
 134 tion 4) which makes indeed (1.6) well-posed. It is based on the existence of remarkable

135 identities which relate the oscillating solution  $(\mathbf{u}_\varepsilon, p_\varepsilon)$  to its formal average  $(\mathbf{u}_\varepsilon^*, p_\varepsilon^*)$ :

$$136 \quad (1.10) \quad \begin{cases} \mathbf{u}_\varepsilon(x) = \sum_{i=0}^{+\infty} \varepsilon^i N^i(x/\varepsilon) \cdot \nabla^i \mathbf{u}_\varepsilon^*(x) \\ p_\varepsilon(x) = p_\varepsilon^*(x) + \sum_{i=0}^{+\infty} \varepsilon^{i-1} \beta^i(x/\varepsilon) \cdot \nabla^i \mathbf{u}_\varepsilon^*(x), \end{cases} \quad \forall x \in D_\varepsilon,$$

137 where  $(N^i(y))_{i \in \mathbb{N}}$  and  $(\beta^i(y))_{i \in \mathbb{N}}$  are different families of respectively matrix valued  
138 and vector valued  $P$ -periodic tensors (of order  $i$ ). The ansatz (1.10) is substantially  
139 different from (1.7); following [15], we call it “criminal” because the expansions of  
140 (1.10) depend on  $\mathbf{u}_\varepsilon^*$  which is itself a formal power series in  $\varepsilon$  (eqn. (1.8)).

141 The order of accuracy at which the solution  $(\mathbf{v}_{\varepsilon,K}^*, p_{\varepsilon,K}^*)$  yields an approximation  
142 of the original solution  $(\mathbf{u}_\varepsilon, p_\varepsilon)$  is determined by how many leading coefficients of (1.6)  
143 and (1.9) coincide (Proposition 4.5). In Proposition 4.10, we show that  $\mathbb{D}_K^k = M^k$  for  
144  $0 \leq k \leq K$ , which allows to infer error estimates of order  $O(\varepsilon^{K+3})$  in the  $L^2(D)$  norm.  
145 It may seem disappointing that one needs to solve an equation of order  $2K+2$  in order  
146 to obtain approximations of order  $O(\varepsilon^{K+3})$  “only”. This shortcoming is related to the  
147 zero-divergence constraint: in the scalar and elasticity cases considered in [34, 33], it  
148 turns out that  $K+1$  extra coefficients coincide, namely  $\mathbb{D}_K^k = M^k$  for  $0 \leq k \leq 2K+1$ ,  
149 which yields error estimates of order  $O(\varepsilon^{2K+4})$ . In the present context devoted to the  
150 Stokes system (1.1), the equation obtained by substituting  $\mathbb{D}_K^k$  with  $M^k$  in (1.6) for  
151  $K+1 \leq k \leq 2K+1$ ,

$$152 \quad (1.11) \quad \begin{cases} \varepsilon^{2K} \mathbb{D}_K^{2K+2} \cdot \nabla^{2K+2} \widehat{\mathbf{v}}_{\varepsilon,K}^* + \sum_{k=0}^{2K+1} \varepsilon^{k-2} M^k \cdot \nabla^k \mathbf{v}_{\varepsilon,K}^* + \nabla \widehat{q}_{\varepsilon,K}^* = \mathbf{f} \\ \operatorname{div}(\widehat{\mathbf{v}}_{\varepsilon,K}^*) = 0 \\ \widehat{\mathbf{v}}_{\varepsilon,K}^* \text{ is } D\text{-periodic,} \end{cases}$$

153 corresponds to applying the truncation method of [53] to the mixed variational for-  
154 mulation rather than to the minimization problem associated with (1.1) (see Re-  
155 mark 4.11). While the minimization principle ensures that (1.6) is well-posed, we do  
156 not know whether this is the case for (1.11). However if it is, then Proposition 4.5  
157 implies that (1.11) improves the approximation accuracy up to the order  $O(\varepsilon^{2K+4})$ .

158 The article outlines as follows. Notation conventions related to tensors and tech-  
159 nical assumptions are exposed in section 2.

160 In section 3, we introduce cell problems and their solution tensors  $(\mathcal{X}^k, \boldsymbol{\alpha}^k)$  which  
161 allow to identify the functions  $\mathbf{u}_i$ ,  $p_i^*$  and  $p_i$  in the ansatz (1.7). We show that the  
162 formal average  $(\mathbf{u}_\varepsilon^*, p_\varepsilon^*)$  solves the infinite order homogenized equation (1.9) involving  
163 the tensors  $M^k$ . After defining the tensors  $N^k(y)$  and  $\beta^k(y)$ , we derive the “criminal”  
164 ansatz (1.10) expressing  $(\mathbf{u}_\varepsilon, p_\varepsilon)$  in terms of  $p_\varepsilon^*$  and of the derivatives of  $\mathbf{u}_\varepsilon^*$ . Through-  
165 out this section, a number of algebraic properties are stated for the various tensors  
166 coming at play, such as the symmetry and the antisymmetry of the matrix valued  
167 tensors  $M^k$  for respectively even and odd values of  $k$ , and the simplifications taking  
168 place in case the obstacle  $\eta T$  is symmetric with respect to the cell axes.

169 Section 4 details the truncation process of the infinite order equation (1.9) leading  
170 to the well-posed model (1.6). We then provide an error analysis of the homogenized  
171 approximations of  $(\mathbf{u}_\varepsilon, p_\varepsilon)$  generated by our procedure: our main result is stated in

172 **Corollary 4.15** where we show that the solution  $(\mathbf{v}_{\varepsilon,K}^*, q_{\varepsilon,K}^*)$  of (1.6) yield approxima-  
 173 tions of  $(\mathbf{u}_\varepsilon, p_\varepsilon)$  in the  $L^2(D_\varepsilon)$  norm of order  $K + 3$  and  $K + 1$  for the velocity and  
 174 the pressure respectively. We establish explicit formulas relating the coefficients  $\mathbb{D}_K^k$   
 175 to the coefficients  $M^k$  and we briefly discuss the improvement provided by (1.11) in  
 176 case it is well-posed.

177 The last **section 5** investigates asymptotics of the tensors  $M^k$  in the low volume  
 178 fraction limit where the scaling of the obstacle  $\eta$  converges to zero. Our main result is  
 179 **Corollary 5.5** where we obtain the “coefficient-wise” convergence of the infinite order  
 180 homogenized equation as well as the one of (1.6) towards either of the Brinkman or  
 181 Darcy regimes (1.4) and (1.5) when  $\eta$  is respectively equivalent or greater than the  
 182 critical size  $\eta_{\text{crit}} \sim \varepsilon^{2/(d-2)}$ , and towards the Stokes regime (1.3) for  $\eta = o(\varepsilon^{2/(d-2)})$   
 183 in the case  $K = 0$ . Although our error estimates for (1.6), are a priori not uniform  
 184 in  $\eta$ , this suggests that our higher order model (1.6) has the potential to yield valid  
 185 approximations in any regime of size of holes (at least for  $K = 0$  or above the critical  
 186 scale). Note that our analysis is unfortunately insufficient to establish the convergence  
 187 of the high order coefficients  $\varepsilon^{k-2}M^k$  with  $k > 2$  towards 0 as  $\eta \rightarrow 0$ . Future works  
 188 will investigate higher order asymptotics of the tensors  $M^k$  in the subcritical regime  
 189  $\eta = o(\varepsilon^{2/(d-2)})$  which are required to establish or invalidate such a claim.

190 **2. Setting and notation conventions related to tensors.** In the sequel, we  
 191 consider the following two classical assumptions for the distributions of the holes  $\omega_\varepsilon$   
 192 (we recall the schematic of **Figure 1**), following [5]:

193 **(H1)**  $Y = P \setminus (\eta T) \subset P$ , as a subset of the unit torus (opposite matching faces  
 194 of  $(0, 1)^d$  are identified) is a smooth connected set with non-empty interior.

195 **(H2)** The fluid component  $D_\varepsilon = D \setminus \omega_\varepsilon$  is a smooth connected set.

196 *Remark 2.1.* Assumption **(H1)** does not necessarily imply **(H2)**, see [3] for a coun-  
 197 terexample. Assumption **(H1)** is not very restrictive and can easily be generalized to  
 198 the case where the subset  $Y$  has  $m$  connected components with  $m \in \mathbb{N}$  (see Appendix  
 199 7.5.6 in [33]). Assumption **(H2)** is stronger, but is also more connected to physical  
 200 applications. It forbids the existence of isolated fluid inclusions. Most of our deri-  
 201 vations only assume **(H1)**. However, we rely on both assumptions **(H1)** and **(H2)** in  
 202 order to obtain error bounds **section 4**, because we use some technical results of [5].

203 Below and further on, we consider scalar and vectorial functions such as

$$204 \quad (2.1) \quad \begin{array}{l} u : D \times P \rightarrow \mathbb{R} \\ (x, y) \mapsto u(x, y) \end{array}, \quad \begin{array}{l} \mathbf{u} : D \times P \rightarrow \mathbb{R}^d \\ (x, y) \mapsto \mathbf{u}(x, y) \end{array}$$

205 which are both  $D$  and  $P$ -periodic with respect to respectively the first and the second  
 206 variable, and which vanish on the hole  $D \times (\eta T)$ . The arguments  $x$  and  $y$  of  $u(x, y)$  are  
 207 respectively called the “slow” and the “fast” or “oscillating” variable. With a small  
 208 abuse of notation, the partial derivative with respect to the variable  $y_j$  (respectively  
 209  $x_j$ ) is simply written  $\partial_j$  instead of  $\partial_{y_j}$  (respectively  $\partial_{x_j}$ ) when the context is clear.

The star-“\*”-symbol is used to indicate that a quantity is “macroscopic” in the  
 sense that it does not depend on the fast variable  $x/\varepsilon$ ; e.g.  $(\mathbf{v}_{\varepsilon,K}^*, q_{\varepsilon,K}^*)$  or  $(\mathbf{u}_\varepsilon^*, p_\varepsilon^*)$  in  
 (1.6) and (1.9). In the particular case where a two-variable quantity  $u(x, y)$  is given  
 such as (2.1),  $u^*(x)$  always denotes the average of  $y \mapsto u(x, y)$  with respect to the  $y$   
 variable:

$$u^*(x) := \int_P u(x, y) dy = \int_Y u(x, y) dy, \quad x \in D,$$

where the last equality is a consequence of  $u$  vanishing on  $P \setminus Y = \overline{\eta T}$ . When a function  $\mathcal{X} : P \rightarrow \mathbb{R}$  depends only on the  $y$  variable, we find occasionally more convenient to write its cell average with the usual angle bracket symbols:

$$\langle \mathcal{X} \rangle := \int_P \mathcal{X}(y) dy.$$

210 In all what follows, unless otherwise specified, the Einstein summation convention  
 211 over repeated *subscript* indices is assumed (but never on *superscript* indices). Vectors  
 212  $\mathbf{b} \in \mathbb{R}^d$  are written in bold face notation.

213 The notation conventions used for tensor related operations are summarized in the  
 214 nomenclature below. Some of them are not standard; they allow to avoid to system-  
 215 atically write partial derivative indices (e.g.  $1 \leq i_1 \dots i_k \leq d$ ) and to distinguish them  
 216 from spatial indices (e.g.  $1 \leq l, m \leq d$ ) associated with vector or matrix components.

### 217 Scalar, vector, and matrix valued tensors and their coordinates

|     |                                   |   |
|-----|-----------------------------------|---|
| 218 | $\mathbf{b}$                      | Vector of $\mathbb{R}^d$  |
| 219 | $(b_j)_{1 \leq j \leq d}$         | Coordinates of the vector $\mathbf{b}$  |
| 220 | $b^k$                             | Scalar valued tensor of order $k$ ( $b_{i_1 \dots i_k}^k \in \mathbb{R}$ for $1 \leq i_1, \dots, i_k \leq d$ )              |
| 221 | $\mathbf{b}^k$                    | Vector valued tensor of order $k$ ( $\mathbf{b}_{i_1 \dots i_k}^k \in \mathbb{R}^d$ for $1 \leq i_1, \dots, i_k \leq d$ )   |
| 222 | $B^k$                             | Matrix valued tensor of order $k$ ( $B_{i_1 \dots i_k}^k \in \mathbb{R}^{d \times d}$ for $1 \leq i_1, \dots, i_k \leq d$ ) |
| 223 | $(b_j^k)_{1 \leq j \leq d}$       | Coordinates of the vector valued tensor $\mathbf{b}^k$ ( $b_j^k$ is a <i>scalar</i> tensor of order<br>224 $k$ ).           |
| 225 | $(B_{lm}^k)_{1 \leq l, m \leq d}$ | Coefficients of the matrix valued tensor $B^k$ ( $B_{lm}^k$ is a <i>scalar</i> tensors of<br>226 order $k$ ).               |
| 227 | $b_{i_1 \dots i_k, j}^k$          | Coefficient of the vector valued tensor $\mathbf{b}^k$ ( $1 \leq i_1, \dots, i_k, j \leq d$ )                               |
| 228 | $B_{i_1 \dots i_k, lm}^k$         | Coefficients of the matrix valued tensor $B^k$ ( $1 \leq i_1, \dots, i_k, l, m \leq d$ )                                    |

### 229 Tensor products

230  $b^p \otimes c^{k-p}$  Tensor product of scalar tensors  $b^p$  and  $c^{k-p}$ :

$$231 \quad (2.2) \quad (b^p \otimes c^{k-p})_{i_1 \dots i_k} := b_{i_1 \dots i_p}^p c_{i_{p+1} \dots i_k}^{k-p}.$$

232  $a^p \otimes \mathbf{b}^{k-p}$  Tensor product of a scalar tensors  $a^p$  and a vector valued tensor  $\mathbf{b}^{k-p}$ :

$$233 \quad (2.3) \quad (a^p \otimes \mathbf{b}^{k-p})_{i_1 \dots i_k} := a_{i_1 \dots i_p}^p \mathbf{b}_{i_{p+1} \dots i_k}^{k-p}.$$

234  $B^p \otimes C^{k-p}$  Tensor product of matrix valued tensors  $B^p$  and  $C^{k-p}$ :

$$235 \quad (2.4) \quad (B^p \otimes C^{k-p})_{i_1 \dots i_k, lm} := B_{i_1 \dots i_p, lj}^p C_{i_{p+1} \dots i_k, jm}^{k-p}.$$

236 Hence a matrix product is implicitly assumed in the notation  $B^p \otimes C^{k-p}$ .  
 237  $B^p : C^{k-p}$  Tensor product and Frobenius product of matrix tensors  $B^p$  and  $C^{k-p}$ :

$$238 \quad (2.5) \quad (B^p : C^{k-p})_{i_1 \dots i_k} := B_{i_1 \dots i_p, lm}^p C_{i_{p+1} \dots i_k, lm}^{k-p}.$$

239  $\mathbf{b}^p \cdot \mathbf{c}^{k-p}$  Tensor product and inner product of vector valued tensors  $\mathbf{b}^p$  and  $\mathbf{c}^{k-p}$ :

$$240 \quad (2.6) \quad (\mathbf{b}^p \cdot \mathbf{c}^{k-p})_{i_1 \dots i_k} := b_{i_1 \dots i_p, m}^p c_{i_{p+1} \dots i_k, m}^{k-p}.$$



241  $B^p \cdot \mathbf{c}^{k-p}$  Tensor product of a matrix tensor  $B^p$  and a vector tensors  $\mathbf{c}^{k-p}$ :

242 (2.7)  $(B^p \cdot \mathbf{c}^{k-p})_{i_1 \dots i_k, l} := B_{i_1 \dots i_p, lm}^p c_{i_{p+1} \dots i_k, m}^{k-p}$ .

243 Hence a matrix-vector product is implicitly assumed in  $B^p \cdot \mathbf{c}^{k-p}$ .

244 **Contraction with partial derivatives**

245  $b^k \cdot \nabla^k$  Differential operator of order  $k$  associated with a scalar tensor  $b^k$ :

246 (2.8)  $b^k \cdot \nabla^k := b_{i_1 \dots i_k}^k \partial_{i_1 \dots i_k}^k$ .

247  $\mathbf{b}^k \cdot \nabla^k$  Differential operator of order  $k$  associated with a vector tensor  $\mathbf{b}^k$ : for  
248 any smooth vector field  $\mathbf{v} \in \mathcal{C}_{per}^\infty(D, \mathbb{R}^d)$ ,

249 (2.9)  $\mathbf{b}^k \cdot \nabla^k \mathbf{v} = b_{i_1 \dots i_k, l}^k \partial_{i_1 \dots i_k}^k v_l$ .

250  $B^k \cdot \nabla^k$  Differential operator of order  $k$  associated with a matrix valued tensor  
251  $B^k$ : for any smooth vector field  $\mathbf{v} \in \mathcal{C}_{per}^\infty(D, \mathbb{R}^d)$ ,

252 (2.10)  $(B^k \cdot \nabla^k \mathbf{v})_l = B_{i_1 \dots i_k, lm}^k \partial_{i_1 \dots i_k}^k v_m$ .

253 **Special tensors**

254  $(e_j)_{1 \leq j \leq d}$  Vectors of the canonical basis of  $\mathbb{R}^d$ .

255  $e_j$  Scalar valued tensor of order 1 given by  $e_{j, i_1} := \delta_{i_1 j}$  (with  $1 \leq j \leq d$ ).

256  $\delta_{ij}$  Kronecker symbol:  $\delta_{ij} = 1$  if  $i = j$  and  $\delta_{ij} = 0$  if  $i \neq j$ .

$I$  Identity tensor of order 2:

$$I_{i_1 i_2} = \delta_{i_1 i_2}.$$

257 The identity tensor is another notation for the Kronecker tensor and it  
258 holds  $I = e_j \otimes e_j$  with summation on the index  $1 \leq j \leq d$ .

$J^{2k}$  Tensor of order  $2k$  defined by:

$$J^{2k} := \overbrace{I \otimes I \otimes \dots \otimes I}^{k \text{ times}}.$$

259

260 With a small abuse of notation, we consider zeroth order tensors  $b^0$  to be constants  
261 (i.e.  $b^0 \in \mathbb{R}$  if  $b^0$  is scalar) and we still denote by  $b^0 \otimes c^k := b^0 c^k$  the tensor product  
262 with a  $k$ -th order tensor  $c^k$ . The same convention also applies to vector valued and  
263 matrix valued tensors.

In all what follows, a  $k$ -th order tensor  $b^k$  (scalar, vector or matrix valued) truly makes sense when contracted with  $k$  partial derivatives, as in (2.8)–(2.10). Therefore all the tensors considered throughout this work are identified to their symmetrization:

$$b_{i_1 \dots i_k}^k \equiv \frac{1}{k!} \sum_{\sigma \in \mathfrak{S}_k} b_{i_{\sigma(1)} \dots i_{\sigma(k)}},$$

264 where  $\mathfrak{S}_k$  is the permutation group of order  $k$ . Consequently, the order in which the  
265 (derivative) indices  $i_1, \dots, i_k$  are written in  $b_{i_1 \dots i_k}^k$  does not matter.

266 Finally, in the whole work, we write  $C$ ,  $C_K$  or  $C_K(\mathbf{f})$  to denote universal constants  
267 that do not depend on  $\varepsilon$  but whose values may change from lines to lines (and which  
268 may depend on  $\eta$  or on the obstacle  $T$ ).

269 *Remark 2.2.* In a limited number of places, the superscript or subscript indices  
270  $p, q \in \mathbb{N}$  are used. Naturally, these are not to be confused with the pressure variables  
271  $p_\varepsilon$  or  $q_\varepsilon$  introduced in (1.1).

272 **3. Infinite order homogenized equation and criminal ansatz.** We start  
 273 by identifying the two-scale structure of  $(\mathbf{u}_\varepsilon, p_\varepsilon)$  which arise in the form of the ansatz  
 274 (1.7). Because it helps emphasizing the arising of Cauchy products, we assume, *in*  
 275 *this section only*, that the right-hand side  $\mathbf{f}$  can be formally decomposed into a power  
 276 series in  $\varepsilon$ :

$$277 \quad (3.1) \quad \forall x \in D, \mathbf{f}(x) = \sum_{i=0}^{+\infty} \varepsilon^i \mathbf{f}^i(x).$$

278 **3.1. Identification of the “classical” ansatz: tensors  $(\mathcal{X}^k, \alpha^k)$ .** Inserting  
 279 (1.7) into the Stokes system (1.1) yields the following cascade of equations:

$$280 \quad (3.2) \quad \left\{ \begin{array}{l} -\Delta_{yy} \mathbf{u}_{i+2} + \nabla_y p_{i+2} = \mathbf{f}_{i+2} - \nabla_x p_{i+2}^* - \nabla_x p_{i+1} + \Delta_{xy} \mathbf{u}_{i+1} + \Delta_{xx} \mathbf{u}_i, \\ \operatorname{div}_y(\mathbf{u}_{i+2}) = -\operatorname{div}_x(\mathbf{u}_{i+1}), \\ \mathbf{u}_{-2} = \mathbf{u}_{-1} = 0, p_{-1} = 0, \\ \mathbf{u}_i(x, \cdot) = 0 \text{ on } \partial(\eta T) \\ \mathbf{u}_i(x, \cdot) \text{ is } P\text{-periodic for any } x \in D, \\ \mathbf{u}_i(\cdot, y) \text{ is } D\text{-periodic for any } y \in P, \end{array} \right.$$

for any  $i \geq -2$ , where the operators  $-\Delta_{yy}$ ,  $-\Delta_{xy}$ ,  $-\Delta_{yx}$  are defined by

$$-\Delta_{xx} = -\operatorname{div}_x(\nabla_x \cdot), \quad -\Delta_{xy} = -\operatorname{div}_x(\nabla_y \cdot) - \operatorname{div}_y(\nabla_x \cdot), \quad -\Delta_{yy} := -\operatorname{div}_y(\nabla_y \cdot).$$

281 In order to solve (3.2), we introduce a family of respectively vector valued tensors  
 282  $(\mathcal{X}_j^k(y))_{1 \leq j \leq d}$  and scalar valued tensors  $(\alpha_j^k(y))_{1 \leq j \leq d}$  defined by induction as the  
 283 unique solutions in  $H_{per}^1(Y, \mathbb{R}^d) \times L^2(Y)/\mathbb{R}$  to the following cell problems:

$$284 \quad (3.3) \quad \left\{ \begin{array}{l} -\Delta_{yy} \mathcal{X}_j^0 + \nabla_y \alpha_j^0 = \mathbf{e}_j \text{ in } Y, \\ \operatorname{div}_y(\mathcal{X}_j^0) = 0 \text{ in } Y \end{array} \right.$$

$$285 \quad (3.4) \quad \left\{ \begin{array}{l} -\Delta_{yy} \mathcal{X}_j^1 + \nabla_y \alpha_j^1 = (2\partial_l \mathcal{X}_j^0 - \alpha_j^0 \mathbf{e}_l) \otimes \mathbf{e}_l \text{ in } Y \\ \operatorname{div}_y(\mathcal{X}_j^1) = -(\mathcal{X}_j^0 - \langle \mathcal{X}_j^0 \rangle) \cdot \mathbf{e}_l \otimes \mathbf{e}_l \text{ in } Y, \end{array} \right.$$

$$286 \quad (3.5) \quad \left\{ \begin{array}{l} -\Delta_{yy} \mathcal{X}_j^{k+2} + \nabla_y \alpha_j^{k+2} = (2\partial_l \mathcal{X}_j^{k+1} - \alpha_j^{k+1} \mathbf{e}_l) \otimes \mathbf{e}_l + \mathcal{X}_j^k \otimes I \text{ in } Y \\ \operatorname{div}_y(\mathcal{X}_j^{k+2}) = -(\mathcal{X}_j^{k+1} - \langle \mathcal{X}_j^{k+1} \rangle) \cdot \mathbf{e}_l \otimes \mathbf{e}_l \text{ in } Y \end{array} \right. \quad \forall k \geq 0.$$

288 Equations (3.3)–(3.5) are supplemented with the following boundary conditions:

$$289 \quad (3.6) \quad \left\{ \begin{array}{l} \int_Y \alpha_j^k dy = 0 \\ \mathcal{X}_j^k = 0 \text{ on } \partial(\eta T) \\ (\mathcal{X}_j^k, \alpha_j^k) \text{ is } P\text{-periodic} \end{array} \right. \quad \forall k \geq 0.$$

290

*Remark 3.1.* In view of the notation conventions of section 2, the non bold symbols  $\otimes \mathbf{e}_l$  and  $\otimes I$  indicate the arising of extra partial derivatives indices. For instance, the first line of (3.5) must be understood as

$$-\Delta_{yy} \mathcal{X}_{j, i_1 \dots i_{k+2}}^{k+2} + \nabla_y \alpha_{j, i_1 \dots i_{k+2}}^{k+2} = 2\partial_{i_{k+2}} \mathcal{X}_{j, i_1 \dots i_{k+1}}^{k+1} - \alpha_{j, i_1 \dots i_{k+1}}^{k+1} \mathbf{e}_{i_{k+2}} + \mathcal{X}_{j, i_1 \dots i_k}^k \delta_{i_{k+1} i_{k+2}}.$$

We introduce the  $k$ -th order matrix valued tensors  $\mathcal{X}^k$  whose columns are the vector valued tensors  $(\mathcal{X}_j^k)$ :

$$(\mathcal{X}_{ij}^k(y))_{1 \leq i, j \leq d} := [\mathcal{X}_1^k(y) \quad \dots \quad \mathcal{X}_d^k(y)], \quad \forall y \in Y, \quad \forall k \geq 0.$$

We also denote by  $\alpha^k$  the  $k$ -th order vector valued tensor whose coordinates are the scalar tensors  $\alpha_j^k$ :

$$\alpha^k(y) := (\alpha_j^k(y))_{1 \leq j \leq d}, \quad \forall y \in Y, \quad \forall k \geq 0.$$

291 Following the conventions of [section 2](#), we use a star notation to denote the average  
292 of respectively the tensor  $\mathcal{X}^k$  and of the vector fields  $\mathbf{u}_i$ :

$$293 \quad (3.7) \quad \mathcal{X}^{k*} := \int_Y \mathcal{X}^k(y) dy, \quad \forall k \geq 0, \quad \mathbf{u}_i^*(x) := \int_Y \mathbf{u}_i(x, y) dy, \quad \forall x \in D, \quad \forall i \geq 0.$$

294 The tensors  $\mathcal{X}^k$  and  $\alpha^k$  enable to solve the cascade of equations [\(3.2\)](#):

295 **PROPOSITION 3.2.** *Assume [\(H1\)](#). The solutions  $\mathbf{u}_i(x, y)$ ,  $p_i(x, y)$  of the cascade*  
296 *of equations [\(3.2\)](#) are given by*

$$297 \quad (3.8) \quad \begin{aligned} \mathbf{u}_i(x, y) &= \sum_{k=0}^i \mathcal{X}^k(y) \cdot \nabla^k (\mathbf{f}_{i-k}(x) - \nabla p_{i-k}^*(x)) \\ p_i(x, y) &= \sum_{k=0}^i \alpha^k(y) \cdot \nabla^k (\mathbf{f}_{i-k}(x) - \nabla p_{i-k}^*(x)), \end{aligned}$$

298 where the functions  $p_i^*$  are uniquely determined recursively as the solutions to the  
299 following elliptic system: for any  $i \geq 0$ ,

$$300 \quad (3.9) \quad \left\{ \begin{array}{l} -\operatorname{div}_x(\mathcal{X}^{0*} \nabla_x p_i^*) = -\operatorname{div}_x(\mathcal{X}^{0*} \mathbf{f}_i) \\ \quad - \sum_{k=1}^i \operatorname{div}(\mathcal{X}^{k*} \cdot \nabla^k (\mathbf{f}_{i-k} - \nabla_x p_{i-k}^*)) \text{ in } D_\varepsilon, \\ \int_D p_i^* dx = 0 \\ p_i^* \text{ is } D\text{-periodic.} \end{array} \right.$$

301 Recognizing Cauchy products, the identities [\(3.8\)](#) and [\(3.9\)](#) rewrite formally in terms  
302 of equality of formal power series:

$$303 \quad (3.10) \quad \mathbf{u}_\varepsilon(x) = \sum_{i=0}^{+\infty} \varepsilon^{i+2} \mathcal{X}^i(x/\varepsilon) \cdot \nabla^i (\mathbf{f}(x) - \nabla p_\varepsilon^*(x)),$$

$$304 \quad (3.11) \quad p_\varepsilon(x) = p_\varepsilon^*(x) + \sum_{i=0}^{+\infty} \varepsilon^{i+1} \alpha^i(x/\varepsilon) \cdot \nabla^i (\mathbf{f}(x) - \nabla p_\varepsilon^*(x)),$$

$$305 \quad (3.12) \quad \operatorname{div}(\mathbf{u}_\varepsilon^*(x)) = 0 \text{ where } \mathbf{u}_\varepsilon^*(x) = \sum_{i=0}^{+\infty} \varepsilon^{i+2} \mathcal{X}^{i*} \cdot \nabla^i (\mathbf{f}(x) - \nabla p_\varepsilon^*(x)).$$

307 *Proof.* The result is proved by induction. The case  $i = -1$  is straightforward  
308 thanks to the convention  $\mathbf{u}_{-1} = p_{-1} = 0$ . In this proof we use the short-hand

309 notation  $\mathbf{h}_i(x) = \mathbf{f}_i(x) - \nabla p_i^*(x)$ . Assuming (3.8) and (3.9) hold till rank  $i + 1$  with  
 310  $i \geq -2$ , we compute, substituting (3.8) into (3.2):

$$311 \quad (3.13) \quad \begin{cases} (-\Delta_{yy}\mathbf{u}_{i+2} + \nabla_y p_{i+2})(x, y) \\ = h_{i+2,j}(x)\mathbf{e}_j + (2\partial_l \boldsymbol{\chi}_j^0(y) - \alpha_j^0(y)\mathbf{e}_l) \otimes \mathbf{e}_l \cdot \nabla h_{i+1,j}(x) \\ + \sum_{k=0}^i ((2\partial_l \boldsymbol{\chi}_j^{k+1}(y) - \alpha_j^{k+1}(y)\mathbf{e}_l) \otimes \mathbf{e}_l + \boldsymbol{\chi}_j^k(y) \otimes I) \cdot \nabla^{k+2} h_{i-k,j}(x) \\ \operatorname{div}_y(\mathbf{u}_{i+2})(x, y) = - \sum_{k=0}^{i+1} (\boldsymbol{\chi}_j^k(y) \cdot \mathbf{e}_l \otimes \mathbf{e}_l) \cdot \nabla^{k+1} h_{i+1-k,j}(x). \end{cases}$$

The system (3.13) admits a unique solution  $(\mathbf{u}_{i+2}, p_{i+2})$  with  $\int_Y p_{i+2}(x, y) dy = 0$  and only if the following compatibility condition (the so-called ‘‘Fredholm alternative’’) holds (for any  $i \geq -1$ ):

$$\int_Y \operatorname{div}_y(\mathbf{u}_{i+2})(x, y) dy = - \sum_{k=0}^{i+1} [(\boldsymbol{\chi}_j^k \cdot \mathbf{e}_l \otimes \mathbf{e}_l) \cdot \nabla^{k+1} h_{i+1-k,j}(x)] = 0.$$

The above equation determines  $p_{i+1}^*$  given the values of  $p_k^*$  for  $0 \leq k \leq i$ :

$$((\boldsymbol{\chi}_j^0 \cdot \mathbf{e}_l) \partial_l (f_{i+1,j} - \partial_j p_{i+1}^*)) = - \sum_{k=1}^{i+1} [(\boldsymbol{\chi}_j^k \cdot \mathbf{e}_l \otimes \mathbf{e}_l) \cdot \nabla^{k+1} (f_{i+1-k,j} - \partial_j p_{i+1-k}^*)],$$

312 which is (3.9) at order  $i + 1$ . This identity allows to rewrite  $\operatorname{div}_y(\mathbf{u}_{i+2})$  as

$$313 \quad (3.14) \quad \operatorname{div}_y(\mathbf{u}_{i+2})(x, y) = - \sum_{k=0}^{i+1} [(\boldsymbol{\chi}_j^k(y) - \langle \boldsymbol{\chi}_j^k \rangle) \cdot \mathbf{e}_l \otimes \mathbf{e}_l] \cdot \nabla^{k+1} h_{i+1-k,j}(x).$$

314 By linearity, (3.13) and (3.14) and the definitions of  $(\boldsymbol{\chi}_j^k, \alpha_j^k)$  through the cell problems  
 315 (3.3)–(3.5) imply the result at rank  $i + 2$ .  $\square$

316 *Remark 3.3.* The truncation of the series (3.12) at first order yields the well-  
 317 known Darcy’s law [52]. The next terms of the series have been obtained in [46, 26],  
 318 at least up to the order  $i = 1$ .

319 *Remark 3.4.* The ansatz (3.10) is already non-standard (when compared to (1.7))  
 320 because it features  $p_\varepsilon^*$  which is a formal power series in  $\varepsilon$  (recall (1.8)); in other words  
 321 it is not an ansatz but rather a compact way of writing the Cauchy products (3.8).

322 The next proposition establishes the symmetry and antisymmetry of the matrices  
 323  $\boldsymbol{\chi}^{k*}$  (eqn. (3.7)) for respectively odd and even values of  $k$ . We note that similar  
 324 identities have been found for the Poisson [34] or the wave equation [1].

325 **PROPOSITION 3.5.** *For any  $k \geq 0$  and  $0 \leq p \leq k$ ,  $1 \leq i, j \leq d$ , the following*  
 326 *identity holds for the matrix valued tensor  $\boldsymbol{\chi}^{k*}$ :*

$$327 \quad (3.15) \quad \boldsymbol{\chi}_{ij}^{k*} = (-1)^p \int_Y ((-\Delta_{yy}\boldsymbol{\chi}_i^p + \nabla\alpha_i^p) \cdot \boldsymbol{\chi}_j^{k-p} + \nabla\alpha_j^{k-p} \cdot \boldsymbol{\chi}_i^p - \boldsymbol{\chi}_j^{k-p-1} \cdot \boldsymbol{\chi}_i^{p-1} \otimes I) dy$$

328 with  $\boldsymbol{\chi}_i^{-1} = 0$  by convention. In particular, for any  $k \geq 0$ ,  $\boldsymbol{\chi}^{2k*}$  and  $\boldsymbol{\chi}^{2k+1*}$  take  
 329 values respectively in the set of  $d \times d$  symmetric and antisymmetric matrices:

$$330 \quad (3.16) \quad \boldsymbol{\chi}_{ij}^{2k*} = (-1)^k \int_Y (\nabla\boldsymbol{\chi}_i^k : \nabla\boldsymbol{\chi}_j^k + \nabla\alpha_i^k \cdot \boldsymbol{\chi}_j^k + \nabla\alpha_j^k \cdot \boldsymbol{\chi}_i^k - \boldsymbol{\chi}_i^{k-1} \cdot \boldsymbol{\chi}_j^{k-1} \otimes I) dy$$

331

$$\begin{aligned}
332 \quad (3.17) \quad \mathcal{X}_{ij}^{2k+1*} &= (-1)^k \int_Y (\mathbf{x}_i^k \cdot \nabla \mathbf{x}_j^k - \mathbf{x}_j^k \cdot \nabla \mathbf{x}_i^k + \alpha_i^k \mathbf{x}_j^k - \alpha_j^k \mathbf{x}_i^k) \cdot \mathbf{e}_l \otimes \mathbf{e}_l dy \\
&+ (-1)^k \int_Y (\mathbf{x}_j^{k-1} \cdot \mathbf{x}_j^k - \mathbf{x}_i^{k-1} \cdot \mathbf{x}_j^k) dy.
\end{aligned}$$

*Proof.* The result holds for  $p = 0$  because

$$\mathcal{X}_{ij}^{k*} = \int_Y \mathbf{x}_j^k \cdot \mathbf{e}_i dy = \int_Y \mathbf{x}_j^k \cdot (-\Delta_{yy} \mathbf{x}_i^0 + \nabla \alpha_i^0) dy.$$

333 Assuming now that (3.15) holds till rank  $p$  with  $k > p \geq 0$ , we prove the result at  
334 rank  $p + 1$ . We write, after an integration by parts and by using (3.3)–(3.5):

$$\begin{aligned}
335 \quad \mathcal{X}_{ij}^{k*} &= (-1)^p \int_Y [-\mathbf{x}_i^p \cdot \Delta \mathbf{x}_j^{k-p} - \alpha_i^p \operatorname{div}(\mathbf{x}_j^{k-p}) - \alpha_j^{k-p} \operatorname{div}(\mathbf{x}_i^p) \\
&- \mathbf{x}^{k-p-1} \cdot \mathbf{x}_i^{p-1} \otimes I] dy \\
336 &= (-1)^p \int_Y [(\mathbf{x}_i^p \cdot (2\partial_l \mathbf{x}_j^{k-p-1} - \alpha_j^{k-p-1} \mathbf{e}_l) \otimes \mathbf{e}_l + \mathbf{x}_j^{k-p-2} \otimes I - \nabla \alpha_j^{k-p}) \cdot \mathbf{x}_i^p \\
337 &+ \alpha_i^p \mathbf{x}_j^{k-p-1} \cdot \mathbf{e}_l \otimes \mathbf{e}_l + \alpha_j^{k-p} \mathbf{x}_i^{p-1} \cdot \mathbf{e}_l \otimes \mathbf{e}_l - \mathbf{x}_j^{k-p-1} \cdot \mathbf{x}_i^{p-1} \otimes I] dy \\
338 &= (-1)^p \int_Y [-\mathbf{x}_j^{k-p-1} \cdot ((2\partial_l \mathbf{x}_i^p - \alpha_i^p \mathbf{e}_l) \otimes \mathbf{e}_l + \mathbf{x}_i^{p-1} \otimes I) + \alpha_j^{k-p-1} \operatorname{div}(\mathbf{x}_i^{p+1}) \\
339 &- \nabla \alpha_j^{k-p} \cdot \mathbf{x}_i^p - \alpha_j^{k-p} \operatorname{div}(\mathbf{x}_i^p) + \mathbf{x}_j^{k-p-2} \cdot \mathbf{x}_i^p \otimes I] dy \\
340 &= (-1)^p \int_Y [-\mathbf{x}_j^{k-p-1} \cdot (-\Delta_{yy} \mathbf{x}_i^{p+1} + \nabla \alpha_i^{p+1}) \\
341 \quad 342 &- \nabla \alpha_j^{k-p-1} \cdot \mathbf{x}_i^{p+1} + \mathbf{x}_j^{k-p-2} \cdot \mathbf{x}_i^p \otimes I] dy,
\end{aligned}$$

343 whence (3.15) at rank  $p + 1$ . Finally, the expression (3.16) for  $\mathcal{X}_{ij}^{2k*}$  is obtained by  
344 setting  $k \leftarrow 2k$  and  $p \leftarrow k$  in (3.15). The expression for  $\mathcal{X}_{ij}^{2k+1*}$  is obtained by setting  
345  $k \leftarrow 2k + 1$  and  $p \leftarrow k$  and performing an integration by parts.  $\square$

346 **3.2. Derivation of the infinite order homogenized equation and of the**  
347 **criminal ansatz.** We now proceed on the derivation of the infinite order homogenized  
348 equation (1.9). Let us recall the classical positive definiteness of the Darcy tensor  $\mathcal{X}^{0*}$ .

349 **COROLLARY 3.6.** *Assume (H1). The matrix  $\mathcal{X}^{0*} = (\mathcal{X}_{ij}^{0*})_{1 \leq i, j \leq d}$  (defined in*  
350 *(3.7)) is positive symmetric definite.*

351 *Proof.* See [52] or Corollary 7.8 in [33].  $\square$

352 Hence, the following definition of the tensors  $(M^k)_{k \in \mathbb{N}}$  makes sense.

353 **PROPOSITION 3.7.** *Let  $M^k$  be the tensor of order  $k$  defined by induction as fol-*  
354 *lows:*

$$355 \quad (3.18) \quad \begin{cases} M^0 = (\mathcal{X}^{0*})^{-1} \\ M^k = -(\mathcal{X}^{0*})^{-1} \sum_{p=0}^{k-1} \mathcal{X}^{k-p*} \otimes M^p, \quad \forall k \geq 1. \end{cases}$$

356 Then the source terms  $\mathbf{f}_i$  (eqn. (3.1)) can be expressed in terms of the averaged  
357 summands  $\mathbf{u}_i^*(x)$  and  $p_i^*(x)$  ((1.8) and (3.7)) through the following identity:

$$358 \quad (3.19) \quad \forall i \geq 0, \mathbf{f}_i(x) - \nabla p_i^*(x) = \sum_{k=0}^i M^k \cdot \nabla^k \mathbf{u}_{i-k}^*(x).$$

359 Recognizing a Cauchy product, (3.19) and (3.12) rewrite formally as the “infinite  
360 order” homogenized system (1.9) for the formal average  $(\mathbf{u}_\varepsilon^*, p_\varepsilon^*)$  defined in (1.8).

361 *Proof.* The proof is identical to the one of Proposition 5 in [33], it amounts to  
362 average the first line of (3.8) with respect to  $y$  and to solve the resulting triangular  
363 system determining  $\mathbf{f}_{i-k} - \nabla p_{i-k}^*$  in terms of  $\mathbf{u}_i^*$ .  $\square$

364 The definition (3.18) essentially states that  $\sum_{k=0}^{+\infty} \varepsilon^{k-2} M^k \cdot \nabla^k$  is the inverse of the  
365 formal power series  $\sum_{k=0}^{+\infty} \varepsilon^{k+2} \mathcal{X}^{k*} \cdot \nabla^k$ . In this spirit, it is even possible to write a  
366 fully explicit formula (see [34], Proposition 6 and Remark 2 for the proof):

367 PROPOSITION 3.8. For any  $k \geq 1$ , the tensor  $M^k$  is explicitly given by

$$368 \quad (3.20) \quad M^k = \sum_{p=1}^k (-1)^p \sum_{\substack{i_1 + \dots + i_p = k \\ 1 \leq i_1, \dots, i_p \leq k}} (\mathcal{X}^{0*})^{-1} \otimes \mathcal{X}^{i_1*} \otimes \dots \otimes (\mathcal{X}^{0*})^{-1} \otimes \mathcal{X}^{i_p*} \otimes (\mathcal{X}^{0*})^{-1}.$$

369 We now introduce matrix valued tensors  $N^k$  and vector valued tensors  $\beta^k$  which allow  
370 to obtain the “criminal ansatz” (1.10) expressing the velocity and pressure  $(\mathbf{u}_\varepsilon, p_\varepsilon)$  in  
371 terms of their formal average  $(\mathbf{u}_\varepsilon^*, p_\varepsilon^*)$ .

PROPOSITION 3.9. Let  $N^k$  and  $\beta^k$  be respectively the  $k$ -th order matrix valued  
and vector valued tensors defined for any  $k \in \mathbb{N}$  by

$$N^k(y) := \sum_{p=0}^k \mathcal{X}^{k-p}(y) \otimes M^p, \quad \beta^k(y) := \sum_{p=0}^k (-1)^p M^p \cdot \alpha^{k-p}(y), \quad \forall y \in Y.$$

372 Then the summands  $\mathbf{u}_i(x, y)$  and  $p_i(x, y)$  of (3.10) and (3.11) are given for any  $i \geq 0$   
373 in terms of the averages  $\mathbf{u}_i^*$  (eqn. (3.7)) and  $p_i^*$  as follows:

$$374 \quad (3.21) \quad \mathbf{u}_i(x, y) = \sum_{k=0}^i N^k(y) \cdot \nabla^k \mathbf{u}_{i-k}^*(x), \quad p_i(x, y) = \sum_{k=0}^i \beta^k(y) \cdot \nabla^k \mathbf{u}_{i-k}^*(x).$$

375 Recognizing Cauchy products, the identities (3.21) can be rewritten formally as the  
376 “criminal ansatz” (1.10).

*Proof.* The result is obtained by substituting (3.19) into (3.8) which yields

$$\begin{aligned} \mathbf{u}_i(x, y) &= \sum_{p=0}^i \sum_{q=0}^{i-p} \mathcal{X}^p(y) \otimes M^q \cdot \nabla^{p+q} \mathbf{u}_{i-p-q}^*(x) \\ &= \sum_{k=0}^i \sum_{p=0}^k (\mathcal{X}^p(y) \otimes M^{p-k}) \cdot \nabla^k \mathbf{u}_{i-k}^*(x) \quad (\text{change of indices } k = p + q) \end{aligned}$$

from where the identity (3.21) for  $\mathbf{u}_i(x, y)$  follows by inverting the summation. Simi-  
larly, we obtain

$$p_i(x, y) = \sum_{k=0}^i \sum_{p=0}^k ((M^{p-k})^T \cdot \alpha^p(y)) \cdot \nabla^k \mathbf{u}_{i-k}^*(x),$$

377 hence (3.21) by using  $(M^{p-k})^T = (-1)^{p-k} M^{p-k}$  (see Corollary 3.11 below).  $\square$

In what follows, we denote by  $(\mathbf{N}_j^k)_{1 \leq j \leq d}$  and by  $(\beta_j^k)_{1 \leq j \leq d}$  respectively the column vectors and the coefficients of  $N^k(y)$  and  $\beta^k(y)$ :

$$\forall 1 \leq i, j \leq d, \mathbf{N}_j^k := N^k \mathbf{e}_j \text{ and } \beta_j^k := \beta^k \cdot \mathbf{e}_j.$$

378 In addition, the convention  $\mathbf{N}_j^{-1} = 0$  is assumed. We shall in the sequel use several  
379 times the following properties of  $(\mathbf{N}_j^k, \beta_j^k)$  which are dual to those of  $(\boldsymbol{\chi}_j^k, \alpha_j^k)$ .

380 PROPOSITION 3.10. *The  $k$ -th order tensors  $N^k$ ,  $(\mathbf{N}_j^k)_{1 \leq j \leq d}$ ,  $\beta^k$  and  $(\beta_j^k)_{1 \leq j \leq d}$*   
381 *satisfy:*

382 (i)  $\int_Y N^0(y) dy = I$  and  $\int_Y N^k(y) dy = 0$  for any  $k \geq 1$ ;

383 (ii)  $\int_Y \beta^k(y) dy = 0$  for any  $k \geq 0$ ;

384 (iii) For any  $k \geq -2$  and  $1 \leq j \leq d$ ,

$$385 \quad (3.22) \quad \begin{cases} -\Delta_{yy} \mathbf{N}_j^{k+2} + \nabla \beta_j^{k+2} = (2\partial_l \mathbf{N}_j^{k+1} - \beta_j^{k+1} \mathbf{e}_l) \otimes \mathbf{e}_l + \mathbf{N}_j^k \otimes I + M^{k+2} \mathbf{e}_j, \\ \operatorname{div}(\mathbf{N}_j^{k+2}) = -(\mathbf{N}_j^{k+1} - \langle \mathbf{N}_j^{k+1} \rangle) \cdot \mathbf{e}_l \otimes \mathbf{e}_l; \end{cases}$$

386 *Proof.* (i) and (ii) are straightforward consequences of (3.18).

387 (iii) is obtained by writing, for  $k \geq 0$  (implicit summation on the repeated index  
388  $j$  assumed):

$$\begin{aligned} -\Delta_{yy} \mathbf{N}_j^{k+2} + \nabla \beta_j^{k+2} &= -\Delta_{yy} \left( \sum_{p=0}^{k+2} \boldsymbol{\chi}_i^{k+2-p}(y) \otimes M_{ij}^p \right) + \nabla \left( \sum_{p=0}^{k+2} \alpha_i^{k+2-p}(y) \otimes M_{ij}^p \right) \\ &= \sum_{p=0}^k \left[ (2\partial_l \boldsymbol{\chi}_i^{k+1-p} - \alpha_i^{k+1-p} \mathbf{e}_l) \otimes \mathbf{e}_l + \boldsymbol{\chi}_i^{k-p} \otimes I \right] M_{ij}^p \\ &\quad + (2\partial_l \boldsymbol{\chi}_i^0 - \alpha_i^0 \mathbf{e}_l) M_{ij}^{k+1} + M_{ij}^{k+2} \mathbf{e}_i \\ &= (2\partial_l \mathbf{N}_j^{k+1} - \beta_j^{k+1} \mathbf{e}_l) \otimes \mathbf{e}_l + \mathbf{N}_j^k \otimes I + M^{k+2} \mathbf{e}_j. \\ \operatorname{div}(\mathbf{N}_j^{k+2}) &= \sum_{p=0}^{k+2} \operatorname{div}(\boldsymbol{\chi}_i^{k+2-p}) M_{ij}^p = -\sum_{p=0}^{k+1} M_{ij}^p (\boldsymbol{\chi}_i^{k+1-p} - \langle \boldsymbol{\chi}_i^{k+1-p} \rangle) \cdot \mathbf{e}_l \otimes \mathbf{e}_l. \end{aligned}$$

389 The proof is identical for  $k = -1$  and  $k = -2$ .  $\square$

390 The identity (3.22) allows to infer important properties characterizing the tensors  $M^k$   
391 which are similar to those of Proposition 3.5.

COROLLARY 3.11. *For any  $1 \leq p \leq k-1$ , it holds*

$$M_{ij}^k = (-1)^{p+1} \int_Y ((-\Delta_{yy} \mathbf{N}_i^p + \nabla \beta_i^p) \cdot \mathbf{N}_j^{k-p} + \nabla \beta_j^{k-p} \cdot \mathbf{N}_i^p - \mathbf{N}_i^{p-1} \cdot \mathbf{N}_j^{k-p-1} \otimes I) dy.$$

392 *Consequently, for any  $k \geq 0$ ,*

- $M^{2k}$  is a symmetric matrix valued tensor, and the following identities hold:

$$M_{ij}^0 = \int_Y \nabla \mathbf{N}_i^0 : \nabla \mathbf{N}_j^0 dy,$$

$$\forall k \geq 1, M_{ij}^{2k} = (-1)^{k+1} \int_Y (\nabla \mathbf{N}_i^k : \nabla \mathbf{N}_j^k + \nabla \beta_i^k \cdot \mathbf{N}_j^k + \nabla \beta_j^k \cdot \mathbf{N}_i^k - \mathbf{N}_i^{k-1} \cdot \mathbf{N}_j^{k-1} \otimes I) dy.$$

- $M^{2k+1}$  is an antisymmetric matrix valued tensor and it holds:

$$M_{ij}^{2k+1} = (-1)^{k+1} \int_Y (\mathbf{N}_i^k \cdot \nabla \mathbf{N}_j^k - \mathbf{N}_j^k \cdot \nabla \mathbf{N}_i^k + \beta_i^k \mathbf{N}_j^k - \beta_j^k \mathbf{N}_i^k) \cdot \mathbf{e}_l \otimes \mathbf{e}_l dy$$

$$+ (-1)^{k+1} \int_Y (\mathbf{N}_j^{k-1} \cdot \mathbf{N}_i^k - \mathbf{N}_i^{k-1} \cdot \mathbf{N}_j^k) \otimes Idy.$$

*Proof.* The proof is very similar to the one of [Proposition 3.5](#) and is omitted, see also [Proposition 7.34](#) in [\[33\]](#).  $\square$

*Remark 3.12.* The antisymmetry of odd order tensors  $M^{2k+1}$  ensures that the associated differential operators  $\varepsilon^{2k-1} M^{2k+1} \cdot \nabla^{2k+1}$  arising in the “infinite order” homogenized equation [\(1.9\)](#) are symmetric. Indeed, the antisymmetry of  $M^{2k+1}$  “compensates” the one induced by odd order derivatives which makes  $M^{2k+1} \cdot \nabla^{2k+1}$  be a symmetric operator: for two vector fields  $\mathbf{u} := (u_i)_{1 \leq i \leq d}$ ,  $\mathbf{v} = (v_i)_{1 \leq i \leq d}$ , it holds

$$\int_Y \mathbf{v} \cdot M^{2k+1} \cdot \nabla^{2k+1} \mathbf{u} dy = \int_Y (M_{ij}^{2k+1} \cdot \nabla^{2k+1} u_j) v_i dy = - \int_Y (M_{ij}^{2k+1} \cdot \nabla^{2k+1} v_i) u_j dy$$

$$= \int_Y (M_{ji}^{2k+1} \cdot \nabla^{2k+1} v_i) u_j dy = \int_Y \mathbf{u} \cdot M^{2k+1} \cdot \nabla^{2k+1} \mathbf{v} dy.$$

*Remark 3.13.* It is not completely straightforward to exhibit an instance of hole  $\partial T$  and  $k \in \mathbb{N}$  for which we can actually prove that  $M^{2k+1}$  is not zero. However simple numerical evidences tend to confirm this conjecture, see section 7.4.5 in [\[33\]](#) for an example featuring  $M^1 \neq 0$  in the case of the elasticity system .

### 3.3. Simplifications for the tensors $\mathcal{X}^{k*}$ and $M^k$ in case of symmetries.

In the final part of this section, we examine how the symmetries of the obstacle  $\eta T$  with respect to the cell axes reflect into the coefficients of the matrix valued tensors  $\mathcal{X}^{k*}$  and  $M^k$ . Our final result is stated in [Corollary 3.16](#), which implies that odd order tensors  $\mathcal{X}^{2k+1}$  and  $M^{2k+1}$  vanish in case  $\eta T$  is symmetric with respect to the cell axes. It is based on the following elementary lemma:

**LEMMA 3.14.** *Let  $S \in \mathbb{R}^{d \times d}$  an orthogonal symmetry, i.e.  $S = S^T$  and  $SS = I$ . The following identities hold for any smooth vector field  $\mathcal{X}$  and scalar field  $\alpha$ :*

$$(3.23) \quad -\Delta(S\mathcal{X} \circ S) + \nabla(\alpha \circ S) = S(-\Delta\mathcal{X} + \nabla\alpha) \circ S,$$

$$(3.24) \quad \operatorname{div}(S\mathcal{X} \circ S) = \operatorname{div}(\mathcal{X}) \circ S,$$

$$(3.25) \quad \partial_i(S\mathcal{X} \circ S) = S_{ij} S(\partial_j \mathcal{X}) \circ S.$$

*Proof.* The first two identities are obtained by writing

$$-\Delta(S\mathcal{X} \circ S) + \nabla(\alpha \circ S) = -S\partial_{ij}\mathcal{X} \circ SS_{il}S_{jl} + S(\nabla\alpha) \circ S$$

$$= -S(\Delta\mathcal{X} + \nabla\alpha) \circ S,$$

$$\operatorname{div}(S\mathcal{X} \circ S) = \operatorname{Tr}(\nabla(S\mathcal{X} \circ S)) = \operatorname{Tr}(S(\nabla\mathcal{X}) \circ SS) = \operatorname{Tr}((\nabla\mathcal{X}) \circ S) = \operatorname{div}(\mathcal{X}) \circ S.$$

Identity [\(3.25\)](#) is an elementary consequence of the chain rule.  $\square$

**PROPOSITION 3.15.** *If the cell  $Y = P \setminus (\eta T)$  is invariant with respect to a symmetry  $S$ , i.e.  $S(Y) = Y$ , then the following identity holds for the tensors  $(\mathcal{X}_l^k, \alpha_l^k)$  (defined in [\(3.3\)](#)–[\(3.5\)](#)):*

$$(3.26) \quad S\mathcal{X}_{i_1 \dots i_k, l}^k \circ S = S_{i_1 j_1} \dots S_{i_k j_k} S_{lm} \mathcal{X}_{j_1 \dots j_k, m}^k,$$



$$430 \quad (3.27) \quad \alpha_{i_1 \dots i_k, l}^k \circ S = S_{i_1 j_1} \dots S_{i_k j_k} S_{lm} \alpha_{j_1 \dots j_k, m}^k,$$

432 *with implicit summation over the repeated indices  $j_1, \dots, j_k$  and  $m$ . As a consequence,*  
 433 *the following identities hold for the constant matrix valued tensors  $\mathcal{X}^{k*}$  and  $M^k$ :*

$$434 \quad (3.28) \quad \mathcal{X}_{i_1 \dots i_k, lm}^{k*} = S_{i_1 j_1} \dots S_{i_k j_k} S_{lp} S_{mq} \mathcal{X}_{j_1 \dots j_k, pq}^{k*}$$

$$435 \quad (3.29) \quad M_{i_1 \dots i_k, lm}^k = S_{i_1 j_1} \dots S_{i_k j_k} S_{lp} S_{mq} M_{j_1 \dots j_k, pq}^k.$$

*Proof.* We prove (3.26) and (3.27) by induction. Applying Proposition 3.15 yields

$$\begin{cases} -\Delta_{yy}(S\mathcal{X}_l^0 \circ S) + \nabla_y(\alpha_l^0 \circ S) = S e_l \circ S = S e_l = S_{mj} e_m, \\ \operatorname{div}(S\mathcal{X}_l^0 \circ S) = 0. \end{cases}$$

Since the cell is symmetric with respect to  $S$ ,  $(S\mathcal{X}_l^0 \circ S, \alpha_l^0 \circ S)$  satisfies the same boundary conditions (3.6) than  $S_{mj}(\mathcal{X}_m^0, \alpha_m^0)$ . Therefore these vector fields are equal and we infer (3.26) and (3.27) at rank  $k = 0$ . We then write, for a given  $1 \leq i_1 \leq d$ :

$$\begin{cases} -\Delta_{yy}(S\mathcal{X}_{i_1, l}^1 \circ S) + \nabla_y(\alpha_{i_1, l}^1 \circ S) = S(2\partial_{i_1} \mathcal{X}_l^0 - \alpha_l^0 e_{i_1}) \circ S \\ \quad = S_{i_1 j_1} (2\partial_{j_1}(S\mathcal{X}_l^0 \circ S) - \alpha_l^0 \circ S e_{j_1}) = S_{i_1 j_1} S_{lm} (2\partial_{j_1} \mathcal{X}_m^0 - \alpha_m^0 e_{j_1}), \\ \operatorname{div}_y(S\mathcal{X}_{i_1, l}^1 \circ S) = -(\mathcal{X}_l^0 \circ S - \langle \mathcal{X}_l^0 \rangle) \cdot e_{i_1} \\ \quad = -S_{lm} S(\mathcal{X}_m^0 - \langle \mathcal{X}_m^0 \rangle) \cdot e_{i_1} = -S_{i_1 j_1} S_{lm} (\mathcal{X}_m^0 - \langle \mathcal{X}_m^0 \rangle) \cdot e_{j_1}, \end{cases}$$

where we have used  $\langle \mathcal{X}_l^0 \rangle = \langle \mathcal{X}_l^0 \circ S \rangle$ . This implies similarly (3.26) and (3.27) at rank  $k = 1$ . Assuming now the result holds till rank  $k + 1$  with  $k \geq 0$ , it holds:

$$\begin{cases} -\Delta_{yy}(S\mathcal{X}_{i_1 \dots i_{k+2}, l}^{k+2} \circ S) + \nabla_y(\alpha_{i_1 \dots i_{k+2}, l}^{k+2} \circ S) \\ \quad = S(2\partial_{i_{k+2}} \mathcal{X}_{i_1 \dots i_{k+1}, l}^{k+1} - \alpha_{i_1 \dots i_{k+1}, l}^{k+1} e_{i_{k+2}}) \circ S + S\mathcal{X}_{i_1 \dots i_k, l}^k \circ S \delta_{i_{k+1} i_{k+2}} \\ \quad = S_{i_{k+2} j_{k+2}} (2\partial_{j_{k+2}}(S\mathcal{X}_{i_1 \dots i_{k+1}, l}^{k+1} \circ S) - \alpha_{i_1 \dots i_{k+1}, l}^{k+1} \circ S e_{j_{k+2}}) \\ \quad \quad + S_{i_{k+1} j_{k+1}} S_{i_{k+2} j_{k+2}} \delta_{j_{k+1} j_{k+2}} S\mathcal{X}_{i_1 \dots i_k, l}^k \circ S \\ \quad = S_{i_1 j_1} \dots S_{i_{k+2} i_{k+2}} S_{lm} [(2\partial_{j_{k+2}} \mathcal{X}_{j_1 \dots j_{k+1}, m}^{k+1} - \alpha_{j_1 \dots j_{k+1}, m}^{k+1} e_{j_{k+2}}) \\ \quad \quad \quad + \delta_{j_{k+1} j_{k+2}} \mathcal{X}_{j_1 \dots j_k, m}^k] \\ \operatorname{div}_y(S\mathcal{X}_{i_1 \dots i_{k+2}}^{k+2} \circ S) = -(\mathcal{X}_{i_1 \dots i_{k+1}, l}^{k+1} \circ S - \langle \mathcal{X}_{i_1 \dots i_{k+1}, l}^{k+1} \rangle) \dots e_{i_{k+2}} \\ \quad = -S_{i_1 j_1} \dots S_{i_{k+1} j_{k+1}} S_{lm} S(\mathcal{X}_{j_1 \dots j_{k+1}, m}^{k+1} - \langle \mathcal{X}_{j_1 \dots j_{k+1}, m}^{k+1} \rangle) \cdot e_{i_{k+2}} \\ \quad = -S_{i_1 j_1} \dots S_{i_{k+2} j_{k+2}} S_{lm} (\mathcal{X}_{j_1 \dots j_{k+1}, m}^{k+1} - \langle \mathcal{X}_{j_1 \dots j_{k+1}, m}^{k+1} \rangle) \cdot e_{j_{k+2}}, \end{cases}$$

hence (3.26) and (3.27) at rank  $k + 2$ . A change of variable then yields:

$$\mathcal{X}_{i_1 \dots i_k, lm}^{k*} = \int_Y e_l \cdot \mathcal{X}_{i_1 \dots i_k, m}^k dy = \int_Y (S e_l) \cdot (S\mathcal{X}_{i_1 \dots i_k, m}^k \circ S) dy.$$

437 This implies (3.28), and then (3.29) by using (3.20). □

438 We apply the above result to two possible families of symmetries:

- for  $1 \leq l \leq d$ , the symmetry  $S^l$  with respect to the cell axis  $e_l$ :

$$S^l = 1 - 2e_l e_l^T;$$

- for  $1 \leq m, l \leq d$  with  $m \neq l$ , the symmetry  $S^{lm}$  with respect to the diagonal axis  $\mathbf{e}_l - \mathbf{e}_m$ :

$$S^{lm} = I - \mathbf{e}_l \mathbf{e}_l^T - \mathbf{e}_m \mathbf{e}_m^T + \mathbf{e}_l \mathbf{e}_m^T + \mathbf{e}_m \mathbf{e}_l^T.$$

COROLLARY 3.16. 1. If the cell  $Y$  is symmetric with respect to all cell axes  $(\mathbf{e}_l)_{1 \leq l \leq d}$ , i.e.  $S^l(Y) = Y$  for any  $1 \leq l \leq d$ , then

$$\mathcal{X}_{i_1 \dots i_k, pq}^{k*} = 0 \text{ and } M_{i_1 \dots i_k, pq}^k = 0$$

439 whenever any given integer  $1 \leq l \leq d$  occurs an odd number of times in the  
440 indices  $i_1 \dots i_k, p, q$ . In particular, this implies  $\mathcal{X}^{2k+1*} = 0$  and  $M^{2k+1} = 0$ .

2. If the cell  $Y$  is symmetric with respect to all diagonal axes  $\mathbf{e}_l - \mathbf{e}_m$ , i.e.  $S^{l,m}(Y) = Y$  for any  $1 \leq l < m \leq d$ , then for any permutation  $\sigma \in \mathfrak{S}_d$ ,

$$\mathcal{X}_{\sigma(i_1) \dots \sigma(i_k), \sigma(p)\sigma(q)}^{k*} = \mathcal{X}_{i_1 \dots i_k, pq}^{k*} \text{ and } M_{\sigma(i_1) \dots \sigma(i_k), \sigma(p)\sigma(q)}^k = M_{i_1 \dots i_k, pq}^k.$$

441 *Proof.* The result is obtained by applying (3.28) and (3.29) to the particular  
442 symmetries  $S^l$  and  $S^{lm}$ . See also Corollary 3 in [34].  $\square$

443 Let us illustrate how the previous properties translate for the tensors  $M^0$ ,  $M^2$  and  
444  $M^4$ :

- if the cell  $Y$  is symmetric with respect to all cell axes  $(\mathbf{e}_l)_{1 \leq l \leq d}$ , only the coefficients of the form  $M_{i,i}^0$  are non zero. For  $M^2$ , only

$$M_{ii,jj}^2, M_{ij,ij}^2, M_{ii,ii}^2$$

with  $i \neq j$  are non zero. For  $M^4$ , only the coefficients of the form

$$M_{ijj,kk}^4, M_{ijk,jk}^4, M_{iii,jj}^4, M_{ijj,ii}^4, M_{ijj,ij}^4, M_{iii,ii}^4$$

445 are non zero with distinct integers  $i, j, k$ .

- If in addition the obstacle is symmetric with respect to all diagonal axes, then the values of the above coefficients do not depend on the choice of the distinct integers  $i, j, k$ . As a result,  $M^0$  is proportional to the identity tensor,  $M^2$  reduces to at most three coefficients (the material is said to be orthotropic), and  $M^4$  reduces to at most 6 coefficients for  $d \geq 3$ , and to 4 coefficients for  $d = 2$ . For instance there are three constants  $\alpha, \beta, \gamma$  such that  $M^2 \cdot \nabla$  is the operator

$$M^2 \cdot \nabla \mathbf{v} = \alpha \Delta \mathbf{v} + \beta \nabla \operatorname{div}(\mathbf{v}) + \gamma \sum_{i=1}^d \partial_{ii} v_i \mathbf{e}_i.$$

446 **4. Homogenized equations of order  $2K + 2$ : tensors  $\mathbb{D}_K^k$ .** In this section,  
447 we derive the well-posed high order homogenized system (1.6) and we justify the  
448 homogenization process by means of quantitative error estimates.

449 The formal identities (1.10) lead us to introduce, for any order  $K \in \mathbb{N}$ , the  
450 truncated ansatz  $\mathbf{W}_{\varepsilon, K}(\mathbf{v})$  and  $Q_{\varepsilon, K}(\mathbf{v}, \phi)$  for the reconstructed velocity and pressure:

$$451 \quad (4.1) \quad \mathbf{W}_{\varepsilon, K}(\mathbf{v})(x, y) := \sum_{k=0}^K \varepsilon^k N^k(y) \cdot \nabla^k \mathbf{v}(x), \quad x \in D, y \in Y$$

$$452 \quad (4.2) \quad Q_{\varepsilon, K}(\mathbf{v}, \phi)(x, y) := \phi(x) + \sum_{k=0}^K \varepsilon^{k-1} \beta^k(y) \cdot \nabla^k \mathbf{v}(x), \quad x \in D, y \in Y$$

453

454 for any  $\mathbf{v} \in H^{K+1}(D, \mathbb{R}^d)$  and  $\phi \in L^2(D)$  which are sought to approximate the  
 455 homogenized averages  $\mathbf{u}_\varepsilon^*$  and  $p_\varepsilon^*$  respectively. Similarly we denote by  $\widetilde{\mathbf{W}}_{\varepsilon, K}(\mathbf{v})$  and  
 456  $\widetilde{Q}_{\varepsilon, K}(\mathbf{v}, \phi)$  the reconstructed *oscillating* functions defined for any  $x \in D_\varepsilon$  by

$$457 \quad (4.3) \quad \widetilde{\mathbf{W}}_{\varepsilon, K}(\mathbf{v})(x) := \mathbf{W}_{\varepsilon, K}(\mathbf{v})(x, x/\varepsilon), \quad \widetilde{Q}_{\varepsilon, K}(\mathbf{v}, \phi)(x) := Q_{\varepsilon, K}(\mathbf{v}, \phi)(x, x/\varepsilon).$$

458

Most of the results of this section are consequences of the following observation:

459

LEMMA 4.1. *For any  $K' \in \mathbb{N}$ ,  $(\mathbf{v}, \phi) \in H^1(D, \mathbb{R}^d) \times L^2(D)$ , the reconstructed  
 460 velocity and pressure  $(\widetilde{\mathbf{W}}_{\varepsilon, K'}(\mathbf{v}), \widetilde{Q}_{\varepsilon, K'}(\mathbf{v}, \phi))$  of (4.3) satisfy*

$$461 \quad (4.4) \quad \begin{aligned} & -\Delta \widetilde{\mathbf{W}}_{\varepsilon, K'}(\mathbf{v}) + \nabla \widetilde{Q}_{\varepsilon, K'}(\mathbf{v}, \phi) \\ & = \sum_{k=0}^{K'} \varepsilon^{k-2} M^k \nabla^k \mathbf{v} - \varepsilon^{K'-1} ((2\partial_l \mathbf{N}_j^{K'} - \beta_j^{K'} \mathbf{e}_l) \otimes \mathbf{e}_l) (\cdot/\varepsilon) \cdot \nabla^{K'+1} v_j \\ & \quad + (\mathbf{N}_j^{K'-1} \otimes I) (\cdot/\varepsilon) \cdot \nabla^{K'+1} v_j - \varepsilon^{K'} \mathbf{N}_j^{K'} (\cdot/\varepsilon) \otimes I \cdot \nabla^{K'+2} v_j, \end{aligned}$$

462

$$463 \quad (4.5) \quad \operatorname{div}(\widetilde{\mathbf{W}}_{\varepsilon, K'}(\mathbf{v})) = \operatorname{div}(\mathbf{v}) + \varepsilon^{K'} \mathbf{N}_j^{K'} (\cdot/\varepsilon) \cdot \mathbf{e}_l \otimes \mathbf{e}_l \cdot \nabla^{K'+1} v_j.$$

464

*Proof.* (4.4) and (4.5) are obtained by applying the Laplace and gradient opera-  
 465 tors on (4.1) and (4.2) and by using the identity (3.22).  $\square$

466

**4.1. Sufficient conditions leading to error estimates.** The purpose of this  
 467 part is to demonstrate that a sequence of functions  $(\mathbf{v}_\varepsilon^*, q_\varepsilon^*)_{\varepsilon>0}$  yields an approxima-  
 468 tion of  $(\mathbf{u}_\varepsilon, p_\varepsilon)$  at the order  $O(\varepsilon^{K'})$  provided it solves the infinite order homogenized  
 469 equation (1.9) up to a remainder of order  $O(\varepsilon^{K'+1})$ . The derivation of a *finite-order*  
 470 homogenized equation such as (1.6) reduces then to determine  $2K + 2 - K'$  tensors  
 471  $\mathbb{D}_K^k$  for  $K' + 1 \leq k \leq 2K + 2$  such that the equation

$$472 \quad (4.6) \quad \sum_{k=K'+1}^{2K+2} \varepsilon^{k-2} \mathbb{D}_K^k \cdot \nabla^k \mathbf{v}_\varepsilon^* + \sum_{k=0}^{K'} \varepsilon^{k-2} M^k \cdot \nabla^k \mathbf{v}_\varepsilon^* + \nabla q_\varepsilon^* = \mathbf{f}$$

473

is well-posed. The proof is based on the next three technical results.

LEMMA 4.2. *There exists a constant  $C$  independent of  $\varepsilon > 0$  such that for any  
 $\mathbf{v} \in H^1(D_\varepsilon, \mathbb{R}^d)$  with  $\mathbf{v} = 0$  on  $\partial\omega_\varepsilon$ , the following Poincaré inequality holds:*

$$\|\mathbf{v}\|_{L^2(D_\varepsilon, \mathbb{R}^d)} \leq C\varepsilon \|\nabla \mathbf{v}\|_{L^2(D, \mathbb{R}^{d \times d})}.$$

474

*Proof.* See e.g. [44] or the appendix of [49].  $\square$

475

The next lemma states the existence of a continuous right inverse for the divergence  
 476  $B_\varepsilon$ —so-called a Bogovskii's operator—with a bound explicit in  $\varepsilon$  on the uniform con-  
 477 tinuity constant.

478

LEMMA 4.3. *Assume (H1) and (H2). Then there exists a linear operator  $B_\varepsilon : L^2(D_\varepsilon) \rightarrow H^1(D_\varepsilon, \mathbb{R}^d)$  satisfying, for any  $\phi \in L^2(D_\varepsilon)$  with  $\int_{D_\varepsilon} \phi dx = 0$ :*

480

(i)  $\operatorname{div}(B_\varepsilon \phi) = \phi$  in  $D_\varepsilon$ ,

481

(ii)  $B_\varepsilon \phi = 0$  on  $\partial\omega_\varepsilon$  and  $B_\varepsilon \phi$  is  $D$ -periodic,

482

(iii)  $\|\nabla(B_\varepsilon \phi)\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})} \leq C\varepsilon^{-1} \|\phi\|_{L^2(D_\varepsilon)}$ , for a constant  $C > 0$  independent of  $\phi$   
 483 and  $\varepsilon$ .

484 *Proof.* See [32], Lemma 2.1, or [33], Lemma 7.9.  $\square$

485 **COROLLARY 4.4.** *Assume (H1) and (H2). For any  $\mathbf{h} \in L^2(D_\varepsilon, \mathbb{R}^d)$  and  $g \in$*   
 486  *$L^2(D_\varepsilon)$  satisfying  $\int_{D_\varepsilon} g dx = 0$ , let  $(\mathbf{v}, \phi) \in H^1(D_\varepsilon, \mathbb{R}^d) \times L^2(D_\varepsilon)$  be the unique solution*  
 487 *to the Stokes problem*

$$488 \quad (4.7) \quad \left\{ \begin{array}{l} -\Delta \mathbf{v} + \nabla \phi = \mathbf{h} \text{ in } D_\varepsilon \\ \operatorname{div}(\mathbf{v}) = g \text{ in } D_\varepsilon \\ \int_{D_\varepsilon} \phi dx = 0 \\ \mathbf{v} = 0 \text{ on } \partial\omega_\varepsilon \\ \mathbf{v} \text{ is } D\text{-periodic.} \end{array} \right.$$

489 *There exists a constant  $C$  independent of  $\varepsilon$ ,  $\mathbf{h}$  and  $g$  such that*

$$490 \quad (4.8) \quad \|\nabla \mathbf{v}\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})} + \varepsilon \|\phi\|_{L^2(D_\varepsilon)} \leq C(\varepsilon \|\mathbf{h}\|_{L^2(D_\varepsilon, \mathbb{R}^d)} + \varepsilon^{-1} \|g\|_{L^2(D_\varepsilon)}),$$

*Proof.* We use the operator  $B_\varepsilon$  of Lemma 4.3 to lift the divergence of  $\mathbf{v}$ . Let us define the vector field  $\mathbf{w} := \mathbf{v} - B_\varepsilon g \in H_{per}^1(D_\varepsilon, \mathbb{R}^d)$  which satisfies

$$\left\{ \begin{array}{l} \operatorname{div}(\mathbf{w}) = 0 \text{ in } D_\varepsilon, \\ \mathbf{w} = 0 \text{ on } \partial\omega_\varepsilon. \end{array} \right.$$

After an integration by part, we obtain:

$$\begin{aligned} \|\nabla \mathbf{w}\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})}^2 &= \int_{D_\varepsilon} \mathbf{h} \cdot \mathbf{w} dx - \int_{D_\varepsilon} \nabla(B_\varepsilon g) : \nabla \mathbf{w} dx \\ &\leq \|\mathbf{h}\|_{L^2(D_\varepsilon, \mathbb{R}^d)} \|\mathbf{w}\|_{L^2(D_\varepsilon, \mathbb{R}^d)} + \|\nabla(B_\varepsilon g)\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})} \|\nabla \mathbf{w}\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})} \\ &\leq C(\varepsilon \|\mathbf{h}\|_{L^2(D_\varepsilon, \mathbb{R}^d)} + \|\nabla(B_\varepsilon g)\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})}) \|\nabla \mathbf{w}\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})}, \end{aligned}$$

where the last inequality is a consequence of Lemma 4.2. Therefore, simplifying by  $\|\nabla \mathbf{w}\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})}$  and using the point (iii) of Lemma 4.3 yields

$$\begin{aligned} \|\nabla \mathbf{v}\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})} &\leq \|\nabla \mathbf{w}\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})} + \|\nabla(B_\varepsilon g)\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})} \\ &\leq C(\varepsilon \|\mathbf{h}\|_{L^2(D_\varepsilon, \mathbb{R}^d)} + \varepsilon^{-1} \|g\|_{L^2(D_\varepsilon)}), \end{aligned}$$

491 which proves the first part of the bound (4.8) on  $\nabla \mathbf{v}$ . The bound on the pressure is  
 492 then obtained by using  $B_\varepsilon \phi$  as a test function: we write

$$\begin{aligned} 493 \quad \|\phi\|_{L^2(D_\varepsilon)}^2 &= \int_{D_\varepsilon} \phi \operatorname{div}(B_\varepsilon \phi) dx = - \int_{D_\varepsilon} \nabla \phi \cdot B_\varepsilon \phi dx \\ 494 \quad &= \int_{D_\varepsilon} (-\Delta \mathbf{v} - \mathbf{h}) \cdot B_\varepsilon \phi dx = \int_{D_\varepsilon} (\nabla \mathbf{v} \cdot \nabla(B_\varepsilon \phi) - \mathbf{h} \cdot B_\varepsilon \phi) dx \\ 495 \quad &\leq \|\nabla \mathbf{v}\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})} \|\nabla(B_\varepsilon \phi)\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})} + \|\mathbf{h}\|_{L^2(D_\varepsilon, \mathbb{R}^d)} \|B_\varepsilon \phi\|_{L^2(D_\varepsilon, \mathbb{R}^d)} \\ 496 \quad &\leq C(\varepsilon \|\mathbf{h}\|_{L^2(D_\varepsilon, \mathbb{R}^d)} + \varepsilon^{-1} \|g\|_{L^2(D_\varepsilon)}) \|\nabla(B_\varepsilon \phi)\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})} \\ 497 \quad &\leq C\varepsilon^{-1} (\varepsilon \|\mathbf{h}\|_{L^2(D_\varepsilon, \mathbb{R}^d)} + \varepsilon^{-1} \|g\|_{L^2(D_\varepsilon)}) \|\phi\|_{L^2(D_\varepsilon)}, \end{aligned}$$

499 which concludes the proof.  $\square$

500 We are now in position to state the main result of this section.

501 **PROPOSITION 4.5.** *Let  $(\mathbf{v}_\varepsilon^*, q_\varepsilon^*)_{\varepsilon>0}$  be a sequence of functions of  $H^1(D_\varepsilon, \mathbb{R}^d) \times$*   
 502  *$L^2(D_\varepsilon)$ ,  $D$ -periodic, depending on  $\varepsilon$  (and possibly on  $K'$  and  $\mathbf{f}$ ) satisfying the follow-*  
 503 *ing conditions:*

504 1.  $(\mathbf{v}_\varepsilon, q_\varepsilon)$  solves the infinite order homogenized equation (1.9) up to an error of  
 505 order  $O(\varepsilon^{K'+1})$ :

$$506 \quad (4.9) \quad \left\| \sum_{k=0}^{K'} \varepsilon^{k-2} M^k \cdot \nabla^k \mathbf{v}_\varepsilon^* + \nabla q_\varepsilon^* - \mathbf{f} \right\|_{L^2(D, \mathbb{R}^d)} \leq C_{K'}(\mathbf{f}) \varepsilon^{K'+1}$$

507

$$508 \quad (4.10) \quad \operatorname{div}(\mathbf{v}_\varepsilon^*) = 0 \text{ in } D$$

509

$$510 \quad (4.11) \quad (\mathbf{v}_\varepsilon^*, p_\varepsilon^*) \text{ is } D\text{-periodic.}$$

511 2. For any  $m \in \mathbb{N}$ , there exists a constant  $C_m$  independent of  $\varepsilon$  such that

$$512 \quad (4.12) \quad \|\mathbf{v}_\varepsilon^*\|_{H^m(D, \mathbb{R}^d)} \leq C_m \varepsilon^2.$$

Then the reconstructed functions  $(\widetilde{\mathbf{W}}_{\varepsilon, K'}(\mathbf{v}_\varepsilon^*), \widetilde{Q}_{\varepsilon, K'-1}(q_\varepsilon^*, \mathbf{v}_\varepsilon^*))$  (eqn. (4.1) and (4.2)) yield approximations of  $(u_\varepsilon, p_\varepsilon)$  of order  $O(K' + 2)$  in the  $H^1(D_\varepsilon, \mathbb{R}^d)$  norm and  $O(\varepsilon^{K'+3})$  in the  $L^2(D_\varepsilon, \mathbb{R}^d)$  norm:

$$\left\| \nabla(\mathbf{u}_\varepsilon - \widetilde{\mathbf{W}}_{\varepsilon, K'}(\mathbf{v}_\varepsilon^*)) \right\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})} + \varepsilon \left\| p_\varepsilon - \widetilde{Q}_{\varepsilon, K'-1}(q_\varepsilon^*, \mathbf{v}_\varepsilon^*) \right\|_{L^2(D_\varepsilon, \mathbb{R}^d)} \leq C_{K'}(\mathbf{f}) \varepsilon^{K'+2},$$

$$\left\| \mathbf{u}_\varepsilon - \widetilde{\mathbf{W}}_{\varepsilon, K'}(\mathbf{v}_\varepsilon^*) \right\|_{L^2(D_\varepsilon, \mathbb{R}^d)} \leq C_{K'}(\mathbf{f}) \varepsilon^{K'+3}.$$

*Proof.* According to Lemma 4.1 and (4.10), it holds

$$-\Delta \widetilde{\mathbf{W}}_{\varepsilon, K'+1}(\mathbf{v}_\varepsilon^*) + \nabla \widetilde{Q}_{\varepsilon, K'+1}(q_\varepsilon^*, \mathbf{v}_\varepsilon^*) = \sum_{k=0}^{K'} \varepsilon^{k-2} M^k \cdot \nabla^k \mathbf{v}_\varepsilon^* + \nabla q_\varepsilon^* + O_{L^2(D_\varepsilon, \mathbb{R}^d)}(\varepsilon^{K'+1})$$

$$\operatorname{div}(\widetilde{\mathbf{W}}_{\varepsilon, K'+1}) = O_{L^2(D_\varepsilon)}(\varepsilon^{K'+3}),$$

where we have used (4.12) to estimate the right-hand side terms. Applying now Corollary 4.4 to  $(\mathbf{v}, \phi) \equiv (\mathbf{u}_\varepsilon - \widetilde{\mathbf{W}}_{\varepsilon, K'+1}(\mathbf{v}_\varepsilon^*), p_\varepsilon - \widetilde{Q}_{\varepsilon, K'+1}(q_\varepsilon^*, \mathbf{v}_\varepsilon^*))$  yields the error estimate

$$\left\| \nabla(\mathbf{u}_\varepsilon - \widetilde{\mathbf{W}}_{\varepsilon, K'+1}(\mathbf{v}_\varepsilon^*)) \right\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})} + \varepsilon \left\| p_\varepsilon - \widetilde{Q}_{\varepsilon, K'+1}(q_\varepsilon^*, \mathbf{v}_\varepsilon^*) \right\|_{L^2(D_\varepsilon)} \leq C_{K'}(\mathbf{f}) \varepsilon^{K'+2}.$$

Finally, remarking that the highest order terms are already of order  $O(\varepsilon^{K'+2})$ , i.e.

$$\left\| \nabla(\widetilde{\mathbf{W}}_{\varepsilon, K'+1}(\mathbf{v}_\varepsilon^*) - \widetilde{\mathbf{W}}_{\varepsilon, K'}(\mathbf{v}_\varepsilon^*)) \right\|_{L^2(D_\varepsilon, \mathbb{R}^d)} \leq C_{K'} \varepsilon^{K'+2},$$

$$\varepsilon \left\| \widetilde{Q}_{\varepsilon, K'+1}(q_\varepsilon^*, \mathbf{v}_\varepsilon^*) - \widetilde{Q}_{\varepsilon, K'-1}(q_\varepsilon^*, \mathbf{v}_\varepsilon^*) \right\|_{L^2(D_\varepsilon)} \leq C_{K'} \varepsilon^{K'+2},$$

513 we obtain the result by using the triangle's inequality.  $\square$

514 *Remark 4.6.* We need only  $K - 1$  derivatives in the truncated criminal ansatz  
 515  $Q_{\varepsilon, K-1}(\mathbf{v}_\varepsilon^*, q_\varepsilon^*)$  for the pressure (eqn. (4.2)), because the term of highest order has a  
 516 norm of order  $\varepsilon^K$  while  $\mathbf{v}_\varepsilon^*$  is of order  $\varepsilon^2$  by the assumption (4.12).

517 *Remark 4.7.* As a result of the scaling  $\varepsilon^{-1}$  in Corollary 4.4, we pay a factor  $\varepsilon^{-1}$   
 518 in the error induced by the non zero divergence constraint. However we are able to  
 519 obtain the right order of  $\varepsilon$  in the error estimates of Proposition 4.5 thanks to the use  
 520 of higher order terms of the ansatz (3.21) which are removed at the end of the proof.  
 521 This strategy is quite classical in the truncation analysis of two-scale expansions, see  
 522 e.g. [26, 11].

523 **4.2. Construction of a well-posed higher order effective models by a**  
 524 **minimization principle.** We now derive the well-posed homogenized equation (1.6)  
 525 of (finite) order  $2K+2$  by following the variational method introduced by Smyshlyaev  
 526 and Cherednychenko in [53] and used in the further works [28, 27, 34]. In the present  
 527 context, of the Stokes system (1.1), we shall see that (1.6) can be obtained as (4.6)  
 528 with  $K' = K$ , which yields error estimates of order  $O(\varepsilon^{K+3})$  in the  $L^2(D_\varepsilon)$  norm.

529 Recall that the velocity  $\mathbf{u}_\varepsilon$  solution to the Stokes system (1.1) is the unique  
 530 minimizer of the constrained minimization problem

$$531 \quad (4.13) \quad \mathbf{u}_\varepsilon = \arg \min_{\mathbf{w} \in H^1(D_\varepsilon, \mathbb{R}^d)} J(\mathbf{w}, \mathbf{f}) := \int_D \left( \frac{1}{2} \nabla \mathbf{w} : \nabla \mathbf{w} - \mathbf{f} \cdot \mathbf{w} \right) dy$$

$$\text{s.t.} \quad \begin{cases} \operatorname{div}(\mathbf{w}) = 0 \text{ in } D_\varepsilon \\ \mathbf{w} = 0 \text{ on } \partial\omega_\varepsilon \\ \mathbf{w} \text{ is } D\text{-periodic.} \end{cases}$$

532 In the context of the homogenization of linearized elasticity, the main idea of the  
 533 method of [53] is to restrict (4.13) to functions of the form  $\mathbf{w} = \widetilde{\mathbf{W}}_{\varepsilon, K}(\mathbf{v})$  given by  
 534 (4.1), where  $\mathbf{v} \in H^{K+1}(D, \mathbb{R}^d)$  is an unknown function sought to approximate  $\mathbf{u}_\varepsilon^*$ . In  
 535 the present setting, we consider the following approximation of (4.13):

$$536 \quad (4.14) \quad \min_{\mathbf{v} \in H^{K+1}(D, \mathbb{R}^d)} J(\widetilde{\mathbf{W}}_{\varepsilon, K}(\mathbf{v}), \mathbf{f})$$

$$\text{s.t.} \quad \begin{cases} \operatorname{div}(\mathbf{v}) = 0 \text{ in } D, \\ \mathbf{v} \text{ is } D\text{-periodic.} \end{cases}$$

537 Note that (4.14) is not exactly the restriction of (4.13) to such functions  $\widetilde{\mathbf{W}}_{\varepsilon, K}(\mathbf{v})$   
 538 because  $\operatorname{div}(\widetilde{\mathbf{W}}_{\varepsilon, K}(\mathbf{v})) \neq 0$  (it is of order  $\varepsilon^K$ , see (4.5)). The next step of the process is  
 539 to eliminate the oscillating variable  $x/\varepsilon$  in  $J(\widetilde{\mathbf{W}}_{\varepsilon, K}(\mathbf{v}), \mathbf{f})$  so as to obtain an effective  
 540 energy  $J_K^*(\mathbf{v}, \mathbf{f}, \varepsilon) \simeq J(\widetilde{\mathbf{W}}_{\varepsilon, K}(\mathbf{v}), \mathbf{f})$  which does not involve oscillating functions. Such  
 541 is achieved thanks to the classical lemma of two-scale convergence [9].

LEMMA 4.8. *Let  $\phi$  be a  $P = (0, 1)^d$ -periodic function and  $f \in C_{per}^\infty(D)$  be a smooth  $D$ -periodic function. Then for any  $p \in \mathbb{N}$ , there exists a constant  $C_p(f, \phi)$  independent of  $\varepsilon$  such that:*

$$\left| \int_D f(x) \phi(x/\varepsilon) dx - \int_D \int_P f(x) \phi(y) dy dx \right| \leq C_p(f, \phi) \varepsilon^p.$$

542 *Proof.* See Appendix C. of [53] or Lemma 7.3 in [33].  $\square$

Applying Lemma 4.8 to (4.14) in order to pass to the limit in the terms of  $J(\widetilde{\mathbf{W}}_{\varepsilon, K}(\mathbf{v}), \mathbf{f})$  which depends on the oscillating variable  $x/\varepsilon$ , we obtain the existence of a functional  $J_K^*$  such that for any  $\mathbf{v} \in C_{per}^\infty(D, \mathbb{R}^d)$ , it holds

$$J(\widetilde{\mathbf{W}}_{\varepsilon, K}(\mathbf{v}), \mathbf{f}) = J_K^*(\mathbf{v}, \mathbf{f}, \varepsilon) + o(\varepsilon^p)$$

543 with  $p \in \mathbb{N}$  arbitrarily large. The functional  $J_K^*$  is given explicitly by

$$544 \quad (4.15) \quad J_K^*(\mathbf{v}, \mathbf{f}, \varepsilon) := \int_D \int_P \frac{1}{2} \left\| (\nabla_x + \varepsilon^{-1} \nabla_y) \left( \mathbf{W}_{\varepsilon, K}(\mathbf{v})(x, y) \right) \right\|^2 dy dx - \int_D \mathbf{f} \cdot \mathbf{v} dx,$$

545 where we have used the point 1 of Proposition 3.10 to simplify the linear part of  
 546 the energy. Replacing  $J(\widetilde{\mathbf{W}}_{\varepsilon, K}(\mathbf{v}), \mathbf{f})$  by  $J_K^*(\mathbf{v}, \mathbf{f}, \varepsilon)$  in (4.14) allows to obtain the  
 547 homogenized equation (1.6) of order  $2K+2$ :

548 DEFINITION 4.9. For any  $K \in \mathbb{N}$ , we call homogenized equation of order  $2K + 2$   
 549 associated with the Stokes system (1.1) the Euler-Lagrange equation of the minimiza-  
 550 tion problem

$$551 \quad (4.16) \quad \begin{array}{l} \min \\ \text{s.t.} \end{array} \begin{cases} J_K^*(\mathbf{v}, \mathbf{f}, \varepsilon) \\ \mathbf{v} \in H^{K+1}(D, \mathbb{R}^d), \\ \operatorname{div}(\mathbf{v}) = 0 \text{ in } D, \\ \mathbf{v} \text{ is } D\text{-periodic.} \end{cases}$$

552 This Euler-Lagrange equation can be written as (1.6) where the constant (matrix val-  
 553 ued) tensors  $\mathbb{D}_K^k$  are inferred from (4.15) and where  $(\mathbf{v}_{\varepsilon, K}^*, q_{\varepsilon, K}^*) \in H^{K+1}(D, \mathbb{R}^d) \times$   
 554  $L^2(D)$  defines the higher order homogenized solution.

555 The next two propositions verify that (1.6) is indeed a “good” candidate effective  
 556 model, by relating the coefficients  $\mathbb{D}_K^k$  to the tensors  $M^k$  (in view of (4.6)), and by  
 557 establishing the well-posedness of (1.6).

558 PROPOSITION 4.10. The coefficients of the matrix valued tensor  $\mathbb{D}_K^k$  are explicitly  
 559 given for any  $1 \leq i, j \leq d$  by:

$$560 \quad (4.17) \quad \mathbb{D}_{K, ij}^k = \begin{cases} M^k & \text{if } 0 \leq k \leq K \\ M^k + \mathbb{A}_K^k & \text{if } K + 1 \leq k \leq 2K + 1 \\ (-1)^{K+1} \int_Y \mathbf{N}_i^K \cdot \mathbf{N}_j^K \otimes \operatorname{Id}_y & \text{if } k = 2K + 2. \end{cases}$$

561 where the matrix valued tensor  $\mathbb{A}_K^k$  is given for any  $K + 1 \leq k \leq 2K + 1$  by

$$562 \quad (4.18) \quad \mathbb{A}_{K, ij}^k := (-1)^{K+1} \int_Y (\nabla \beta_j^{k-K-1} \cdot \mathbf{N}_i^{K+1} + (-1)^k \nabla \beta_i^{k-K-1} \cdot \mathbf{N}_j^{K+1}) \operatorname{d}y.$$

563 *Proof.* Let us denote by  $V_K$  the space

$$564 \quad (4.19) \quad V_K := \{\mathbf{v} \in H^{K+1}(D, \mathbb{R}^d) \mid \operatorname{div}(\mathbf{v}) = 0 \text{ and } \mathbf{v} \text{ is } D\text{-periodic}\}.$$

565 We identify the coefficients  $\mathbb{D}_K^k$  by computing the Euler-Lagrange equation associated  
 566 with (4.15). For any  $(\mathbf{v}, \mathbf{w}) \in V_K$ , it holds, in a distributional sense:

$$\begin{aligned} 567 & \int_D \int_P (\nabla_x + \varepsilon^{-1} \nabla_y) \mathbf{W}_{\varepsilon, K}(\mathbf{v}) : (\nabla_x + \varepsilon^{-1} \nabla_y) \mathbf{W}_{\varepsilon, K}(\mathbf{w}) \operatorname{d}x \operatorname{d}y \\ 568 & = \int_D \int_P [(-\Delta_{xx} - \varepsilon^{-1} \Delta_{xy} - \varepsilon^{-2} \Delta_{yy}) \mathbf{W}_{\varepsilon, K}(\mathbf{v}) \\ 569 & \quad + (\nabla_x + \varepsilon^{-1} \nabla_y) Q_{\varepsilon, K}(\mathbf{v}, 0)] \cdot \mathbf{W}_{\varepsilon, K}(\mathbf{w}) \operatorname{d}x \operatorname{d}y \\ 570 & \quad + \int_D \int_Y Q_{\varepsilon, K}(\mathbf{v}, 0) [(\operatorname{div}_x + \varepsilon^{-1} \operatorname{div}_y) \mathbf{W}_{\varepsilon, K}(\mathbf{w})] \operatorname{d}x \operatorname{d}y. \\ 571 \end{aligned}$$

572 By using (4.1) and the point (i) of Proposition 3.10, the above quantity is equal to

$$\begin{aligned} 573 & \int_D \int_Y \left[ \sum_{k=0}^K \varepsilon^{k-2} M^k \nabla^k \mathbf{v}(x) \right] \cdot \sum_{k=0}^K \varepsilon^k N^k(y) \cdot \nabla^k \mathbf{w}(x) \operatorname{d}x \operatorname{d}y \\ 574 & - \int_D \int_Y \varepsilon^{K-1} [(2\partial_l N_j^K(y) - \beta_j^K(y) e_l) \otimes e_l] \cdot \nabla^{K+1} v_j(x) \cdot \mathbf{W}_{\varepsilon, K}(\mathbf{w}) \operatorname{d}x \operatorname{d}y \end{aligned}$$

$$\begin{aligned}
575 & - \int_D \int_Y [\varepsilon^{K-1} (\mathbf{N}_j^{K-1}(y) \otimes I) \cdot \nabla^{K+1} \mathbf{v}(x)] \cdot \mathbf{W}_{\varepsilon,K}(\mathbf{w}) dx dy \\
576 & - \int_D \int_Y [\varepsilon^K (\mathbf{N}_j^K(y) \otimes I) \cdot \nabla^{K+2} \mathbf{v}(x)] \cdot \mathbf{W}_{\varepsilon,K}(\mathbf{w}) dx dy \\
577 & + \int_D \int_Y \sum_{k=0}^K \varepsilon^{k+K-1} (\beta_j^k(y) \cdot \nabla^k v_j(x)) (\mathbf{N}_i^K(y) \cdot \mathbf{e}_l \otimes \mathbf{e}_l \cdot \nabla^{K+1} w_i(x)) dy dx \\
578 & = \int_D \left( \sum_{k=0}^K \varepsilon^{k-2} M^k \cdot \nabla^k \mathbf{v} + \sum_{k=K+1}^{2K+2} \varepsilon^{k-2} \mathbb{D}_K^k \cdot \nabla^k \mathbf{v} \right) \cdot \mathbf{w} dx \\
579 &
\end{aligned}$$

where we identify (by integration by parts)  $\mathbb{D}_{K,ij}^{2K+2} := -(-1)^K \int_Y \mathbf{N}_i^K \cdot \mathbf{N}_j^K \otimes Idy$  as claimed. The coefficients of the tensor  $\mathbb{D}_K^k$  are given for  $K+1 \leq k \leq 2K+1$  by

$$\begin{aligned}
\mathbb{D}_{K,ij}^k &= -(-1)^{k-K-1} \int_Y ((2\partial_l \mathbf{N}_j^K - \beta_j^K \mathbf{e}_l) \otimes \mathbf{e}_l + \mathbf{N}_j^{K-1} \otimes I) \cdot \mathbf{N}_i^{k-K-1} dy \\
& - (-1)^{k-K-2} \int_Y \mathbf{N}_j^K \cdot \mathbf{N}_i^{k-K-2} \otimes Idy + (-1)^{K+1} \int_Y \beta_j^{k-K-1} \mathbf{N}_i^K \cdot \mathbf{e}_l \otimes \mathbf{e}_l dy \\
&= -(-1)^{K+1} \int_Y (-1)^k (-\Delta_{yy} \mathbf{N}_j^{K+1} + \nabla \beta_j^{K+1} - M^{K+1} \mathbf{e}_j) \cdot \mathbf{N}_i^{k-K-1} dy \\
& + (-1)^{K+1} \int_Y [(-1)^k \mathbf{N}_j^K \cdot \mathbf{N}_i^{k-K-2} \otimes I + \beta_j^{k-K-1} \mathbf{N}_i^K \cdot \mathbf{e}_l \otimes \mathbf{e}_l] dy,
\end{aligned}$$

580 where we have used extensively [Proposition 3.10](#). We now distinguish two cases:

1. if  $k = K+1$ , then the above expression reads

$$\begin{aligned}
\mathbb{D}_{K,ij}^{K+1} &= (M^{K+1} \mathbf{e}_j) \cdot \mathbf{e}_i - \int_Y \mathbf{N}_j^{K+1} \cdot (-\Delta_{yy} \mathbf{N}_i^0 + \nabla \beta_i^0) dy + \int_Y \nabla \beta_i^0 \cdot \mathbf{N}_j^{K+1} \\
& + (-1)^{K+1} \int_Y \nabla \beta_j^{k-K-1} \cdot \mathbf{N}_i^{K+1} dy = M_{ij}^{K+1} + \mathbb{A}_{ij}^{K+1},
\end{aligned}$$

581 whence the result for  $k = K+1$ ;

2. if  $K+2 \leq k \leq 2K+1$ , then we read instead

$$\begin{aligned}
\mathbb{D}_{K,ij}^k &= (-1)^{k+K} \int_Y ((-\Delta_{yy} \mathbf{N}_j^{K+1} + \nabla \beta_j^{K+1}) \cdot \mathbf{N}_i^{k-K-1} + \nabla \beta_i^{k-K-1} \cdot \mathbf{N}_j^{K+1}) dy \\
& - (-1)^{k+K} \int_Y \mathbf{N}_j^K \cdot \mathbf{N}_i^{k-K-2} \otimes Idy + \mathbb{A}_{ij}^k.
\end{aligned}$$

582 Applying finally [Corollary 3.11](#) with  $p = K+1$ , we obtain that the first two term of  
583 the above equation are equal to  $(-1)^k M_{ji}^k = M_{ij}^k$ , which yields the final result.  $\square$

584 *Remark 4.11.* In view of the proof of [Proposition 4.10](#), it is possible to show that  
585 [\(1.11\)](#) (with the same definition for the leading coefficient  $\mathbb{D}_K^{2K+2}$ ) is the strong form  
586 of the following “mixed” variational formulation: find  $(\widehat{\mathbf{v}}_{\varepsilon,K}^*, \widehat{q}_{\varepsilon,K}^*) \in V_K \times L^2(D)$  such  
587 that for any  $(\mathbf{w}, \phi) \in V_K \times L^2(D)$ ,

$$\begin{aligned}
588 & \\
589 & (4.20) \quad \int_D \int_Y [(\varepsilon^{-1} \nabla_y + \nabla_x) \mathbf{W}_{\varepsilon,K}(\widehat{\mathbf{v}}_{\varepsilon,K}^*)] : [(\varepsilon^{-1} \nabla_y + \nabla_x) \mathbf{W}_{\varepsilon,K}(\mathbf{w})] dy dx \\
590 & \quad - \int_D \int_Y Q_{\varepsilon,K}(\widehat{\mathbf{v}}_{\varepsilon,K}^*, \widehat{q}_{\varepsilon,K}^*) [(\varepsilon^{-1} \operatorname{div}_y + \operatorname{div}_x) \mathbf{W}_{\varepsilon,K}(\mathbf{w})] dy dx
\end{aligned}$$



$$- \int_D \int_Y Q_{\varepsilon,K}(\mathbf{w}, \phi) [(\varepsilon^{-1} \operatorname{div}_y + \operatorname{div}_x) \mathbf{W}_{\varepsilon,K}(\widehat{\mathbf{v}}_{\varepsilon,K}^*)] dy dx = \int_D \mathbf{f} \cdot \mathbf{w} dx.$$

This result is quite surprising. Indeed, (4.20) is built from the truncated ansatz  $(\mathbf{W}_{\varepsilon,K}(\widehat{\mathbf{v}}_{\varepsilon,K}^*), Q_{\varepsilon,K}(\widehat{\mathbf{v}}_{\varepsilon,K}^*, \widehat{q}_{\varepsilon,K}^*))$  which is expected to yield approximations of  $(\mathbf{u}_\varepsilon, p_\varepsilon)$  at order  $O(\varepsilon^{K+3})$  only (eqn. (4.1) and (4.2)). However, the strong form (1.11) turns out to exhibit  $2K+1$  “correct” coefficients  $M^k$ . As a result, if (1.11) is well-posed, the reconstructed oscillating functions  $\widetilde{\mathbf{W}}_{\varepsilon,2K+1}(\widehat{\mathbf{v}}_{\varepsilon,K}^*)$  and  $\widetilde{Q}_{\varepsilon,2K}(\widehat{\mathbf{v}}_{\varepsilon,K}^*, \widehat{q}_{\varepsilon,K}^*)$  approximate  $\mathbf{u}_\varepsilon$  and  $p_\varepsilon$  with an error rate as good as  $O(\varepsilon^{2K+4})$  in the  $L^2(D_\varepsilon)$  norm (Proposition 4.5). This improvement (which had not been noticed in the original paper [53]) actually holds in the context of the Poisson or elasticity equations for which there is no difference between (1.6) and (1.11) (see [34, 33]). Unfortunately in the case of the Stokes system, we do not know whether the mixed formulation (4.20) with the “velocity-dependent” pressure  $Q_{\varepsilon,K}(\mathbf{w}, \phi)$  yields a well-posed problem, hence our commitment to consider (1.6) instead of (1.11).

The leading tensor  $\mathbb{D}_K^{2K+2}$  is nonnegative according to (4.17). Under a rather unrestrictive additional non-degeneracy assumption, we obtain that the minimization principle (4.16) makes (1.6) be a well posed problem.

PROPOSITION 4.12. *Assume the dominant tensor  $\mathbb{D}_K^{2K+2} = (-1)^{K+1} \mathbb{B}_K^{K+1, K+1}$  is non-degenerate, that is there exists a constant  $\nu > 0$  such that for any constant vector tensor  $\boldsymbol{\xi}^{K+1} = \xi_{i_1 \dots i_{K+1}, p}^{K+1} \in \mathbb{R}^{d^{K+1}} \times \mathbb{R}^d$  of order  $K+1$ , it holds*

$$(4.21) \quad \int_Y [(N^K \otimes e_l) \cdot \boldsymbol{\xi}^{K+1}] \cdot [(N^K \otimes e_l) \cdot \boldsymbol{\xi}^{K+1}] dy \geq \nu \xi_{i_1 \dots i_{K+1}}^{K+1} \cdot \xi_{i_1 \dots i_{K+1}}^{K+1}.$$

Then there exists a unique velocity and pressure couple  $(\mathbf{v}_{\varepsilon,K}^*, q_{\varepsilon,K}^*) \in H^{K+1}(D, \mathbb{R}^d) \times L^2(D)/\mathbb{R}$  solving the higher order homogenized equation (1.6).

*Proof.* The proof relies on the positivity of the quadratic part of the energy  $J_K^*(\mathbf{v}, \mathbf{f}, \varepsilon)$ . By adapting the arguments of the proof of Proposition 12 in [34], we obtain indeed that the bilinear form associated with the energy (4.15) is coercive on the space  $V_K$  defined in (4.19). This is enough to apply standard theory for saddle point problems involving the zero divergence constraint (see e.g. the textbooks [55, 54, 38, 31]) which ensures the existence and uniqueness of a solution for (1.6).  $\square$

Remark 4.13. The assumption (4.21) could fail for  $K \geq 1$  in case the obstacle  $\eta T$  is invariant along some of the directions  $\mathbf{e}_i$  of the cell  $P$ , however it is not restrictive. Indeed, since the leading order tensor  $\mathbb{D}_K^{2K+2}$  has no influence on the error estimates of Proposition 4.5, it is always possible to add to  $\mathbb{D}_K^{2K+2}$  a small non-negative tensor making it non-degenerate.

**4.3. Error estimates: justification of the homogenization process.** We conclude this section by stating error estimates holding for the solution  $(\mathbf{v}_{\varepsilon,K}^*, q_{\varepsilon,K}^*)$  to the high order homogenized model (1.6). We know from Proposition 4.10 that  $\mathbb{D}_K^k = M^k$  for  $0 \leq k \leq K$ , therefore the assumptions of Proposition 4.5 are satisfied provided we verify the uniform regularity estimate (4.12).

LEMMA 4.14. *The solution  $(\mathbf{v}_{\varepsilon,K}^*, q_{\varepsilon,K}^*)$  of (1.6) is smooth and for any  $m \in \mathbb{N}$ , there exists a constant  $C_m(\mathbf{f})$  depending only on  $m$  and  $\mathbf{f}$  such that*

$$\|\mathbf{v}_{\varepsilon,K}^*\|_{H^m(D, \mathbb{R}^d)} \leq C_m(\mathbf{f}) \varepsilon^2.$$

*Proof.* Using Fourier series in the periodic domain  $D$ , the well-posedness of (1.6) is equivalent to the invertibility of the matrix

$$P(\xi) := \begin{bmatrix} \sum_{k=0}^{2K+2} (2i\pi/L)^k \mathbb{D}_K^k \cdot \xi^k & (2i\pi/L)\xi \\ (2i\pi/L)\xi^T & 0 \end{bmatrix}.$$

630 The variable  $\xi = (\xi_i) = (\varepsilon q_i)$  is the product of the Fourier variable  $q$  and  $\varepsilon$  and we have  
 631 denoted by  $\xi^k$  the scalar tensor defined by  $\xi_{i_1 \dots i_k}^k := \xi_{i_1} \dots \xi_{i_k}$  (hence  $\mathbb{D}_K^{2K+2} \cdot \xi^{2K+2}$   
 632 and  $M^k \cdot \xi^k$  are  $d \times d$  matrix). The results are obtained by using the positivity of  
 633 (4.15) and adapting the arguments of the proof of Lemma 5 in [34].  $\square$

634 Since we have verified that all the assumptions of Proposition 4.5 hold with  $K' = K$ ,  
 635 we are finally in position to state the following error bounds.

COROLLARY 4.15. *Let  $(\mathbf{v}_{\varepsilon, K}^*, q_{\varepsilon, K}^*)$  be the unique solution to the high order homogenized equation (1.6). There exists a constant  $C_K(\mathbf{f})$  independent of  $\varepsilon$  (but depending on  $K$ ,  $\mathbf{f}$ , and a priori on the shape of the hole  $(\eta T)$ ) such that the following error estimates hold:*

$$\begin{aligned} \left\| \mathbf{u}_\varepsilon - \sum_{k=0}^K \varepsilon^k N^k(\cdot/\varepsilon) \cdot \nabla^k \mathbf{v}_{\varepsilon, K}^* \right\|_{L^2(D_\varepsilon, \mathbb{R}^d)} &\leq C_K(\mathbf{f}) \varepsilon^{K+3}, \\ \left\| \nabla \left( \mathbf{u}_\varepsilon - \sum_{k=0}^K \varepsilon^k N^k(\cdot/\varepsilon) \cdot \nabla^k \mathbf{v}_{\varepsilon, K}^* \right) \right\|_{L^2(D_\varepsilon, \mathbb{R}^{d \times d})} &\leq C_K(\mathbf{f}) \varepsilon^{K+2}, \\ \left\| p_\varepsilon - \left( q_{\varepsilon, K}^* + \sum_{k=0}^{K-1} \varepsilon^{k-1} \beta^k(\cdot/\varepsilon) \cdot \nabla^k \mathbf{v}_{\varepsilon, K}^* \right) \right\|_{L^2(D_\varepsilon)} &\leq C_K(\mathbf{f}) \varepsilon^{K+1}. \end{aligned}$$

636 *Remark 4.16.* As the reader may expect, error bounds with the same order of  
 637 convergence hold for the truncation at order  $K$  of the “classical” ansatz (1.7), see  
 638 [26, 46] up to the order  $K = 1$ , and in Proposition 7.37 of [33] at all orders.

639 **5. Low volume fraction limits when the scaling  $\eta$  of the obstacle vanishes.**  
 640 In this section, we provide evidences that (1.6) is “well-behaved” in the sense  
 641 that it has the potential to capture the homogenized regimes (1.2)–(1.4) in the low  
 642 volume fraction limit where the size of the obstacles vanish. Our results supporting  
 643 this claim are obtained by analyzing the asymptotics of the tensors  $\mathcal{X}^{k*}$ ,  $M^k$  and  
 644  $\mathbb{D}_K^{2K+2}$  as the scaling ratio  $\eta$  converges to 0.

In this whole subsection, we assume for simplicity, that the space dimension is greater than 3:

$$d \geq 3.$$

645 Similar results are expected to hold in dimension  $d = 2$  but would require a different  
 646 treatment, as e.g. in [6, 41]. The hole  $\eta T$  is assumed to be an non-empty open subset  
 647 strictly included in the unit cell for any  $\eta \leq 1$  (it does not touch the boundary):  
 648  $\eta T \subset\subset P$ .

649 Let us recall the definition of the Deny-Lions (or Beppo-Levi) space denoted by  
 650  $\mathcal{D}^{1,2}(\mathbb{R}^d \setminus T, \mathbb{R}^d)$  (the reader is referred to [6, 4, 8] and also [48], p.59. for more details).

DEFINITION 5.1 (Deny-Lions space). *The Deny-Lions space  $\mathcal{D}^{1,2}(\mathbb{R}^d \setminus T, \mathbb{R}^d)$  is the completion of the space of smooth vector fields by the  $L^2$  norm of their gradients:*

$$\mathcal{D}^{1,2}(\mathbb{R}^d \setminus T, \mathbb{R}^d) := \overline{\mathcal{D}(\mathbb{R}^d \setminus T, \mathbb{R}^d)}^{\|\cdot\|_{L^2(\mathbb{R}^d \setminus T, \mathbb{R}^d)}},$$

651 where  $\mathcal{D}(\mathbb{R}^d \setminus T, \mathbb{R}^d)$  is the space of compactly supported smooth vector fields. When  
652  $d \geq 3$ , it admits the following characterization:  
653

$$654 \quad \mathcal{D}^{1,2}(\mathbb{R}^d \setminus T, \mathbb{R}^d) \\ 655 \quad = \{ \mathbf{v} \text{ measurable} \mid \|\mathbf{v}\|_{L^{2d/(d-2)}(\mathbb{R}^d \setminus T, \mathbb{R}^d)} < +\infty \text{ and } \|\nabla \mathbf{v}\|_{L^2(\mathbb{R}^d \setminus T, \mathbb{R}^{d \times d})} < +\infty \}.$$

657 For any  $1 \leq j \leq d$ , we consider the unique solution  $(\Psi_j, \sigma_j)$  to the exterior Stokes  
658 problem

$$659 \quad (5.1) \quad \left\{ \begin{array}{l} -\Delta \Psi_j + \nabla \sigma_j = 0 \text{ in } \mathbb{R}^d \setminus T \\ \operatorname{div}(\Psi_j) = 0 \text{ in } \mathbb{R}^d \setminus T \\ \Psi_j = 0 \text{ on } \partial T \\ \Psi_j \rightarrow \mathbf{e}_j \text{ at } \infty \\ \sigma_j \in L^2(\mathbb{R}^d \setminus T). \end{array} \right.$$

660 The convergence condition  $\Psi_j \rightarrow \mathbf{e}_j$  at infinity must be understood in the sense that  
661  $\Psi_j - \mathbf{e}_j$  belongs to  $\mathcal{D}^{1,2}(\mathbb{R}^d \setminus T, \mathbb{R}^d)$ . Similarly, the pressures  $(\sigma_j)_{1 \leq j \leq d}$  are uniquely  
662 determined by the condition  $\sigma_j \in L^2(\mathbb{R}^d \setminus T)$  (see e.g. Lemma 1.1, article V. of [36]).  
663 We denote by  $F := (F_{ij})_{1 \leq i, j \leq d}$  the matrix collecting the drag force components:

$$664 \quad (5.2) \quad F_{ij} := \int_{\mathbb{R}^d \setminus T} \nabla \Psi_i : \nabla \Psi_j dx = - \int_{\partial T} \mathbf{e}_j \cdot (\nabla \Psi_i - \sigma_i I) \cdot \mathbf{n} ds,$$

665 where the normal  $\mathbf{n}$  is pointing inward  $T$ .

666 **5.1. Technical estimates in the growing periodic domain  $\eta^{-1}P \setminus T$ .** In all  
667 this section, vector fields of the rescaled cell  $\eta^{-1}P$  are indicated by a tilde  $\tilde{\cdot}$  notation.  
668 For a given vector field  $\tilde{\mathbf{v}} \in L^2(\eta^{-1}P, \mathbb{R}^d)$ , we denote by  $\langle \tilde{\mathbf{v}} \rangle$  the average  $\langle \tilde{\mathbf{v}} \rangle :=$   
669  $\eta^d \int_{\eta^{-1}P} \tilde{\mathbf{v}}(y) dy$ .

670 Let us recall that for any  $\mathbf{v} \in H^1(P \setminus (\eta T), \mathbb{R}^d)$ , if  $\tilde{\mathbf{v}}$  is the rescaled function defined  
671 by  $\tilde{\mathbf{v}}(y) := \mathbf{v}(\eta y)$  in the rescaled cell  $\eta^{-1}P \setminus T$ , then the  $L^2$  norms of  $\mathbf{v}$ ,  $\tilde{\mathbf{v}}$  and of their  
672 gradients are related by the following identities:

$$673 \quad \|\mathbf{v}\|_{L^2(P \setminus (\eta T), \mathbb{R}^d)} = \eta^{d/2} \|\tilde{\mathbf{v}}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^d)} \\ 674 \quad \|\nabla \mathbf{v}\|_{L^2(P \setminus (\eta T), \mathbb{R}^{d \times d})} = \eta^{d/2-1} \|\nabla \tilde{\mathbf{v}}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})}.$$

676 The asymptotic behaviors of the tensors  $\mathcal{X}^{k*}, M^k$  are obtained by following the  
677 methodology of [6, 41, 34], which relies on several technical results stated in this part.

678 LEMMA 5.2. *Assume  $d \geq 3$ . There exists a constant  $C > 0$  independent of  $\eta > 0$   
679 such that for any  $\tilde{\mathbf{v}} \in H^1(\eta^{-1}P \setminus T, \mathbb{R}^d)$  which vanishes on the hole  $\partial T$  and which is  
680  $\eta^{-1}P$  periodic, the following inequalities hold:*

$$681 \quad (5.3) \quad \|\tilde{\mathbf{v}}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^d)} \leq C \eta^{-d/2} \|\nabla \tilde{\mathbf{v}}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})},$$

$$682 \quad (5.4) \quad |\langle \tilde{\mathbf{v}} \rangle| \leq C \|\nabla \tilde{\mathbf{v}}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})},$$

$$683 \quad (5.5) \quad \|\tilde{\mathbf{v}} - \langle \tilde{\mathbf{v}} \rangle\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^d)} \leq C \eta^{-1} \|\nabla \tilde{\mathbf{v}}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})},$$

$$684 \quad (5.6) \quad \|\tilde{\mathbf{v}} - \langle \tilde{\mathbf{v}} \rangle\|_{L^{2d/(d-2)}(\eta^{-1}P \setminus T, \mathbb{R}^d)} \leq C \|\nabla \tilde{\mathbf{v}}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})}.$$

686 *Proof.* See [41, 45, 6, 42]. □

687 LEMMA 5.3. Consider  $\mathbf{h} \in L^2(\eta^{-1}P \setminus T, \mathbb{R}^d)$  and  $g \in L^2(\eta^{-1}P \setminus T)$  a function  
688 satisfying  $\int_{\eta^{-1}P \setminus T} g dx = 0$ . Let  $(\mathbf{v}, \phi) \in H^1(\eta^{-1}P \setminus T, \mathbb{R}^d) \times L^2(\eta^{-1}P \setminus T)$  be the  
689 unique solution to the following Stokes system:

$$690 \quad (5.7) \quad \begin{cases} -\Delta \mathbf{v} + \nabla \phi = \mathbf{h} & \text{in } \eta^{-1}P \setminus T \\ \operatorname{div}(\mathbf{v}) = g & \text{in } \eta^{-1}P \setminus T \\ \int_{\eta^{-1}P \setminus T} \phi dx = 0 \\ \mathbf{v} = 0 & \text{on } \partial T \\ \mathbf{v} \text{ is } \eta^{-1}P\text{-periodic.} \end{cases}$$

691 There exists a constant  $C > 0$  independent of  $\eta$ ,  $\mathbf{h}$  and  $g$  such that

$$692 \quad (5.8) \quad \|\nabla \mathbf{v}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})} + \|\phi\|_{L^2(\eta^{-1}P \setminus T)} \\ 693 \quad \leq C(\eta^{-1}\|\mathbf{h} - \langle \mathbf{h} \rangle\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^d)} + \eta^{-d}|\langle \mathbf{h} \rangle| + \|g\|_{L^2(\eta^{-1}P \setminus T)}).$$

694 *Proof.* From Lemma 2.2.4 in [7], for any  $\eta > 0$ , there exists a linear ‘‘Bogovskii’s’’  
697 operator  $B_\eta : L^2(P \setminus (\eta T)) \rightarrow H^1(P \setminus (\eta T), \mathbb{R}^d)$  satisfying for any  $\phi \in L^2(P \setminus (\eta T))$   
698 such that  $\int_{P \setminus (\eta T)} \phi dy = 0$ :

- 699 (i)  $\operatorname{div}(B_\eta \phi) = \phi$ ,
- 700 (ii)  $B_\eta \phi = 0$  on  $\partial(\eta T)$ ,
- 701 (iii)  $B_\eta \phi$  is  $P$ -periodic,
- 702 (iv)  $\|\nabla(B_\eta \phi)\|_{L^2(P \setminus (\eta T), \mathbb{R}^{d \times d})} \leq C\|\phi\|_{L^2(P \setminus (\eta T))}$  for a constant  $C$  independent of  $\eta$   
703 and  $\phi$ .

For any  $\tilde{\phi} \in L^2(\eta^{-1}P \setminus T)$  such that  $\int_{\eta^{-1}P \setminus T} \tilde{\phi} dy = 0$ , we define

$$\tilde{B}_\eta(\tilde{\phi}) := \eta^{-1}[B_\eta(\tilde{\phi}(\eta^{-1} \cdot))](\eta \cdot).$$

704 The operator  $\tilde{B}_\eta : L^2(\eta^{-1}P \setminus T) \rightarrow H^1(\eta^{-1}P \setminus T, \mathbb{R}^d)$  satisfies the following properties:  
705 for any  $\tilde{\phi} \in L^2(\eta^{-1}P \setminus T)$  such that  $\int_{\eta^{-1}P \setminus T} \tilde{\phi} dx = 0$ ,

- 706 (i)  $\operatorname{div}(\tilde{B}_\eta \tilde{\phi}) = \tilde{\phi}$  in  $\eta^{-1}P \setminus T$ ,
- 707 (ii)  $\tilde{B}_\eta \tilde{\phi} = 0$  on  $\partial T$ ,
- 708 (iii)  $\tilde{B}_\eta \tilde{\phi}$  is  $\eta^{-1}P$ -periodic,
- 709 (iv)  $\|\nabla(\tilde{B}_\eta \tilde{\phi})\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})} \leq C\|\tilde{\phi}\|_{L^2(\eta^{-1}P \setminus T)}$  for a constant  $C$  independent of  $\eta$   
710 and  $\tilde{\phi}$ .

711 The proof follows then classically along the lines of Corollary 4.4. Upon an integration  
712 by parts and by using Lemma 5.2, it is readily obtained with  $\mathbf{w} := \mathbf{v} - \tilde{B}_\eta g$ :

$$713 \quad \|\nabla \mathbf{w}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})}^2 = \int_{\eta^{-1}P \setminus T} \mathbf{h} \cdot \mathbf{w} dy \\ 714 \quad = \int_{\eta^{-1}P \setminus T} (\mathbf{h} - \langle \mathbf{h} \rangle) \cdot (\mathbf{w} - \langle \mathbf{w} \rangle) dy + \int_{\eta^{-1}P \setminus T} \langle \mathbf{h} \rangle \cdot \langle \mathbf{w} \rangle dy \\ 715 \quad \leq C(\|\mathbf{h} - \langle \mathbf{h} \rangle\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^d)} \|\mathbf{w} - \langle \mathbf{w} \rangle\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^d)} + \eta^{-d}|\langle \mathbf{h} \rangle| |\langle \mathbf{w} \rangle|) \\ 716 \quad (5.9) \quad \leq C(\eta^{-1}\|\mathbf{h} - \langle \mathbf{h} \rangle\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^d)} + \eta^{-d}|\langle \mathbf{h} \rangle|) \|\nabla \mathbf{w}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})}$$

for a constant  $C > 0$  independent of  $\eta$  and  $\mathbf{h}$ . This implies

$$\begin{aligned} \|\nabla \mathbf{v}\|_{L^2(\eta^{-1}P \setminus T)} &\leq \|\nabla \mathbf{w}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})} + \|\nabla(\tilde{B}_\eta g)\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})} \\ &\leq C(\|\nabla \mathbf{w}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})} + \|g\|_{L^2(\eta^{-1}P \setminus T)}), \end{aligned}$$

whence the bound on  $\|\nabla \mathbf{v}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})}$  by using (5.9). The bound for the pressure is obtained by writing

$$\begin{aligned} \int_{\eta^{-1}P \setminus T} \phi^2 dx &= \int_{\eta^{-1}P \setminus T} \phi \operatorname{div}(B_\eta \phi) dx \\ &= - \int_{\eta^{-1}P \setminus T} \nabla \phi \cdot B_\eta \phi dx = \int_{\eta^{-1}P \setminus T} (\nabla \mathbf{v} : \nabla(B_\eta \phi) - \mathbf{h} \cdot (B_\eta \phi)) dx, \end{aligned}$$

from where (5.8) follows analogously.  $\square$

**5.2. Asymptotic convergences of homogenized tensors in the low volume fraction limit  $\eta \rightarrow 0$ .** The asymptotics of the corrector tensors  $(\mathcal{X}_j^0, \alpha_j^0)$  and of  $\mathcal{X}^{0*}$  (defined in (3.3) and (3.7)) have been obtained in of Theorem 3.1 in [6]. The following proposition extends this result to the whole family of tensors  $(\mathcal{X}^k, \alpha_j^k)_{k \in \mathbb{N}}$  and  $(\mathcal{X}^{k*})_{k \in \mathbb{N}}$ .

**PROPOSITION 5.4.** *Assume  $d \geq 3$ . For any  $k \geq 0$  and  $1 \leq j \leq d$ , denote by  $(\tilde{\mathcal{X}}_j^{2k}, \tilde{\alpha}_j^{2k})$  and  $(\tilde{\mathcal{X}}_j^{2k+1}, \tilde{\alpha}_j^{2k+1})$  the rescaled tensors in  $\eta^{-1}P \setminus T$  defined by*

$$\begin{cases} \tilde{\mathcal{X}}_j^{2k}(x) := \eta^{(d-2)(k+1)} \mathcal{X}_j^{2k}(\eta x) & \tilde{\mathcal{X}}_j^{2k+1}(x) := \eta^{(d-2)(k+1)} \mathcal{X}_j^{2k+1}(\eta x) \\ \tilde{\alpha}_j^{2k}(x) := \eta^{(d-2)(k+1)-1} \alpha_j^{2k}(\eta x) & \tilde{\alpha}_j^{2k+1}(x) := \eta^{(d-2)(k+1)-1} \alpha_j^{2k+1}(\eta x) \end{cases}$$

for any  $x \in \eta^{-1}P \setminus T$ . Then:

1. there exists a constant  $C$  independent of  $\eta > 0$  such that

$$\forall \eta > 0, \|\nabla \tilde{\mathcal{X}}_j^{2k}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})} + \|\tilde{\alpha}_j^{2k}\|_{L^2(\eta^{-1}P \setminus T)} \leq C,$$

$$\forall \eta > 0, \|\nabla \tilde{\mathcal{X}}_j^{2k+1}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})} + \|\tilde{\alpha}_j^{2k+1}\|_{L^2(\eta^{-1}P \setminus T)} \leq C;$$

2. the following convergences hold as  $\eta \rightarrow 0$ :

$$(5.10) \quad (\tilde{\mathcal{X}}_i^{2k}, \tilde{\alpha}_i^{2k}) \rightharpoonup (c_{ij}^{2k} \Psi_j, c_{ij}^{2k} \sigma_j) \quad \text{weakly in } H_{loc}^1(\mathbb{R}^d \setminus T, \mathbb{R}^d) \times L_{loc}^2(\mathbb{R}^d \setminus T),$$

$$(5.11) \quad (\tilde{\mathcal{X}}_i^{2k+1}, \tilde{\alpha}_i^{2k+1}) \rightharpoonup (0, 0) \quad \text{weakly in } H_{loc}^1(\mathbb{R}^d \setminus T, \mathbb{R}^d) \times L_{loc}^2(\mathbb{R}^d \setminus T),$$

$$(5.12) \quad \mathcal{X}^{2k*} \sim \frac{1}{\eta^{(d-2)(k+1)}} c^{2k},$$

$$(5.13) \quad \mathcal{X}^{2k+1*} = o\left(\frac{1}{\eta^{(d-2)(k+1)}}\right),$$

where  $c_{ij}^{2k}$  denotes the coefficients of the matrix valued tensor  $c^{2k} := (c_{ij}^{2k})_{1 \leq i, j \leq d}$  of order  $2k$  given by

$$c^{2k} := F^{-(k+1)} J^{2k} \quad \text{with } J^{2k} = \overbrace{I \otimes I \otimes \cdots \otimes I}^{k \text{ times}}.$$

737 *Proof.* The result is proved by induction on  $k$ .

738 1. *Case 2k with  $k = 0$ .* The tensor  $(\tilde{\mathcal{X}}_i^0, \tilde{\alpha}_i^0)$  satisfies

$$739 \quad (5.14) \quad \begin{cases} -\Delta \tilde{\mathcal{X}}_i^0 + \nabla \tilde{\alpha}_i^0 = \eta^d \mathbf{e}_i & \text{in } \mathbb{R}^d \setminus T \\ \operatorname{div}(\tilde{\mathcal{X}}_i^0) = 0 & \text{in } \mathbb{R}^d \setminus T, \end{cases}$$

as well as the other boundary conditions of (5.7). Lemma 5.3 implies then

$$\|\nabla \tilde{\mathcal{X}}_i^0\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})} + \|\tilde{\alpha}_i^0\|_{L^2(\eta^{-1}P \setminus T)} \leq C \eta^{-d} \eta^d |\langle \mathbf{e}_i \rangle| \leq C.$$

From (5.4), we also obtain that  $\langle \tilde{\mathcal{X}}_i^0 \rangle$  is bounded. Hence, up to extracting a subsequence, there exists a constant matrix  $c^0 := (c_{ij}^0)_{1 \leq i, j \leq d}$ , and fields  $(\hat{\Psi}_i^0, \hat{\sigma}_i^0)_{1 \leq i \leq d}$  such that

$$\langle \tilde{\mathcal{X}}_i^0 \rangle \cdot \mathbf{e}_j \rightarrow c_{ij}^0,$$

$$(\tilde{\mathcal{X}}_i^0, \tilde{\alpha}_i^0) \rightharpoonup (\hat{\Psi}_i^0, \hat{\sigma}_i^0) \text{ weakly in } H_{loc}^1(\eta^{-1}P \setminus T, \mathbb{R}^d) \times L_{loc}^2(\eta^{-1}P \setminus T).$$

Multiplying (5.14) by a compactly supported test function  $\Phi \in C_c^\infty(\mathbb{R}^d \setminus T)$  and integrating by parts yields

$$\int_{\eta^{-1}P \setminus T} (\nabla \tilde{\mathcal{X}}_i^0 : \nabla \Phi - \tilde{\alpha}_i^0 \operatorname{div}(\Phi)) dx = \int_{\eta^{-1}P \setminus T} \eta^d \Phi \cdot \mathbf{e}_i dx.$$

Passing to the limit as  $\eta \rightarrow 0$  implies then

$$\begin{cases} -\Delta \hat{\Psi}_i^0 + \nabla \hat{\sigma}_i^0 = 0 & \text{in } \mathbb{R}^d \setminus T \\ \operatorname{div}(\hat{\Psi}_i^0) = 0 & \text{in } \mathbb{R}^d \setminus T \\ \hat{\Psi}_i^0 = 0 & \text{on } \partial T. \end{cases}$$

By applying the point (5.6) of Lemma 5.2 and by using the lower semi-continuity of the Lebesgue space norms, we infer  $(\hat{\Psi}_i^0 - c_{ij}^0 \mathbf{e}_j, \hat{\sigma}_i^0) \in \mathcal{D}^{1,2}(\mathbb{R}^d \setminus T) \times L^2(\mathbb{R}^d \setminus T)$  (see the proof of Theorem 3.1 in [6] for a detailed justification). By linearity, it is then necessary that  $(\hat{\Psi}_i^0, \hat{\sigma}_i^0) = (c_{ij}^0 \Psi_j, c_{ij}^0 \sigma_j)$  where  $(\Psi_j, \sigma_j)$  are the solution to the exterior problem (5.1). In order to identify the coefficient  $c_{ij}^0$ , we integrate (5.1) by parts against the test function  $\Phi = \mathbf{e}_j$  then yields

$$0 = \eta^d \int_{\eta^{-1}P \setminus T} \delta_{ij} dx + \int_{\partial T} \mathbf{e}_j \cdot (\nabla \tilde{\mathcal{X}}_i^0 - \tilde{\alpha}_i^0 I) \cdot \mathbf{n} dx.$$

Passing to the limit as  $\eta \rightarrow 0$  by using the continuity of the drag force with respect to the weak convergence and (5.2) yields then

$$0 = \delta_{ij} + \int_{\partial T} \mathbf{e}_j \cdot (\nabla \hat{\Phi}_i^0 - \hat{\sigma}_i^0) \cdot \mathbf{n} dx = \delta_{ij} - c_{ip}^0 F_{pj}.$$

This implies  $c^0 = F^{-1}$  as claimed and the convergence of the whole sequence by uniqueness of the limit. The asymptotic for  $\mathcal{X}^{0*}$  as  $\eta \rightarrow 0$  follows by the change of variable  $y = \eta x$ :

$$\mathcal{X}_{ij}^{0*} = \mathbf{e}_i \cdot \int_{P \setminus (\eta T)} \mathcal{X}_j^0 dy = \eta^{2-d} \eta^d \mathbf{e}_i \cdot \int_{\eta^{-1}P \setminus T} \tilde{\mathcal{X}}_j^0 dy \sim \eta^{2-d} \langle \tilde{\mathcal{X}}_j^0 \rangle \cdot \mathbf{e}_i \sim \eta^{2-d} c_{ji}^0.$$

740 2. *Case  $2k + 1$  with  $k = 0$ .* The tensor  $(\tilde{\boldsymbol{\chi}}_i^1, \tilde{\alpha}_i^1)$  satisfies

$$741 \quad (5.15) \quad \begin{cases} -\Delta \tilde{\boldsymbol{\chi}}_i^1 + \nabla \tilde{\alpha}_i^1 = \eta(2\partial_l \tilde{\boldsymbol{\chi}}_i^0 - \tilde{\alpha}_j^0 \mathbf{e}_l) \otimes \mathbf{e}_l \text{ in } \eta^{-1}P \setminus T \\ \operatorname{div}(\tilde{\boldsymbol{\chi}}_i^1) = -\eta(\tilde{\boldsymbol{\chi}}_j^0 - \langle \tilde{\boldsymbol{\chi}}_j^0 \rangle) \cdot \mathbf{e}_l \otimes \mathbf{e}_l \text{ in } \eta^{-1}P \setminus T. \end{cases}$$

Applying [Lemma 5.3](#) and remarking that  $\langle 2\partial_l \tilde{\boldsymbol{\chi}}_i^0 - \tilde{\alpha}_i^0 \mathbf{e}_l \rangle = 0$ , we obtain

$$\|\nabla \tilde{\boldsymbol{\chi}}_i^1\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})} + \|\tilde{\alpha}_i^1\|_{L^2(\eta^{-1}P \setminus T)} \leq C.$$

Integrating [\(5.15\)](#) by parts against a compactly supported test function  $\Phi \in C^c(\mathbb{R}^d \setminus T)$  and passing to the limit as  $\eta \rightarrow 0$ , we obtain similarly the existence of a matrix valued tensor  $c^1 := (c_{ij}^1)_{1 \leq i, j \leq d}$  (of order 1) such that, up to the extraction of a subsequence:

$$\langle \tilde{\boldsymbol{\chi}}_i^1 \rangle \cdot \mathbf{e}_j \rightarrow c_{ij}^1,$$

$$(\tilde{\boldsymbol{\chi}}_i^1, \tilde{\alpha}_i^1) \rightharpoonup (c_{ij}^1 \Psi_j, c_{ij}^1 \sigma_j) \text{ weakly in } H_{loc}^1(\eta^{-1}P \setminus T, \mathbb{R}^d) \times L_{loc}^2(\eta^{-1}P \setminus T).$$

742 Integrating [\(5.15\)](#) by parts against the test function  $\mathbf{e}_j$  and passing to the limit as  
743  $\eta \rightarrow 0$  yields in this situation  $0 = c_{ij}^1 F_{pj}$  whence  $c^1 = 0$ .

744 3. *General case.* Assuming that the result holds till rank  $k$ , the differential equations  
745 satisfied by the rescaled tensors in  $\eta^{-1}P \setminus T$  read:

$$746 \quad (5.16) \quad \begin{cases} -\Delta \tilde{\boldsymbol{\chi}}_i^{2k+2} + \nabla \tilde{\alpha}_i^{2k+2} = \eta^{d-1}(\partial_l \tilde{\boldsymbol{\chi}}_i^{2k+1} - \tilde{\alpha}_i^{2k+1} \mathbf{e}_l) \otimes \mathbf{e}_l + \eta^d \tilde{\boldsymbol{\chi}}_i^{2k} \otimes I \\ \operatorname{div}(\tilde{\boldsymbol{\chi}}_i^{2k+2}) = -\eta^{d-1}(\tilde{\boldsymbol{\chi}}_i^{2k+1} - \langle \tilde{\boldsymbol{\chi}}_i^{2k+1} \rangle) \cdot \mathbf{e}_l \otimes \mathbf{e}_l. \end{cases}$$

747

$$748 \quad (5.17) \quad \begin{cases} -\Delta \tilde{\boldsymbol{\chi}}_i^{2k+3} + \nabla \tilde{\alpha}_i^{2k+3} = \eta(\partial_l \tilde{\boldsymbol{\chi}}_i^{2k+2} - \tilde{\alpha}_i^{2k+2} \mathbf{e}_l) \otimes \mathbf{e}_l + \eta^d \tilde{\boldsymbol{\chi}}_i^{2k+1} \otimes I \\ \operatorname{div}(\tilde{\boldsymbol{\chi}}_i^{2k+3}) = -\eta(\tilde{\boldsymbol{\chi}}_i^{2k+2} - \langle \tilde{\boldsymbol{\chi}}_i^{2k+2} \rangle) \cdot \mathbf{e}_l \otimes \mathbf{e}_l. \end{cases}$$

Using [Lemma 5.2](#), [Lemma 5.3](#) and the point 1. of the proposition at rank  $k$ , we readily obtain

$$\|\nabla \tilde{\boldsymbol{\chi}}_i^{2k+2}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})} + \|\tilde{\alpha}_i^{2k+2}\|_{L^2(\eta^{-1}P \setminus T)} \leq C,$$

$$\|\nabla \tilde{\boldsymbol{\chi}}_i^{2k+3}\|_{L^2(\eta^{-1}P \setminus T, \mathbb{R}^{d \times d})} + \|\tilde{\alpha}_i^{2k+3}\|_{L^2(\eta^{-1}P \setminus T)} \leq C.$$

Repeating the above arguments, we obtain, up to the extraction of a subsequence, the existence of matrix valued tensors  $c^{2k+2}$  and  $c^{2k+3}$  such that

$$\langle \tilde{\boldsymbol{\chi}}_i^{2k+2} \rangle \cdot \mathbf{e}_j \rightarrow c_{ij}^{2k+2} \text{ and } \langle \tilde{\boldsymbol{\chi}}_i^{2k+3} \rangle \cdot \mathbf{e}_j \rightarrow c_{ij}^{2k+3},$$

$$(\tilde{\boldsymbol{\chi}}_i^{2k+2}, \tilde{\alpha}_i^{2k+2}) \rightharpoonup (c_{ij}^{2k+2} \Psi_j, c_{ij}^{2k+2} \sigma_j) \text{ weakly in } H_{loc}^1(\mathbb{R}^d \setminus T, \mathbb{R}^d) \times L_{loc}^2(\mathbb{R}^d \setminus T),$$

$$(\tilde{\boldsymbol{\chi}}_i^{2k+3}, \tilde{\alpha}_i^{2k+3}) \rightharpoonup (c_{ij}^{2k+3} \Psi_j, c_{ij}^{2k+3} \sigma_j) \text{ weakly in } H_{loc}^1(\mathbb{R}^d \setminus T, \mathbb{R}^d) \times L_{loc}^2(\mathbb{R}^d \setminus T).$$

The last step consists in integrating [\(5.16\)](#) and [\(5.17\)](#) by part against the test function  $\mathbf{e}_j$  and to pass to the limit as  $\eta \rightarrow 0$  in order to identify  $c_{ij}^{2k+2}$  and  $c_{ij}^{2k+3}$ . Performing this computation as above yields

$$0 = c_{ij}^{2k} \otimes I - c_{ip}^{2k+2} F_{pj},$$

$$0 = c_{ij}^{2k+1} \otimes I - c_{ip}^{2k+3} F_{pj}$$

749 from where we infer  $c^{2k+2} = c^{2k} F^{-1} \otimes I$ ,  $c^{2k+3} = c^{2k+1} F^{-1} \otimes I$ , whence the result  
750 (recall  $c^1 = 0$  from the point 2. of the proof).  $\square$

751 Using the identity of (3.20), we obtain the asymptotics for the coefficients  $M^k$  of the  
752 infinite order homogenized equation (1.9).

753 **COROLLARY 5.5.** *Assume  $d \geq 3$ . The following convergences hold for the matrix*  
754 *valued tensors  $M^k$  as  $\eta \rightarrow 0$ :*

$$755 \quad (5.18) \quad M^0 \sim \eta^{d-2} F,$$

$$756 \quad (5.19) \quad M^1 = o(\eta^{d-2}),$$

$$757 \quad (5.20) \quad M^2 \rightarrow -I,$$

$$758 \quad (5.21) \quad \forall k \geq 2, M^{2k} = o\left(\frac{1}{\eta^{(d-2)(k-1)}}\right),$$

$$759 \quad (5.22) \quad \forall k \geq 1, M^{2k+1} = o\left(\frac{1}{\eta^{(d-2)(k-1)}}\right).$$

760

*Proof.* We replace the asymptotics of (5.4) in the explicit formula for the tensors  $M^k$  given in (3.20). (5.18) is an immediate consequence of  $M^0 = (\mathcal{X}^{0*})^{-1}$ . The convergence (5.20) is obtained by writing, according to (3.20):

$$\begin{aligned} M^2 &= -(\mathcal{X}^{0*})^{-1} \otimes \mathcal{X}^{2*} \otimes (\mathcal{X}^{0*})^{-1} + (\mathcal{X}^{0*})^{-1} \otimes \mathcal{X}^{1*} \otimes (\mathcal{X}^{0*})^{-1} \otimes \mathcal{X}^{1*} \otimes (\mathcal{X}^{0*})^{-1} \\ &= -\frac{\eta^{2(d-2)}}{\eta^{2(d-2)}} F \otimes c^2 \otimes F + o\left(\frac{\eta^{3(d-2)}}{\eta^{2(d-2)}}\right) = -(FF^{-2}F) \otimes I + o(\eta^{d-2}) \\ &= -I + o(\eta^{d-2}). \end{aligned}$$

761 For  $M^{2k+1}$  with  $k \geq 0$ , we use (3.20) and we observe that, for any  $0 \leq p \leq 2k+1$   
762 and indices  $1 \leq i_1 \dots i_p \leq 2k+1$  such that  $i_1 + \dots + i_p = 2k+1$ , there exists at least  
763 one odd index  $i_q$  with  $1 \leq q \leq p$ . Using (5.12) and (5.13), we arrive at

764

$$\begin{aligned} 765 \quad & (\mathcal{X}^{0*})^{-1} \otimes \mathcal{X}^{i_1*} \otimes \dots \otimes (\mathcal{X}^{0*})^{-1} \otimes \mathcal{X}^{i_p*} \otimes (\mathcal{X}^{0*})^{-1} \\ &= o\left(\frac{\eta^{(p+1)(d-2)}}{\eta^{(p+\lfloor i_1/2 \rfloor + \dots + \lfloor i_p/2 \rfloor)(d-2)}}\right) = o\left(\frac{1}{\eta^{(d-2)(k-1)}}\right), \end{aligned}$$

766

767

768 which implies (5.19) and (5.22). For  $M^{2k}$  with  $k > 1$ , we separate the summands  
769 of (3.20) into two categories. For a given  $p$  indices such that  $1 \leq p \leq 2k$  and  
770  $i_1 + \dots + i_p = 2k$ , there are only two possibilities:

1. either there exists at least one odd index  $i_q$ , in that case the above reasoning implies as well

$$(\mathcal{X}^{0*})^{-1} \otimes \mathcal{X}^{i_1*} \otimes \dots \otimes (\mathcal{X}^{0*})^{-1} \otimes \mathcal{X}^{i_p*} \otimes (\mathcal{X}^{0*})^{-1} = o\left(\frac{1}{\eta^{(d-2)(k-1)}}\right).$$

771 2. or all indices  $i_1 + \dots + i_p$  are even, in that case we may write, as  $\eta \rightarrow 0$ :

$$\begin{aligned} 772 \quad & (\mathcal{X}^{0*})^{-1} \otimes \mathcal{X}^{i_1*} (\mathcal{X}^{0*})^{-1} \otimes \dots \otimes (\mathcal{X}^{0*})^{-1} \otimes \mathcal{X}^{i_p*} \otimes (\mathcal{X}^{0*})^{-1} \\ 773 \quad & \sim \frac{\eta^{(d-2)(p+1)}}{\eta^{(d-2)(p+k)}} F \otimes c^{i_1} \otimes \dots \otimes F \otimes c^{i_p} \otimes F \\ 774 \quad & \sim \frac{1}{\eta^{(d-2)(k-1)}} (FF^{-(i_1/2+1)}) \times \dots \times (FF^{-(i_p/2+1)}) F J^{2k} \\ 775 \quad & \sim \frac{1}{\eta^{(d-2)(k-1)}} F^{-(k-1)} \otimes J^{2k}. \end{aligned}$$



776

Note that in the latter case, the asymptotic does not depend on the choice of indices  $i_1 + \dots + i_p = 2k$ . Therefore, by isolating the terms featuring only even indices  $i_1 := 2j_1, \dots, i_p := 2j_p$  in (3.20), we obtain finally

$$M^{2k} = \frac{1}{\eta^{(d-2)(k-1)}} F^{-(k-1)} \otimes J^{2k} \left( \sum_{p=1}^{2k} (-1)^p \sum_{\substack{2j_1 + \dots + 2j_p = 2k \\ 1 \leq j_1, \dots, j_p \leq k}} 1 \right) + o\left(\frac{1}{\eta^{(d-2)(k-1)}}\right).$$

777 The asymptotic (5.21) follows from the fact that the summation over  $p$  in the above  
778 expression is zero (see e.g. the end of the proof of Corollary 6 in [34]).  $\square$

779 *Remark 5.6.* We have therefore obtained the following asymptotic estimates for  
780 the coefficients  $\varepsilon^{k-2} M^k$  of the infinite order homogenized equation (1.9) as  $\eta \rightarrow 0$ :

$$\begin{aligned} 781 \quad & \varepsilon^{-2} M^0 \sim (\eta^{d-2}/\varepsilon^2) F, \\ 782 \quad & \varepsilon^{-1} M^1 = o(\varepsilon(\eta^{d-2}/\varepsilon^2)), \\ 783 \quad & \varepsilon^0 M^2 \rightarrow -I, \\ 784 \quad & \varepsilon^{2k-2} M^{2k} = o\left((\varepsilon^2/\eta^{d-2})^{k-1}\right) \text{ for } k \geq 2, \\ 785 \quad & \varepsilon^{2k-1} M^{2k+1} = o\left(\varepsilon(\varepsilon^2/\eta^{d-2})^{k-1}\right) \text{ for } k \geq 1. \end{aligned}$$

787 These asymptotics bring into play the ratio  $\varepsilon^2/\eta^{d-2}$  and so the critical scaling  $\eta_{\text{crit}} \sim$   
788  $\varepsilon^{2/(d-2)}$ . They imply thus the ‘‘coefficient-wise’’ convergence of (1.9) to the Brinkman  
789 regime (1.3) at the critical rate  $\eta \sim \varepsilon^{2/(d-2)}$ , in which case  $\varepsilon^{-2} M^0 \rightarrow F$  and  
790  $\varepsilon^{k-2} M^k \rightarrow 0$  for any  $k > 2$ . Note that  $\varepsilon^0 M^2 \rightarrow -I$  whatever the rate of conver-  
791 gence at which  $\eta \rightarrow 0$ . The Darcy regimes (1.4) and (1.5) correspond to the situation  
792 where  $\eta^{d-2}/\varepsilon^2 \rightarrow +\infty$ ; in that case the zeroth order term  $\varepsilon^{-2} M^0$  is dominant.

793 Finally, the leading coefficients of the Stokes regime (1.2) are retrieved for  $\eta =$   
794  $o(\varepsilon^{2/(d-2)})$ , since in this case,  $\varepsilon^{-2} M^0 \rightarrow 0$ ,  $\varepsilon^{-1} M^1 \rightarrow 0$  and  $\varepsilon^0 M^2 \rightarrow -I$ . However  
795 the present analysis is not sufficient to conclude that the coefficients  $\varepsilon^{k-2} M^k$  of order  
796  $k > 2$  converge to zero in the subcritical regime  $\eta = o(\varepsilon^{2/(d-2)})$ . Indeed  $\varepsilon^{k-2} M^k$  is just  
797 bounded by  $(\varepsilon^2/\eta^{d-2})^k$ , a quantity which can potentially blow up for too small values  
798 of  $\eta$ . This matter is to be addressed in a future work through a more accurate analysis  
799 of the rate of convergence of the coefficients  $\mathcal{X}^{2k*}$  and  $\mathcal{X}^{2k+1*}$  in the asymptotic (5.12)  
800 and (5.13). To date, let us note that Jing obtained recently  $\mathcal{X}^{0*} = F/\eta^{d-2} + O(1)$  in  
801 the scalar case (proof of the Lemma 5.1 in [41]) by using layer potential techniques.

*Remark 5.7.* From the estimates of (5.4), we obtain that the coefficients  $(\mathbb{D}_K^k)$  of  
(1.6) satisfy the same asymptotic convergences of Corollary 5.5. Indeed, by using the  
definition (3.21) we find that there exists a constant  $C > 0$  independent of  $\eta$  such  
that for any  $K \geq 0$ ,  $K + 1 \leq k \leq 2K + 1$  and  $1 \leq j \leq d$ :

$$\begin{aligned} & \|\nabla \mathbf{N}_j^K\|_{L^2(Y, \mathbb{R}^{d \times d})} \leq C \eta^{-(d-2)\lfloor K/2 \rfloor} \eta^{d/2-1} \\ & \|\beta_j^{k-K-1}\|_{L^2(Y, \mathbb{R}^d)} \leq C \eta^{-(d-2)\lfloor \frac{k-K-1}{2} \rfloor + 1} \eta^{d/2}. \end{aligned}$$

Applying the inequality  $\lfloor x \rfloor + \lfloor y \rfloor \leq \lfloor x + y \rfloor$ , we obtain that the coefficients  $\mathbb{A}_{ij}^k$  of  
Proposition 4.10 satisfy for  $K + 1 \leq k \leq 2K + 1$ ,

$$|\mathbb{A}_{ij}^k| \leq C \eta^d \eta^{-\lfloor \frac{k-1}{2} \rfloor (d-2)} \leq C \eta^2 M_{ij}^k.$$

802 Hence the discrepancy induced by the coefficients  $A_{ij}^k$  is small and  $\mathbb{D}_{K,ij}^k$  also satisfies  
 803 (5.21) and (5.22) for  $K + 1 \leq k \leq 2K + 1$ . Similarly (see Corollary 7 of [34]), we may  
 804 show that  $\mathbb{D}_0^2 \rightarrow -I$ . The remaining coefficients  $\mathbb{D}_K^k$  are equal to  $M^k$ .

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