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Fluid flow in thin fractured porous media using a TPM-phase-field model and microfluidic experiments

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Abstract The Theory of Porous Media (TPM) with an embedded phase-field approach to fracture provides an elegant opportunity to study complex flow phenomena in fractured porous materials in a unified single-domain approach. On this basis, the interactive flow behaviour between free flow and porous-media flow is studied using the example of flow through a thin porous plate containing a rectangular channel. By considering different boundary conditions and investigating the flow behaviour for a range of hydraulic conductivities, our study is designed to reveal insights into phenomena which are relevant for various sub-surface geo-engineered applications. Furthermore, we show that the applied macroscopic single-domain approach is able to reveal local flow effects near the porous interface (channel walls), namely the so-called velocity profile inversion phenomenon. Moreover, we introduce a geometrically motivated estimation of the length-scale parameter ϵ used in phase-field approaches, which is directly related to the roughness of the fracture surface. Thus, values for ϵ are proposed for microfluidic devices and different rock types. Furthermore, we apply fully three-dimensional simulations to evaluate the influence of the thickness of thin porous plates on the overall flow resistance, which is typically relevant in microfluidic devices. In a combined numerical–experimental study, we compare results from representative microfluidic experiments and simulations and confirmed the choice of ϵ to correctly predict the flow transition across the porous interface.

Keywords Porous media · Fractures · TPM · Phase-field method · Diffuse interface · Microfluidics · Coupled flow

1 Introduction

The understanding of coupled flow processes occurring in the transition zone between free flow and porous-media flow is of crucial importance in many engineering fields, ranging from geo- and bio-mechanical applications to engineered technical systems, such as geothermal energy plants, vascular tissues or fuel cells.

In general, a fractured porous material can be divided into an intact and a naturally or artificially fractured region, cf. Fig. 1 (left). In these two domains, typical characteristic flow phenomena occur. To describe these flow phenomena, various modelling approaches in different length scales exist. For example, the flow behaviour in an intact porous material can be described macroscopically using the famous Darcy’s law [9], which assumes, among others, creeping-flow conditions with negligible accelerations. For higher fluid velocities, the Forchheimer equation [18] provides an extension of Darcy’s law including a quadratic velocity term which considers a pressure loss due to high velocities and, furthermore, an additional parameter accounting for the tortuosity

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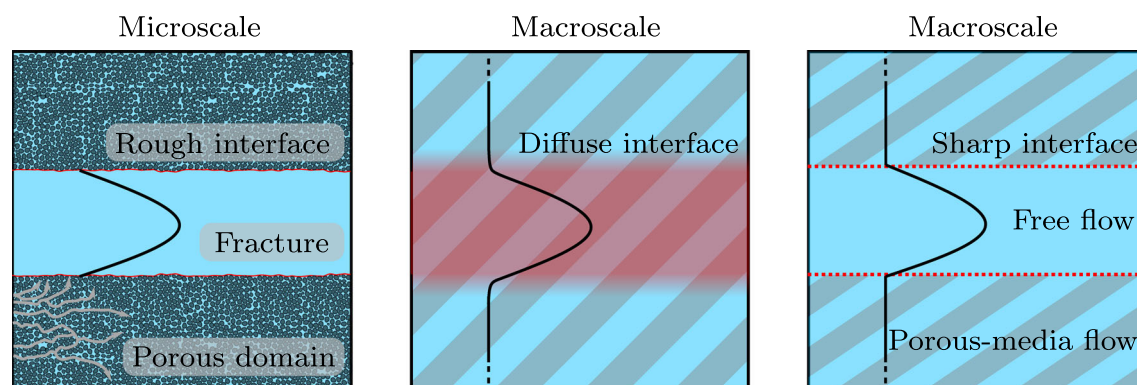


Fig. 1 Modelling approaches for coupled flow phenomena. From left to right: fully resolved porous domain with fracture, single-domain approach on the macroscale including a phase-field for the diffuse fracture description, and a classic two-domain approach with a sharp interface coupling between free flow and porous-media flow

of the microscopic pore-network architecture, cf. [2]. For a detailed overview on the macroscopic, continuum-mechanical description of flow in intact porous media, the interested reader is further referred to the works of Coussy [8], Helmig [24] and Ehlers [12].

In a fractured porous material, one can further distinguish between an open and a closed fracture, cf. [14]. In this regard, flow in a closed fracture can still be described by means of a porous-media flow, whereas in an open fracture, free fluid-flow conditions are given. In classical fluid mechanics, the free flow of a fluid through a channel or a pipe is described by the continuum-mechanical Navier–Stokes equation, comprehensively discussed in textbooks such as the ones of von Böckh and Saumweber [5] or Sigloch [38]. In the case of creeping flow (Reynolds number $Re < 1$), the inertial forces are small compared to the viscous forces and can therefore be neglected. The resulting Stokes equation is one example of possible simplifications which are often used for simulations of connected pore networks, cf. [28]. Therein, the geometrically resolved porous domain (macroscale) depends on the underlying physical behaviour of the fluid on the pore scale (microscale) and includes a scale linking. As an overview, a comprehensive summary of methods for describing flow in fractured porous media is provided by Berre et al. [4].

To study flow phenomena on the pore scale, one can either use experiments, e.g. microfluidic experiments as described in Karadimitriou et al. [27] in combination with particle image velocimetry (PIV) measurements, cf. [43], or pore-scale models which describe the pore-resolved flow processes. The gained information can then be taken to verify assumptions or estimate material parameters for the macroscopic approaches, cf. [45]. Proceeding to the modelling of the transition between two flow regimes, specific model-dependent challenges regarding their meaningful coupling arise. In this regard, there exist so-called single-domain or two-domain approaches, cf. Fig. 1. A single-domain approach solves a single set of coupled equations for the complete domain with either continuous, cf. [20,44], or discontinuous variation of physical properties, cf. [39,40], such as the hydraulic conductivity or porosity. To name an example, the standard Darcy–Brinkman equation, cf. [6], results in either a Stokes-type flow for high hydraulic conductivities or a Darcy-type flow for low hydraulic conductivities. In contrast, a two-domain approach couples two different flow types such as Stokes flow and Darcy flow at a sharp interface via suitable coupling conditions. Typically, these are based on the conservation of mass and momentum, as proposed in the fundamental works of Beaver and Joseph [3] and Saffman [37] and more recent contributions, e.g., Rybak et al. [36] or Strohbeck et al. [42]. However, the above-mentioned two-domain approaches encounter difficulties in modelling the transition zone between the two flow regimes since a physically feasible choice for the individual model parameters, the location of the interface and fitting coupling conditions need to be considered.

To avoid these difficulties, the Theory of Porous Media (TPM) with an embedded phase-field approach to fracture has been proven useful in describing coupled fluid-flow phenomena over diffuse interfaces and therefore provides an elegant single-domain approach. In this contribution, we mainly refer to the works of Ehlers and Luo [13,14] and related works of Kuhn et al. [30], Miehe et al. [32] and Heider et al. [23]. Apart from the convenient properties of the model, this choice is also based on the fact that the group around Wolfgang Ehlers has a long history and experience in this area and made a number of significant contributions in recent years, cf. [15,41,46,47]. A key feature of the TPM-phase-field approach is that the momentum equation of the liquid is able to switch between a Darcy-type or a Navier–Stokes-type equation depending on the local fracturing

state of the solid that is governed by the single scalar phase-field variable ϕ^S . Moreover, the transition length from fractured to unfractured material is governed by the length-scale parameter ϵ . In this diffuse interface approach, one heads towards the rather theoretical (mathematical) sharp interface approach for ϵ towards zero. However, it is physically reasonable to use a certain diffuseness of the interface, in particular for applications. Since no specific attention has yet been paid to study ϵ with regard to coupled flow regimes, this is one main focus in this contribution. Using a combined numerical and experimental investigation, we will present reliable theoretical assumptions and confirm them with tailor-made microfluidic experiments.

In particular, the manuscript is structured as follows. In Sect. 2, the modelling and simulation approach is presented. For this, the considered TPM-phase-field model of Ehlers and Luo [13] is briefly introduced and theoretically discussed in Sect. 2.1 with special attention paid to the fluid behaviour relevant for the focussed research questions. In this regard, the estimation of the length-scale parameter ϵ for specific fracture surface topologies is discussed in Sect. 2.2. In Sect. 3, the setup of a general numerical study of a thin porous plate containing a straight rectangular channel is introduced and the numerical results are discussed. Therein, we study in Sect. 3.2 the coupled fluid-flow behaviour arising at the porous interface for two different boundary conditions and a wide range of hydraulic conductivities relevant for various sub-surface geo-engineering issues. Furthermore, we show in Sect. 3.3 that the TPM-phase-field model is even able to capture very detailed effects, such as the widely known “velocity profile inversion”. In contrast to Recı et al. [35] and Hausteın and Kashi [21] discussing flow within impermeable boundaries, we were here able, for the first time, to discuss the phenomenon for a free-flow channel with porous boundaries (interfaces). Moreover, in Sect. 3.4 the influence of the thickness of thin fractured porous media on the flow resistance is evaluated and the importance of fully three-dimensional simulations is revealed. This preparatory numerical study motivated the challenging fabrication of microfluidic samples with a reasonable thickness for tailored microfluidic experiments for validation purposes. In addition, the role of solid deformations is evaluated for the conducted microfluidic experiments. In Sect. 4, the results of the combined numerical–experimental study are presented. This includes the specific production of appropriate microfluidic chips and the customised experimental setup in Sects. 4.1 and 4.2, respectively. On this basis, the estimation of hydraulic conductivities and local velocity fields using pressure measurements and PIV is described in detail. Subsequently, the experimental data and the determination of material parameters for the related numerical simulation of the microfluidic chips are shown in Sect. 4.3. Overall, we were able to verify our choice of the length-scale parameter ϵ and at the same time showed the predictive capabilities of the TPM-phase-field model. Finally, this manuscript concludes in Sect. 5 with a detailed discussion of the findings.

2 Modelling and simulation approach

2.1 Biphasic TPM model for fractured porous media

In this section, the well-established biphasic porous-media model with an embedded phase field to describe diffuse fractures is briefly summarised with a specific focus on the issues of coupled fluid-flow phenomena. For a more comprehensive insight in the phase-field-based modelling approach, the interested reader is referred to the fundamental works of Ehlers and Luo [13, 14] or Heider and Markert [22].

2.1.1 Basic model setup

The considered biphasic model is based on the works of Ehlers and Luo [13, 14], where a linear–elastic porous solid skeleton φ^S is considered fully saturated with a single incompressible viscous liquid φ^L . The TPM provides a macroscopic description of this biphasic aggregate via

$$\varphi = \bigcup_{\alpha} \varphi^{\alpha} = \varphi^S \cup \varphi^L \quad \text{with } \alpha = \{S, L\} \quad (1)$$

as superimposed and mutually interacting continua with individual motion functions, cf., e.g., [11] for a comprehensive overview on the TPM. In terms of the underlying volume averaging, the so-called representative elementary volume (REV) acts as a control volume which captures a large enough space of the porous domain, allowing for a meaningful local averaging process for the constituent’s properties. To quantify the amount of each constituent on the local volume element dv , the concept of volume fractions is introduced as

$$n^{\alpha} := \frac{dv^{\alpha}}{dv}, \quad \text{such that } n^S + n^L = 1. \quad (2)$$

Therein, dv^α is the local volume element of a constituent φ^α , while (2)₂ is known as the saturation condition. Strongly connected, the partial density ρ^α and the real density $\rho^{\alpha R}$ of the constituents are found by comparing the local mass element dm^α to either the partial volume element dv^α or the (total) volume element dv , yielding

$$\rho^{\alpha R} = \frac{dm^\alpha}{dv^\alpha} \quad \text{and} \quad \rho^\alpha = \frac{dm^\alpha}{dv} \quad \longrightarrow \quad \rho^\alpha = n^\alpha \rho^{\alpha R}. \quad (3)$$

Within the TPM, the motion of the porous solid skeleton is described in a Lagrangean setting via the deformation vector $\mathbf{u}_S$ as the basic variable for the solid velocity $\mathbf{v}_S$, the solid deformation gradient $\mathbf{F}_S$ and the linearised solid strain tensor $\boldsymbol{\epsilon}_S$. Describing a biphasic material, the solid skeleton contains the pore liquid in a hierarchical manner, meaning that the liquid is percolating through a deforming porous solid acting as its reference system. This leads to a modified Eulerian description of the liquid using the seepage velocity $\mathbf{w}_L$ relating the absolute liquid velocity $\mathbf{v}_L$ to the velocity $\mathbf{v}_S$ of the deforming solid skeleton. The underlying individual motion or placement function χ_α of a material point of the studied biphasic aggregate describes the current position $\mathbf{x}$ at time t with respect to the individual reference position $\mathbf{X}_\alpha$ at the initial time t_0 . This leads to the following basic kinematical description of the constituents, viz.:

$$\mathbf{x} = \chi_\alpha(\mathbf{X}_\alpha, t) \rightarrow \begin{cases} \mathbf{u}_S = \mathbf{x} - \mathbf{X}_S, & \mathbf{v}_S = \dot{\mathbf{x}}_S = (\mathbf{u}_S)'_S = (\chi_S)'_S, \\ \mathbf{F}_S = \frac{\partial \mathbf{x}}{\partial \mathbf{X}_S} = \text{Grad}_S \mathbf{x}, \\ \boldsymbol{\epsilon}_S = \frac{1}{2} (\text{Grad}_S \mathbf{u}_S + \text{Grad}_S^T \mathbf{u}_S), \\ \mathbf{v}_L = (\chi_L)'_L, & \mathbf{w}_L = \mathbf{v}_L - \mathbf{v}_S, \\ \mathbf{D}_L = \frac{1}{2} (\text{grad} \mathbf{v}_L + \text{grad}^T \mathbf{v}_L). \end{cases} \quad (4)$$

Herein, $(\cdot)'_\alpha$ denotes the material time derivative with respect to the motion of the constituent φ^α , while $\partial(\cdot)/\partial \mathbf{X}_S = \text{Grad}_S(\cdot)$ and $\partial(\cdot)/\partial \mathbf{x} = \text{grad}(\cdot)$ are the gradient operators related to the referential and the current configuration. $\mathbf{D}_L$ is the rate of deformation tensor of the liquid.

2.1.2 Phase-field description of diffuse fractures

The phase-field approach applied to fracturing porous materials originates from an energetic formulation depending on the so-called phase-field variable ϕ^S that describes the state of the solid, cf., e.g., the articles of Miehe et al. [32], Kuhn and Müller [30] or Ehlers and Luo [13, 14] and citations therein. In particular, the state of the solid is between intact ($\phi^S = 0$) and fully fractured ($\phi^S = 1$), which leads to the value range of the phase-field variable, viz.:

$$0 \leq \phi^S \leq 1. \quad (5)$$

In order to accurately describe propagating fractures, an evolution equation of the phase-field variable ϕ^S was proposed by Miehe et al. [33] that contains the history $\mathcal{H} = \max\{W^{S+}\}$ of the positive part W^{S+} (tensile energy) of the solid strain energy W^S . This evolution equation is of Ginzburg–Landau type reading

$$(\phi^S)'_S = \frac{1}{M} \left[2(1 - \phi^S)\mathcal{H} - \frac{G_c}{\epsilon} (\phi^S - \epsilon^2 \text{div grad} \phi^S) \right]. \quad (6)$$

Therein, $\text{div}(\cdot)$ is the divergence operator corresponding to $\text{grad}(\cdot)$, while G_c describes the fracture toughness of the porous solid per unit fractured area, $M > 0$ is the mobility parameter, and ϵ a length-scale parameter governing the fracture diffusivity. The evolution equation (6) can be reduced to the ordinary differential equation

$$0 = \phi^S - \epsilon^2 \text{div grad} \phi^S, \quad (7)$$

by following the argumentation of Miehe et al. [32] and Kuhn and Müller [30] assuming $\mathcal{H} = 0$ and $(\phi^S)'_S = 0$. Therefore, the transition from a fully fractured to an intact state can be displayed via

$$\phi^S = \exp(-|x|/\epsilon), \quad (8)$$

which is a non-trivial solution of (7). The above equation describes the diffuse fracture topology. In Fig. 2, the width w_r characterises the transition between $\phi^S = 1$ and $\phi^S \approx 0$. This transition width is regulated by the length-scale parameter ϵ . Furthermore, following the idea of a fully open static fracture existing throughout

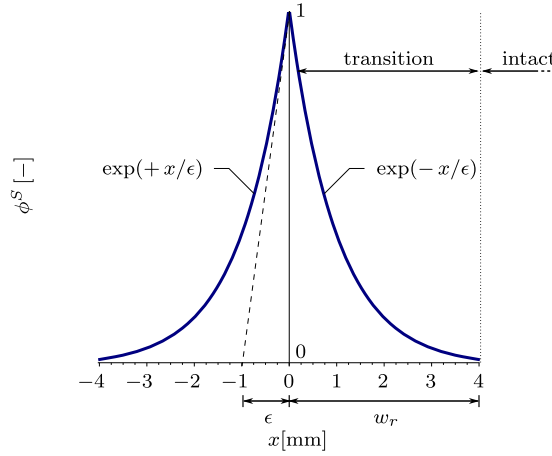


Fig. 2 Schematic one-dimensional sketch of the phase field in the context of a diffuse fracture approach for an exemplary length-scale parameter of $\epsilon = 1$ mm

the whole investigated process, the phase-field variable has to be constant in space and time in the fractured domain. As a result, $(\phi^S)'_S$ and $\text{div grad } \phi^S$ vanish, and the evolution equation (6) can be solved for $\mathcal{H} = \mathcal{H}_0$ yielding

$$\mathcal{H}_0 = \frac{G_c \phi^S}{2\epsilon(1 - \phi^S)}, \quad (9)$$

cf. [41]. Since $\mathcal{H}_0$ would aim for an infinite value in the limiting case $\phi^S \rightarrow 1$, a value of ϕ^S very close to one is typically chosen. Additionally, it is important to note that for a static, non-evolving fracture the mobility parameter M has no contribution to the physical behaviour. At the same time, this also applies to the fracture toughness G_c which, apart from setting an appropriate $\mathcal{H}_0$, does not further contribute to the problem.

2.1.3 Balance equations

For standard Cauchy continua in an isothermal setting, we consider material incompressibility through $\rho^{\alpha R} = \text{const.}$ and exclude mass-exchange processes between both constituents, solid and pore liquid, such that the following volume and momentum balance equations are obtained [11]:

$$\begin{aligned} (\rho^\alpha)'_\alpha + \rho^\alpha \text{div } \dot{\mathbf{x}}_\alpha &= 0 \quad \longrightarrow \quad (n^\alpha)'_\alpha + n^\alpha \text{div } \dot{\mathbf{x}}_\alpha = 0, \\ \rho^\alpha \ddot{\mathbf{x}}_\alpha &= \text{div } \mathbf{T}^\alpha + \rho^\alpha \mathbf{g} + \hat{\mathbf{p}}^\alpha \quad \text{with } \sum_\alpha \hat{\mathbf{p}}^\alpha = \mathbf{0}. \end{aligned} \quad (10)$$

In (10)₂, $\mathbf{T}^\alpha$ is the symmetric partial Cauchy stress, $\hat{\mathbf{p}}^\alpha$ defines the direct momentum production or the local interaction force, respectively, while $\mathbf{g}$ is the gravitation vector.

2.1.4 Constitutive setting

Basic considerations: By use of thermodynamic restrictions and a rigorous modelling approach for TPM formulations as was shown in Ehlers and Luo [13, 14], the entropy inequality, or more precisely, the Clausius–Planck inequality for isothermal processes yields

$$\sum_\alpha \left[\mathbf{T}^\alpha \cdot \mathbf{D}_\alpha - \rho^\alpha (\psi^\alpha)'_\alpha - \hat{\mathbf{p}}^\alpha \cdot \dot{\mathbf{x}}_\alpha \right] \geq 0. \quad (11)$$

This inequality, where ψ^α defines the mass-specific Helmholtz energy, acts as the basis for the exploitation of thermodynamic restrictions for all necessary constitutive equations. In the framework of fully or partially saturated fracturing porous media, compare Ehlers and Luo [13, 14] and Sonntag et al. [41], the following results are valid for the problem under study:

$$\mathbf{T}^\alpha = -n^\alpha p \mathbf{I} + \mathbf{T}_E^\alpha, \quad \hat{\mathbf{p}}^L = p \text{grad } n^L + \hat{\mathbf{p}}_E^L. \quad (12)$$

Therein, p is the pore pressure acting everywhere in the porous medium, while $\mathbf{T}_E^\alpha$ and $\hat{\mathbf{p}}_E^\alpha$ are the extra terms of stresses and momentum productions acting in the particular partial bodies, solid and pore liquid. Thereby, $\mathbf{T}_E^S$ defines the solid extra or effective stress governed by the solid deformation through $\boldsymbol{\varepsilon}_S$, while $\mathbf{T}_E^L$ characterises the liquid extra or frictional stress depending on the liquid deformation velocity $\mathbf{D}_L$. Furthermore, $\hat{\mathbf{p}}_E^L$ is the extra term of the direct momentum production governed by the seepage velocity $\mathbf{w}_L = \mathbf{v}_L - \mathbf{v}_S$.

Elastic solid with fracture: For fractured porous media with small deformations, the effective solid stress reads

$$\begin{aligned} \mathbf{T}_E^S = & [(1 - \phi^S)^2 + \eta_r^S] \left[2\mu^S \boldsymbol{\varepsilon}_S^+ + \lambda^S \left(\frac{\text{tr} \boldsymbol{\varepsilon}_S + |\text{tr} \boldsymbol{\varepsilon}_S|}{2} \right) \mathbf{I} \right] \\ & + 2\mu^S \boldsymbol{\varepsilon}_S^- + \lambda^S \left(\frac{\text{tr} \boldsymbol{\varepsilon}_S - |\text{tr} \boldsymbol{\varepsilon}_S|}{2} \right) \mathbf{I}. \end{aligned} \quad (13)$$

Therein, $\boldsymbol{\varepsilon}_S^+$ and $\boldsymbol{\varepsilon}_S^-$ are the tensile and compressive eigentensors of $\boldsymbol{\varepsilon}_S$ yielding

$$\boldsymbol{\varepsilon}_S^+ = \sum_i \frac{\lambda_{Si} + |\lambda_{Si}|}{2} \mathbf{n}_{Si} \otimes \mathbf{n}_{Si}, \quad \boldsymbol{\varepsilon}_S^- = \sum_i \frac{\lambda_{Si} - |\lambda_{Si}|}{2} \mathbf{n}_{Si} \otimes \mathbf{n}_{Si} \quad (14)$$

with eigenvalues λ_{Si} and eigendirections $\mathbf{n}_{Si}$, while μ^S and λ^S are the partial Lamé constants. Furthermore, as the tensile part of $\mathbf{T}_E^S$ might vanish for $\phi^S = 1$, a residual stiffness η_r^S has been included to prevent the numerical scheme from collapsing.

Viscous pore fluid: In addition to the above, the frictional liquid stress and the extra momentum production are

$$\mathbf{T}_E^L = 2(\phi^S)^2 n^L \mu^{LR} \mathbf{D}_L, \quad \hat{\mathbf{p}}_E^L = -(1 - \phi^S)^2 \frac{(n^L)^2 \gamma^{LR}}{k^L} \mathbf{w}_L. \quad (15)$$

In these equations, μ^{LR} is the effective dynamic viscosity of the liquid, $\gamma^{LR} = \rho^{LR} |\mathbf{g}|$ is its specific weight, and k^L is the hydraulic conductivity. Apart from the liquid deformation velocity and the seepage velocity, the above equations also depend on ϕ^S . In case that ϕ^S is zero, we are in the porous-media domain. Here, $\mathbf{T}_E^L$ vanishes and $\hat{\mathbf{p}}_E^L$ is fully dominant, meaning that we find a Darcy-flow regime. In the opposite case, when ϕ^S is one, $\hat{\mathbf{p}}_E^L$ vanishes and $\mathbf{T}_E^L$ takes fully over, such that we are in the Navier–Stokes regime. Thus, we have a switch between a pore-fluid-flow and a free-flow regime. Between these regimes, there is a diffuse transition zone with $0 < \phi^S < 1$, cf. Fig. 2, where both the pore fluid and the free fluid are active. To illustrate the above argumentation, one looks at the momentum balance of the pore fluid in a quasi-static case under creeping-flow conditions, and thus, with neglected inertia terms yielding

$$\mathbf{0} = \text{div} \left[2(\phi^S)^2 n^L \mu^{LR} \mathbf{D}_L \right] - n^L \text{grad } p + \rho^L \mathbf{g} - (1 - \phi^S)^2 \frac{(n^L)^2 \gamma^{LR}}{k^L} \mathbf{w}_L. \quad (16)$$

This equation describes the fluid flow in the transition zone and takes a reduced shape in the fractured zone with $\phi^S = 1$ and in the porous-media domain with $\phi^S = 0$:

$$\begin{aligned} \phi^S = 1 : \quad \mathbf{0} &= \text{div} \left[2n^L \mu^{LR} \mathbf{D}_L \right] - n^L \text{grad } p + \rho^L \mathbf{g}, \\ \phi^S = 0 : \quad \mathbf{0} &= -n^L \text{grad } p + \rho^L \mathbf{g} - \frac{(n^L)^2 \gamma^{LR}}{k^L} \mathbf{w}_L. \end{aligned} \quad (17)$$

It is seen that (17)₁ describes the Navier–Stokes equation in the reduced Stokes form, while solving (17)₂ with respect to the filter velocity $n^L \mathbf{w}_L$ yields the Darcy equation:

$$n^L \mathbf{w}_L = -\frac{k^L}{\gamma^{LR}} (\text{grad } p - \rho^{LR} \mathbf{g}). \quad (18)$$

2.1.5 Governing equations and solution procedure

The numerical treatment of porous-media problems with a single pore content is based on the mass and momentum balances of solid and fluid, where, in the case of material incompressibility, the mass balances reduce to volume balances, cf. (10)₁. Generally, one builds weak forms for the sum of the volume and momentum balances and, additionally, for the fluid momentum balance alone. This set of equations allows for solving problems, where inertia forces are integrated and where the fluid can be in the Darcy and/or the Navier–Stokes regime.

Following the above, the present problem, defined by pressing a liquid through a porous domain given by a tiny chip with an embedded open channel numerically described by the constant history variable $\mathcal{H}_0$, can easily be handled by the finite-element (FE) solver PANDAS¹ together with the material description in the version of Ehlers and Luo [13]. For this model, some simplifications are made and will therefore be integrated in the following set of governing weak equations. Firstly, as the chips will not be loaded by external forces or pressures, it is not necessary to use the combined momentum balance of solid and fluid. At this point, it should be noted that porous media generally need the coupling of the solid and fluid momentum balances mentioned before, as only by this procedure, the overall porous medium can decide by itself what portion of the external load is taken by the solid and what portion has to be carried by the pore content, cf. [16]. As this is not the case in the present consideration, where the fluid influx is prescribed while the necessary pressure has to be computed by the numerical scheme, the coupled solid–liquid momentum is reduced to the weak momentum balance of the solid alone. Therein, the inertia terms of the solid are negligible for the problems under consideration. In addition, gravitational forces have been neglected due to the thinness of the computed chips. Moreover, the thin chips are lying horizontally in the microfluidic experiments.

For the numerical solution in PANDAS, the set of primary variables $PV = \{p, \mathbf{v}_S, \mathbf{v}_L, \phi^S\}$ is used. Note that $\mathbf{u}_S$ and $\mathbf{v}_S$ are coupled by $\mathbf{v}_S = (\mathbf{u}_S)'_S$, such that $\mathbf{u}_S$ can internally be found. Corresponding to the primary variables, the test functions in a Bubnov–Galerkin scheme are $\delta PV = \{\delta p, \delta \mathbf{v}_S, \delta \mathbf{v}_L, \delta \phi^S\}$. By this means, the weak formulation of the governing equations is obtained via integration over the spatial domain Ω followed by an additional definition of the necessary boundary integrals $\int_{\partial\Omega} (\cdot) da$ by use of the Gaussian integral theorem, viz.:

$$\begin{aligned}
 \mathcal{G}_p &= \int_{\Omega} \left(\operatorname{div} \mathbf{v}_S \delta p - n^L \mathbf{w}_L \cdot \operatorname{grad} \delta p \right) dv + \int_{\partial\Omega} \underbrace{(n^L \mathbf{w}_L \cdot \mathbf{n})}_{:=\bar{v}} \delta p da = 0, \\
 \mathcal{G}_{\mathbf{v}_S} &= \int_{\Omega} \left(\mathbf{T}_E^S \cdot \operatorname{grad} \delta \mathbf{v}_S + n^S \operatorname{grad} p \cdot \delta \mathbf{v}_S + \hat{\mathbf{p}}_E^L \cdot \delta \mathbf{v}_S \right) dv - \int_{\partial\Omega} \underbrace{\left(\mathbf{T}_E^S \mathbf{n} \right)}_{\bar{\mathbf{t}}_E^S} \cdot \delta \mathbf{v}_S da = 0, \\
 \mathcal{G}_{\mathbf{v}_L} &= \int_{\Omega} \left(\mathbf{T}_E^L \cdot \operatorname{grad} \delta \mathbf{v}_L + n^L \operatorname{grad} p \cdot \delta \mathbf{v}_L - \hat{\mathbf{p}}_E^L \cdot \delta \mathbf{v}_L \right) dv - \int_{\partial\Omega} \underbrace{\left(\mathbf{T}_E^L \mathbf{n} \right)}_{\bar{\mathbf{t}}_E^L} \cdot \delta \mathbf{v}_L da = 0, \\
 \mathcal{G}_{\phi^S} &= \int_{\Omega} \left([M(\phi^S)'_S - 2(1 - \phi^S)\mathcal{H} + \frac{G_c}{\epsilon} \phi^S] \delta \phi^S \right. \\
 &\quad \left. + G_c \epsilon \operatorname{grad} \phi^S \cdot \operatorname{grad} \delta \phi^S \right) dv - \int_{\partial\Omega} G_c \epsilon \underbrace{\operatorname{grad} \phi^S \cdot \mathbf{n}}_{\equiv 0} \delta \phi^S da. \tag{19}
 \end{aligned}$$

In particular, the set of coupled equations consists of the volume balance of solid and fluid multiplied by the test function δp , the quasi-static solid momentum balance multiplied by the test function $\delta \mathbf{v}_S$, the quasi-static fluid momentum balance multiplied by the test function $\delta \mathbf{v}_L$ and the phase-field evolution equation multiplied by $\delta \phi^S$. The boundary term $\bar{v}$ in (19)₁ is later on used to induce flow in the fractured porous material. Furthermore, the present formulation additionally includes the loading boundary terms $\bar{\mathbf{t}}_E^S$ and $\bar{\mathbf{t}}_E^L$ which are, however, not applied in the context of this study. This means that solid deformations are only triggered by the pore-fluid flow. As p is the driving force for the liquid mass $\bar{v}$ of (19)₁, p has not been transferred from the volume integral to the surface integral because then, p would have to be described with exactly that value that is

¹ (Porous media adaptive nonlinear FE solver based on differential algebraic systems, <http://www.get-pandas.com>.)

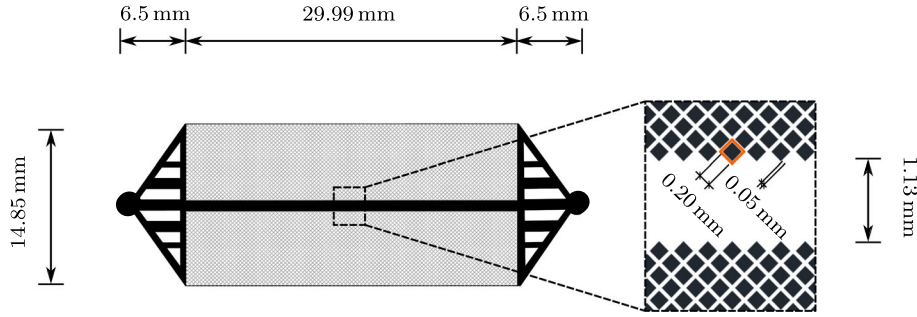


Fig. 3 Design and geometry of the considered microfluidic chip. (Color figure online)

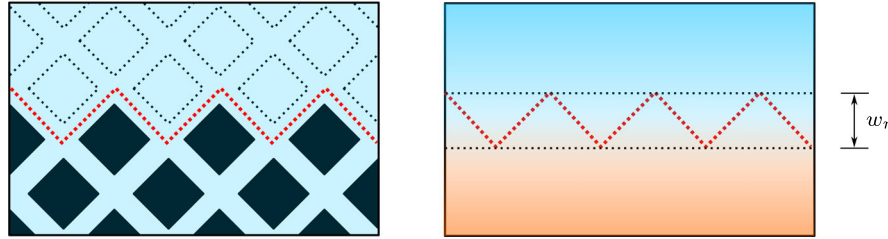


Fig. 4 Fracture approximation for the investigated microfluidic chips. (Color figure online)

necessary to press $\bar{v}$ into the porous medium. This, however, is not possible. Instead, p is obtained by the coupled computation of the whole problem. Furthermore, note in passing that the restriction $\text{grad } \phi^S \cdot \mathbf{n} \equiv 0$ follows from the evaluation of the entropy inequality (11). For the numerical solution, the set of equations is discretised in space using a Taylor–Hood formulation with quadratic approximation functions for $\mathbf{v}_S$ and $\mathbf{v}_L$ and linear approximation functions for p and ϕ^S to fulfil the inf–sup criterion for a stable computation, cf. [19]. Moreover, the time discretisation is realised by an implicit finite-difference scheme (backward Euler), leading to a monolithic solution of the numerical problem.

2.2 Discussion of the length-scale parameter

As stated earlier, the length-scale parameter ϵ is of particular importance in phase-field models. However, there are different ways to interpret and use this parameter. For fractures in single-phasic solid materials, it could be stated that ϵ should be chosen as small as possible to approximate a sharp fracture as tightly as possible. This, however, might not be the case for the fluid-saturated material studied in this contribution, since a transition between a faster flow in the fracture and a slower flow in the surrounding porous material is occurring. The existence of a transition zone is reported in Beaver and Joseph [3] for flow over a fully saturated porous material. In this case, the length-scale parameter needs to be chosen small enough to represent the fracture geometry but on the other hand large enough to capture this transition region. For the spatial discretisation, the mesh size for the FE simulations needs to be in agreement with the chosen transition zone, as was recommended, for example, by Miehe et al. [32]. This set of thoughts gives rise to the general idea to find physically feasible values of ϵ based on the natural properties of the materials or processes in agreement with the chosen discretisation. In the considered case of modelling fractures in a fully saturated solid material, the length-scale parameter ϵ in (8) determines the transition length between two limiting states of the solid body, fully broken and intact. To study the flow interaction between the fully broken and intact region, we will later (Sect. 3.4) use a microfluidic chip which contains a regular porous structure with repeating unit cells, as shown in Fig. 3 (orange square), and a rectangular channel in the middle as a representative replacement model. A real-world analogy would be an open, single fracture in a saturated aquifer. However, for the general discussion we stay in the frame of the simple (academic) example of the microfluidic device in Fig. 3. Here, we assume that the channel walls represent rough fracture surfaces, where an expected fracture path can be anticipated on the repeating unit-cell boundaries, as shown in Fig. 4 in red.

Hence, inspired by Chabaan et al. [7], the length-scale parameter needs to be selected such that the transition zone’s width corresponds to a relative width w_r between local minima and maxima (amplitude) of the red-coloured fracture path, i.e. one half of the unit cell’s diagonal, cf. Fig. 3. In the context of the existing straight

Table 1 Estimated values for ϵ for fractured rock samples based on the experimental investigations presented by Młynarczuk [34]

Rock type	Grain size (μm)	Width w_r (μm)	Estimated ϵ (μm)
Wisniowka sandstone	80–200	70	15
Tumlin sandstone	40–400	148	32
Redziny Dolomite	100–300	120	26
Laskowa Góra dolomite	200–600	101	22
Limestone	30–50	61	13

fracture aligned with the flow direction under steady state conditions, we assume the physical transition region between free flow and porous-media flow to be related to the diffuse transition of the phase field in Eq. (8). To estimate the corresponding length-scale parameter ϵ for this pore structure, Eq. (8) is rearranged as follows

$$\epsilon = -\frac{|x|}{\ln(\phi^S)} = -\frac{w_r}{\ln(\phi^S)} = -\frac{\frac{250 \mu\text{m}}{\sqrt{2}}}{\ln(0.01)} \approx 40 \mu\text{m}. \quad (20)$$

Since we aim for a value of ϵ which leads to a meaningful transition width, matching the experimental observations presented in Sect. 4.3.2, the limit value for the phase-field variable is chosen as $\phi^S = 0.01$, such that the material beyond the transition domain is to 99% in its intact state. The obtained value of $\epsilon \approx 40 \mu\text{m}$ is used for the corresponding numerical simulations of the microfluidic samples later on.

However, the advantage of the proposed approach is that it can also be transferred to fracture surfaces in real porous rocks. In [34], the fracture surface of various rock samples was prepared using the Brazilian fracturing test and subsequently scanned using laser profilometry. The dataset was evaluated by an algorithm determining the relative height between local minima and maxima, which corresponds to the minimum and maximum of the fracture path described above. This allows to calculate values as estimates for the length-scale parameter ϵ for the different rock types analysed in the mentioned article [34], cf. Table 1. For granular materials, such as sandstone, it is apparent that roughly doubling the grain size doubles the relative width, which further implies a dependency between fracture-path amplitude and grain size.

As a remark, this simple approach only considers geometric properties of the microscopic pore structure to describe the transition region. Therefore, the idea can be used for macroscopic fracturing problems, regardless of considering single-phasic or saturated multiphase solid materials. This may avoid an arbitrary choice of the length-scale parameter in many phase-field simulations.

3 General numerical study

3.1 Problem setup for the general study

The general numerical study presented in this section examines the flow behaviour in thin porous plates (chips) under different flow boundary conditions. These conditions of the initial-boundary-value problem (IBVP) are motivated by the potential application of modelling microfluidic chips or similar technical devices with relatively low flow velocities, cf. Sect. 4. In Fig. 5, a top view of the geometry with corresponding boundary conditions is sketched. In particular, the plate has a rectangular base area of depth $d = 200 \mu\text{m}$ in the $\mathbf{e}_3$ -direction perpendicular to the top view. In the centre of the plate, there is a channel [$l/w_f/d = 40/1/0.2(\text{mm})$] running through the chip in $\mathbf{e}_1$ -direction from one side to the other for the complete depth d as a fully open fracture modelled by use of the phase-field approach via the assignment of $\mathcal{H}_0$ calculated from (9). The value for $\mathcal{H}_0$ is set in the geometric domain of the channel as an initial condition in the sense of a material parameter. In the subsequent monolithic calculation, the value for $\phi^S \approx 1$ is then obtained from the system in the first computation step. Thereafter, the evolution equation of the phase field remains a part of the coupled system of equations (19), but does no longer provide any contributions since a stationary fracture state in the channel is present. This channel has two opposing porous boundaries (interfaces) that allow for liquid mass exchange between the coupled flow regimes. At the top and bottom of the porous plate, a no-slip (Dirichlet) boundary condition $\mathbf{v}_L = \mathbf{0}$ is applied, whereas the boundaries perpendicular to $\mathbf{e}_2$ are featuring slip. The solid skeleton of the porous plate is considered sufficiently rigid and supported to endure the forces imposed by the liquid-flux boundary conditions on the left edge. Furthermore, the pore pressure p , here taken as the excess pore pressure, is set to zero along the entire right edge. The plate is exposed to a flux $Q_i = \bar{v} A_i$ from the left edge, either

Table 3 Fluxes across the entire interface between the porous domain and the channel for different hydraulic conductivities, evaluated at the upper porous interface marked as dotted, red line in Fig. 5

k^L (m/s)	Case I	Case II
	Q (ml/min)	Q (ml/min)
10^{-6}	-0.0822	0.0006
10^{-5}	-0.0473	0.0014
10^{-4}	-0.0417	0.0036
10^{-3}	-0.0301	0.0155

In particular, the focus is here on the interaction between the porous region and the free-flow channel. Fig. 6 shows the streamlines for both cases using a hydraulic conductivity of $k^L = 10^{-4}$ m/s. It is apparent that in Case I the liquid percolates from the porous domain towards the channel, leading to high velocities around point A. In contrast, the liquid is pushed from the channel into the surrounding porous material in Case II. Note that the in- or outflow of the channel is evaluated at the upper porous interface marked as a dotted red line in Fig. 5.

In the following, the results of Case I are discussed. While studying the effects of different hydraulic conductivity values, it was found for lower values that the vertical velocity components near the inlet were higher than for larger values. Figure 7 (left) shows the vertical velocity over the diffuse interface plotted over the length of the model. Furthermore, considering the general flow development in the channel, Fig. 8 shows the axial velocity in the centre, plotted over the length of the model. As is seen from Fig. 7 (left), the porous material feeds the channel until an equilibrium between the domains is reached and thus, the velocities stay constant until the influence of the right boundary takes over. Moreover, higher axial velocities are observed for lower hydraulic conductivities, which makes sense since the liquid's mass is conserved. Generally, the liquid's cross-flow behaviour to reach an equilibrium between the domains strongly depends on the hydraulic conductivity. For larger values, the liquid is able to percolate in the basic direction of flow, whereas lower values lead to a distinct flux towards the channel, in particular in the vicinity of the inlet region. This finding coincides with a certain "well-effect" observed from the global velocity profile near the inlet, cf. the blue line in Fig. 6 (top), which vanishes further downstream. In contrast to Case I, the flux for Case II is exclusively applied to the channel's left boundary which mimics channel flow within porous boundaries. As already implied, liquid from the channel drains to the porous material depending on the hydraulic conductivity until an equilibrium state is reached, cf. Fig. 8 (right). For low values, nearly no interaction between the domains is observed whereas increasing the value leads to a significant liquid flow across the two domains. This is additionally reflected in Fig. 7 (right). Studying the global velocity profile close to the inlet does not show a significant effect at the diffuse transition region for the displayed hydraulic conductivity. However, the large vertical flux for larger values of hydraulic conductivity displayed in Fig. 7 indicates that, close to the inlet, more liquid cross flow is present in the permeable transition zone between the domains. To quantify the occurring mass exchange over the permeable interface, the velocities are integrated over the entire length of the upper porous interface marked as a dotted, red line in Fig. 5. The resulting fluxes are given in Table 3 for four different hydraulic conductivities. It is observed that for Case II, and especially for low hydraulic conductivities, the interaction between both domains is small enough to argue that there is mainly flow occurring in the channel. These findings can be very useful for the determination of, for example, initial pumping rates for the planning of injection–production systems such as geothermal energy plants.

3.3 Velocity profile inversion phenomena

Looking at the local flow behaviour in the channel, interesting effects are observed in the entrance region concerning the development of the liquid velocity profile. The entrance region is defined as the region where the effects are observed, whereas the development region is referred to as the length required for the flow to fully develop, in this study at approximately $x_1 > 20$ mm, cf. Fig. 6. During the investigation of the developing velocity profiles along the length of the model, it has been found that over a certain entrance length from the inlet, off-centre velocity peaks develop near the porous interfaces. The velocity peaks converge towards the centre line of the channel as the flow develops, cf. Fig. 9. Such velocity peaks were observed experimentally by Reci et al. [35] and given the name velocity profile inversion. The reason of this inversion phenomenon is

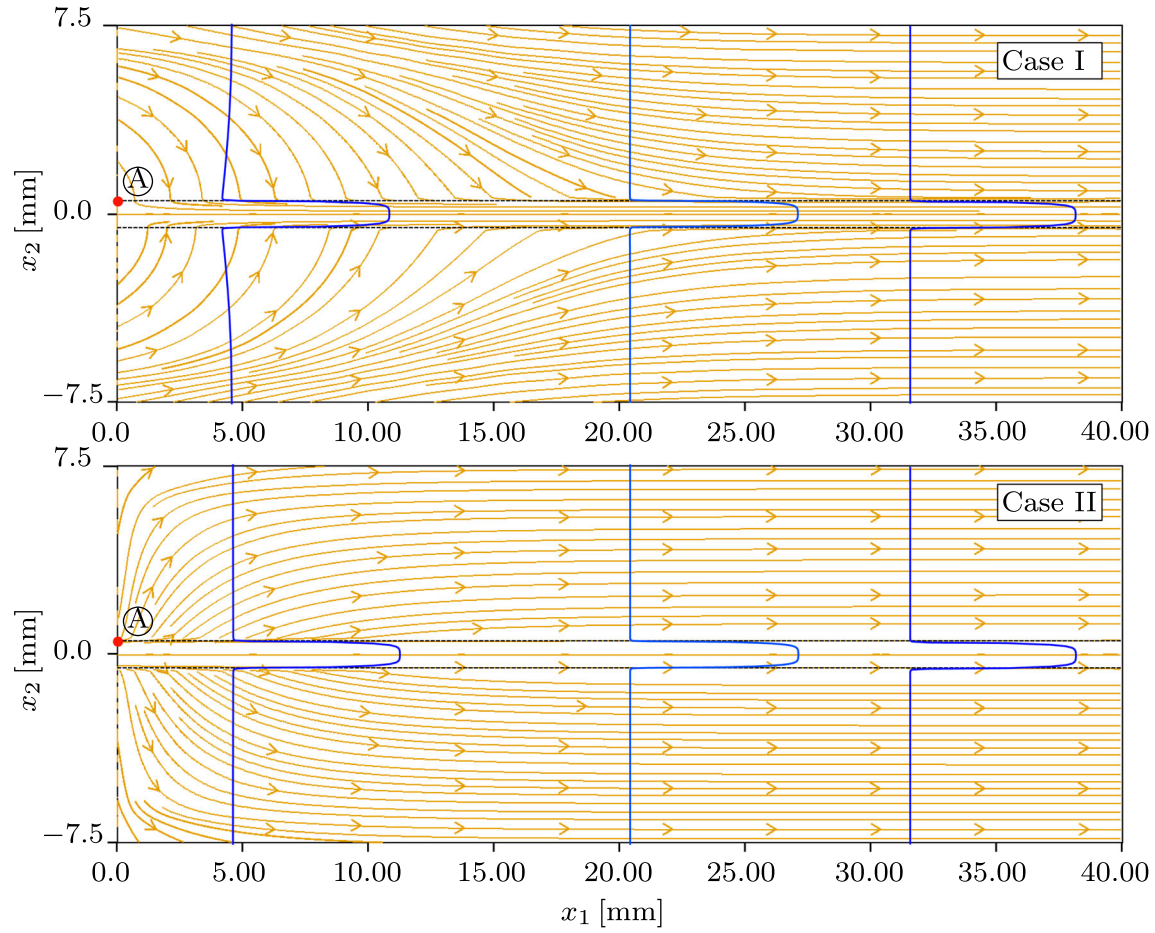


Fig. 6 Streamlines for Case I (top) and Case II (bottom) with global velocity profiles at distinct locations. (Color figure online)

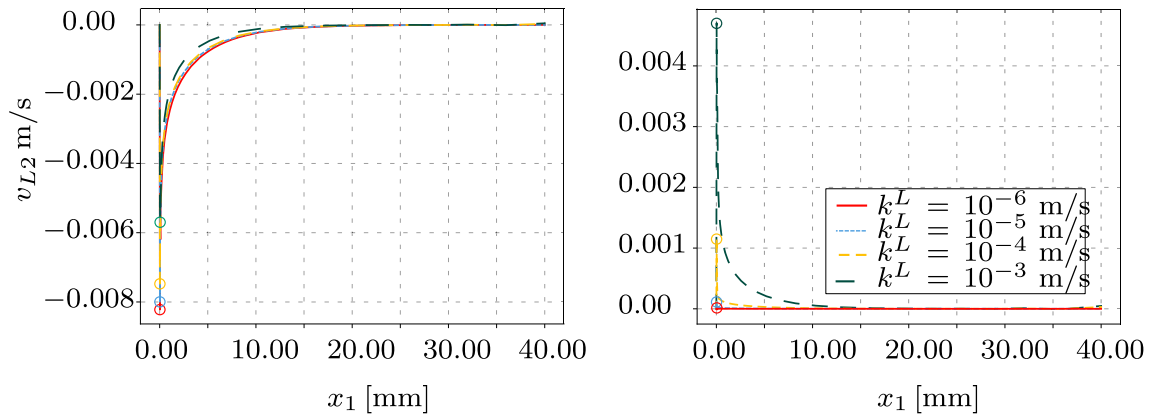


Fig. 7 Vertical velocity component over the porous interface over the length of the domain for Case I (left) and Case II (right)

thoroughly discussed for different inlet conditions and varying fluxes in pipe flow, cf. [21]. It has been shown that not only the inlet geometry has a huge impact on the inversion but also effects due to a vertical flow in the development region. As long as vertical velocities are included in the modelling approach, their presence is intuitively explained by mass conservation, included in the liquid mass balance for regimes with constant porosity n^L :

$$\operatorname{div} \mathbf{v}_L = \frac{\partial v_1}{\partial x_1} + \frac{\partial v_2}{\partial x_2} + \frac{\partial v_3}{\partial x_3} = 0. \quad (21)$$

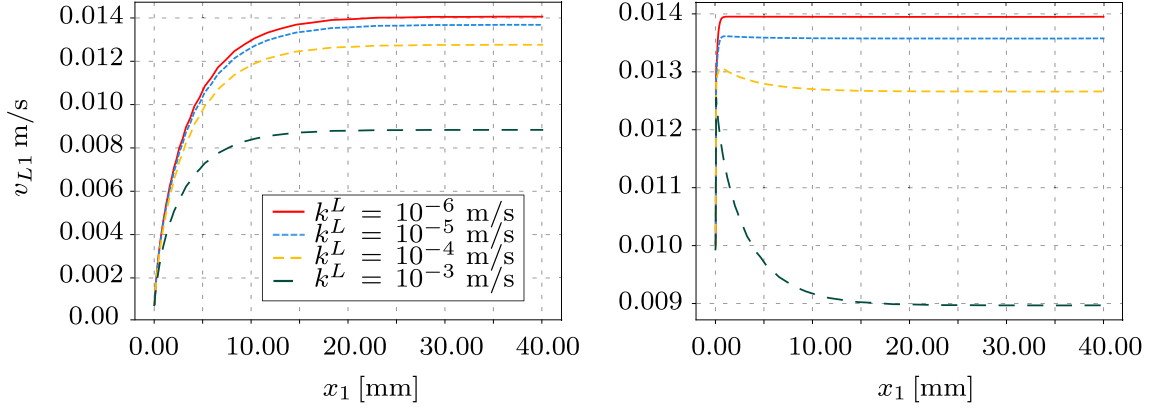


Fig. 8 Centre-line velocity along the x_1 -axis in the channel over the length of the sample for Case I (left) and Case II (right)

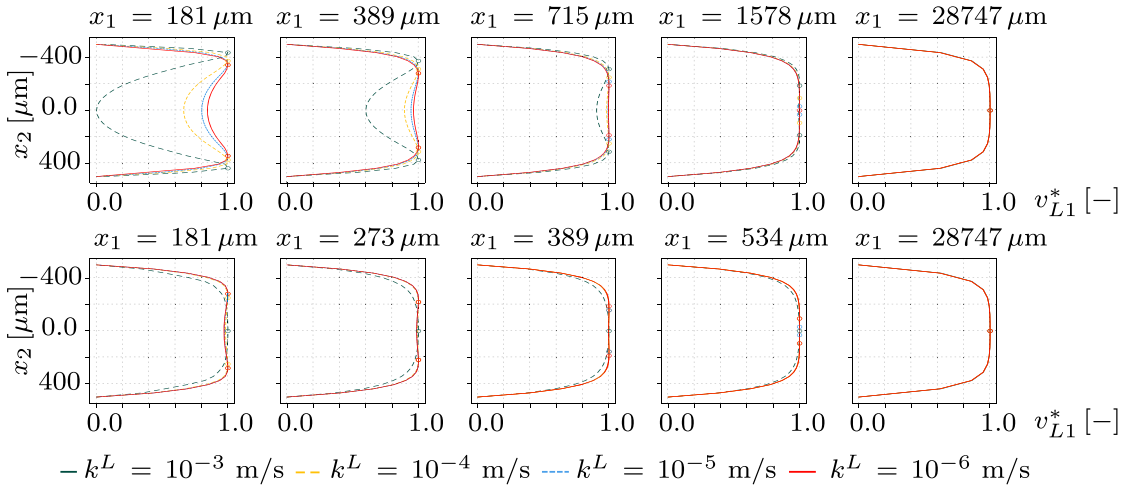


Fig. 9 Development of the normalised velocity v_{L1}^* showing the inversion phenomena for Case I (upper row) and Case II (lower row) along the channel width for different hydraulic conductivities

In the development region, the spatial change of the axial velocity $\partial v_1 / \partial x_1$ is not equal to zero which, as a result of spreading liquid into the porous domain, must lead to nonzero values for the vertical velocity components. Additionally, geometrical effects, such as sharp narrowing of a channel, lead to higher velocities at the channel walls close to the inlet. In line with those findings, the same observations were made by Lobo and Chatterjee [31] considering rectangular channels with a narrowing inlet plenum.

In this contribution, a specific focus is placed on the influence of flux inwards or outwards of the channel. Obviously, the permeable porous interfaces (boundaries) have a considerable effect on the inversion phenomena. Figure 9 shows the normalised velocity profiles $v_{L1}^*(x_2)$ at different cross sections through the channel measured from the inlet at $x_1 = 0$. Note that the shown normalised velocity in the channel only represents a local section of the whole model domain. To make the inversion effect better visible, a min-max normalisation via $v_{L1}^*(x_2) = (v_{L1} - v_{L1\min}) / (v_{L1\max} - v_{L1\min})$ was used. Generally, the velocity peaks appear near the porous channel walls and, in line with the observations in the above-mentioned literature, develop towards the centre of the channel and decrease in magnitude as the flow evolves. Furthermore, it is observed that for Case I, where liquid is sucked into the channel, the velocity overshoots are more pronounced and the profile takes considerably longer to lose the velocity peaks. In contrast to Case II, again referring to Lobo and Chatterjee [31], the abrupt restriction of area available for flow additionally increases the effect, since larger vertical velocities arise at the inlet, cf. Fig. 7. In Fig. 10, the maximum velocity peaks are quantified (as a percentage) for both cases via a comparison to the axial velocity in the considered cross section over the channel via $(v_{1\max} - v_{1\text{centre}}) / v_{1\text{centre}}$. It is observed for both cases that the magnitude of the peaks decrease with an

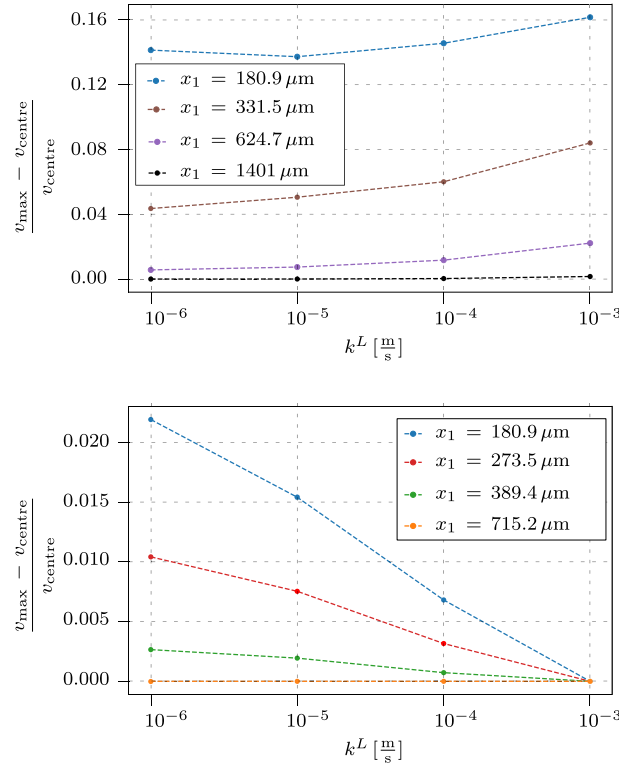


Fig. 10 Velocity overshoots at the porous boundary at different cross sections given for different hydraulic conductivities for Case I (top) and Case II (bottom)

increase in distance from the inlet. However, the overshoots are largest for the largest hydraulic conductivity for Case I, whereas the opposite is observed for Case II. Considering Case I, this outcome is also reflected in the large vertical velocities at the corner point A, referred to in Fig. 6, for small values of hydraulic conductivities. To conclude the outcomes, the fact that the inversion phenomenon is increased for fluxes into the channel and is relaxed for fluxes out of the channel is particularly notable. Furthermore, it is observed that the appearance of the velocity inversion is strongly connected to arising vertical velocities, which in the considered study depend on the applied boundary conditions and hydraulic conductivities of the porous domain.

3.4 Numerical preparatory studies of microfluidic chips

In the preceding general studies, we presented the ability of the TPM-phase-field approach to model complex, coupled flow phenomena. To proceed to a practical application, we present in the following a numerical study of microfluidic chips in an (iterative) numerical–experimental context with the aim to confirm the theoretical ideas discussed in Sect. 2.2 for the flow behaviour over rough porous walls and verify the overall model. In particular, two types of microfluidic chips have been investigated experimentally, uniform porous samples to estimate the base hydraulic conductivity of the porous domain and samples with an embedded rectangular channel, in analogy to Fig. 3, for the study of the interaction between free flow and porous-media flow. The porous domain of both chips has a solid volume fraction of $n^S = 0.61$ and a maximum throat size of the pores of $50 \mu\text{m}$. Furthermore, the chips are produced with an inlet and outlet domain, which is technically necessary to provide an equally distributed flow throughout the porous domain under study. In the numerical model shown in Fig. 11, the in- and outlet domains are macroscopically considered as a porous material with a solid volume fraction of $n_i^S = 0.40$ (geometrically evaluated from the structural composition) and the hydraulic conductivity k_i^L . The hydraulic conductivity of the porous domain in the chip is denoted as k_p^L . In this preparatory study, the hydraulic conductivities for the in- and outlets and the porous domain were chosen to $k_i^L = k_p^L = 1.30 \text{ m/s}$, without relation to the experiments given in Sect. 4.3.1, and independent from the model height d . The remaining material parameters can be extracted from Table 4. The hydraulic boundary conditions

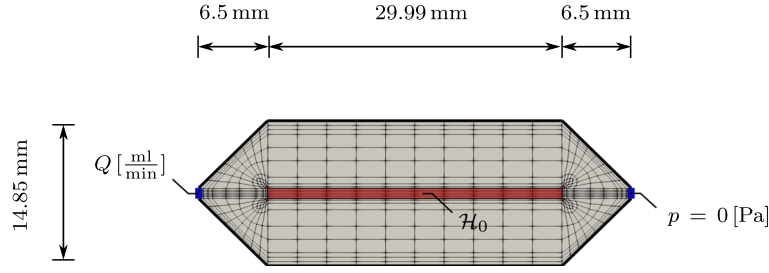


Fig. 11 Corresponding numerical model of a microfluidic chip with embedded fracture (rectangular channel)

Table 4 Material parameters for the microfluidic PDMS chip

$\lambda^S = 3.41 \times 10^8$	(Pa)	1st Lamé parameter of the solid skeleton
$\mu^S = 6.8 \times 10^5$	(Pa)	2nd Lamé parameter of the solid skeleton
$G_c = 0.1$	(Pa m)	Crack resistance
$\epsilon = 40 \times 10^{-6}$	(m)	Length-scale parameter
$\eta_r^S = 1.0 \times 10^{-3}$	(–)	Residual stiffness
$\mu^{LR} = 1.002 \times 10^{-3}$	(Pa s)	Dynamic viscosity of the pore liquid
$\rho^{SR} = 965$	(kg/m ³)	Real density of the solid skeleton
$\rho^{LR} = 1000$	(kg/m ³)	Real density of the pore liquid

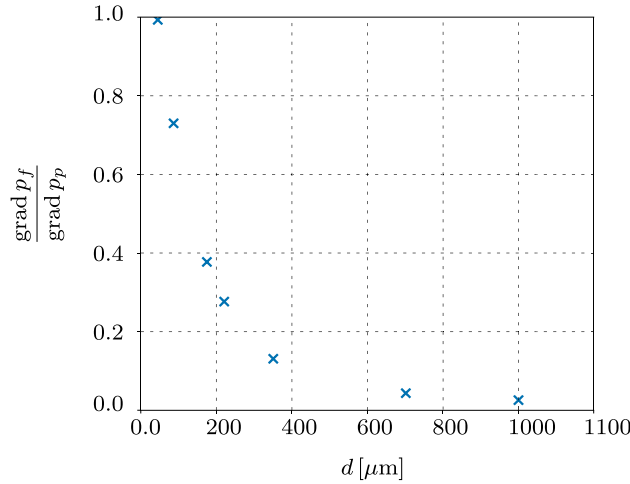


Fig. 12 Numerical results for the comparison of the pressure gradients in microfluidic devices with and without a fracture for different chip depths d

are applied according to Fig. 11 with a flux $Q = \bar{v}A$ on the left edge and a zero (excess) pressure condition at the right edge. To prevent deformations of the outer sides, the chip is supported by zero displacement boundary conditions. Regarding liquid flow, no-slip boundary conditions are applied at all outer surfaces of the sample. The assignment of the fracture via $\mathcal{H}_0$ is conducted as described in Sect. 3.1. Furthermore, to study the basic deformation behaviour of the chips, the Lamé parameters of the solid poly-di-methyl-siloxane (PDMS) body, given in Johnston et al. [25], are used for the sake of simplicity as effective parameters due to the lack of tailored mechanical experiments on the investigated microfluidic chips, see Table 4. The total number of elements for meshing the microfluidic chips is 4336 and as in Sect. 2 similar choices regarding the refinement are made, cf. Fig. 11. By means of the mentioned iterative numerical–experimental approach, a preparatory numerical study is conducted to evaluate the influence of the thickness of the microfluidic chips. In Fig. 12, the results from a numerical study of the ratio of the pressure gradients for fractured ($\text{grad } p_f$) and non-fractured ($\text{grad } p_p$) porous models, respectively, are shown for varying model depths d .

One can see clearly that, as expected for a decreasing thickness, the pressure gradient of the fractured model is getting closer to the pressure gradient of the non-fractured model. This is caused by the circumstance that the thickness is dominating the hydraulic conductivity by the fact that top and bottom of the chip exhibits

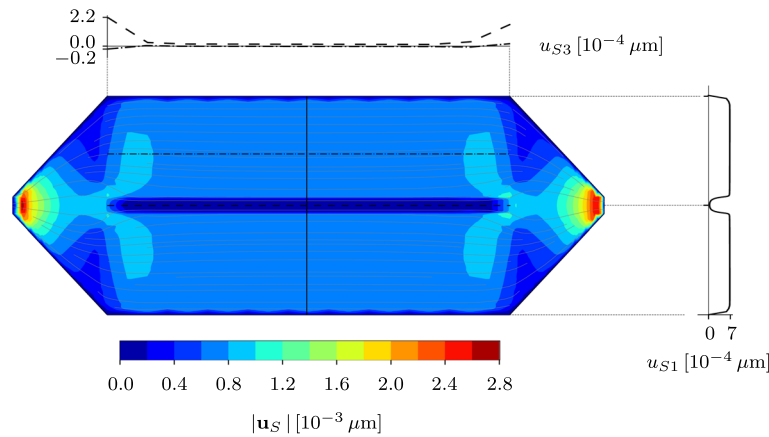


Fig. 13 Displacement field and liquid streamlines within the microfluidic chip

no-slip boundary conditions. As a result of a decreasing chip depth, hydraulic conductivity of the porous domain without fracture shrinks faster than the conductivity of the fractured domain, what naturally affects the mean conductivity of the chips. The influence of the channel (fracture) disappears when the depth of the microfluidic chips (and the depth of the channel) tends towards the throat size of $50\ \mu\text{m}$ in the porous domain, cf. Fig. 12. Moreover, from the ratios presented in Fig. 12, it can be concluded that for a thickness between 200 and $400\ \mu\text{m}$ a pronounced drop in the pressure gradient ratio occurs, while for ratios $> 400\ \mu\text{m}$, the curve flattens and converges to zero. This indicates the need to produce higher microfluidic chips since a standard thickness is around $100\ \mu\text{m}$. In general, it can be concluded that accounting in microfluidic studies for the influence of the model depth while studying the global hydraulic resistance of a microfluidic chip (e.g. for the estimation of hydraulic conductivities) is of great importance. Obviously, this accounts for both, intact and fractured porous samples. Certainly, the ideal way to cope with this is a three-dimensional simulation, which can naturally take into account all boundary influences. However, if computing time or model limitations require a two-dimensional simulation, the three-dimensional effects need to be considered in an adequate manner for a dimensionally reduced formulation, cf., e.g., the works of Flekkøy et al. [17], Weishaupt et al. [48] or Krach et al. [29].

A further aim of the preparatory study is to study the role of solid deformations. Therefore, the simulated solid displacement field $|\mathbf{u}_S|$ is evaluated for a maximum applied flux of $2.5\ \text{ml/min}$, which corresponds to a maximum applied pressure of approximately 25 mbar in the experiments, cf. Sect. 4.2. The simulation results are shown in Fig. 13. Compared to the minimum pore size of $50\ \mu\text{m}$ in the porous domain, cf. Fig. 3, the deformations are very small with a maximum value of approximately $0.9 \times 10^{-3}\ \mu\text{m}$ in the porous domain. As mentioned above, the deformations might be slightly underestimated in this preparatory study due to the overestimated effective Lamé parameters of the PDMS, but certainly still extremely small and not measurable with the used measuring devices described in Sect. 4.2. Therefore, it can be stated that solid deformations are not relevant for the flow processes in this study. This is also seen, implicitly, in the obtained linear flux–pressure relationship in Fig. 15. Nevertheless, these simulation results show the capability of the TPM-phase-field model to predict solid displacements. The extracted line plot of the solid displacements in the $\mathbf{e}_1$ -direction shows the basic deformation behaviour. The resistance to flow and therefore the resulting solid deformation, is much higher in the porous region than in the free-flow channel due to the absence of solid material there. In this regard, the streamlines in Fig. 13 follow the slightly higher displacements in the regions where the liquid flows into and out of the channel indicating higher velocities. Finally, one can directly relate the flow behaviour in the simulated microfluidic device to the flow behaviour in Case I of the general study while comparing the streamlines in Figs. 6 and 13.

In conclusion, the performed general numerical simulations in Sect. 3 delivered useful knowledge for the design and the setup of the following experiments on microfluidic chips in Sect. 4. Overall, we have drawn two conclusions from this. Firstly, we need the production of microfluidic samples with a reasonable height and, secondly, we were strongly encouraged in our approach to carry out fully three-dimensional simulations promising greater success than simplified two-dimensional approaches.

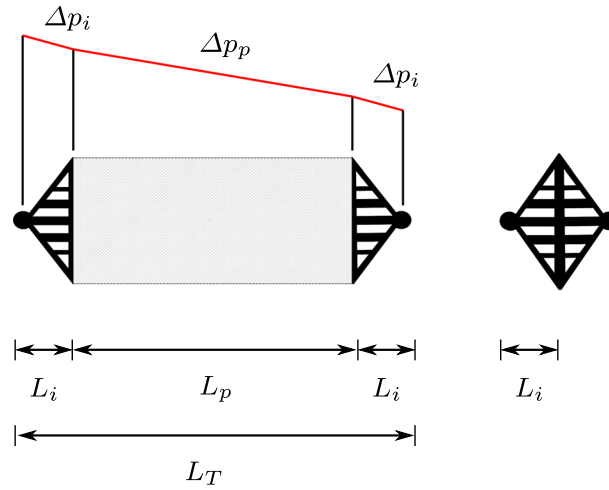


Fig. 14 Microfluidic chip (left) and connected inlet and outlet (right)

4 Microfluidic experiments and their simulation

In the pursued combined numerical–experimental strategy, we build on tailored microfluidic experiments, investigated at the Porous Media Lab (PML) of the University of Stuttgart. Obviously, a successful combination of experiments and simulations is only possible through a very close collaboration between researchers from both fields. As a result, an iterative process naturally arises in which both areas can benefit greatly.

4.1 Manufacturing process and properties of microfluidic chips

The microfluidic chips used in this work were made of PDMS. PDMS is a naturally hydrophobic, silicone-based polymer known for its flexibility, transparency and biocompatibility. It is chemically inert, non-toxic and highly resistant to temperature variations. The process of producing a microfluidic chip is described in detail in Xia and Whitesides [49]. In short, PDMS micromodels are created using a combination of soft lithography and optical lithography. First, a silicon wafer is coated with a photosensitive polymer (photoresist). Using optical lithography, ultraviolet (UV) light is shined through a mask to pattern specific areas, creating a mould with raised features that correspond to the desired microstructures. A mixture of an elastomer base and a curing agent of PDMS is then poured over the patterned silicon mould. After curing, the PDMS layer is peeled off, capturing the negative of the micro-patterned structure. This PDMS slab is bonded to glass or another PDMS layer to create a sealed microfluidic channel network that can be used for experiments. For the needs of our experiments, a mask was created bearing the exact structure as displayed in Figs. 3 and 14 (left) to manufacture our PDMS replicas. The accuracy of micromodel fabrication relative to the design is primarily influenced by two stages of the production process. First, the photomask is printed from the original AutoCAD[®] design at a resolution of 30,000 dpi, achieving a precision of 0.84μ per dot. That of course induces a, minor but still, deviation from the initial design. Second, variations in the exposure process during fabrication can cause slight deviations from the design, typically resulting in a higher actual porosity. In this work, the experimental (real) porosity was optically measured as 39%, compared to the intended 36% defined in the AutoCAD[®] design, providing the used solidity of $n^S = 0.61$ for the numerical simulations of the microfluidic chips.

4.2 Basic experimental setup

Two independent experimental setups are investigated, targeting different sets of measurements. First, the measurement of the hydraulic conductivity and, second, the determination of the velocity field for a variety of flux boundary conditions. For the estimation of the hydraulic conductivity of the microfluidic chip, a Cetoni[®] mid-pressure syringe pump and an MPS0 Elveflow[®] pressure sensor were used. The syringe pump was used with a 2.5 ml glass syringe and was controlled by a computer via QmixElements (Cetoni[®]) for the application of various flow rates at the inlet of the microfluidic chip. The MPS0 sensor, capable of accurately recording pressures of up to 70 mbar, was also connected to the computer and controlled via QmixElements, for the

logging of the pressure values at a rate of 10 Hz. The experimental setup presented here is similar to the one used in Wagner et al. [45], with the only difference that no second sensor was used and the outlet pressure was taken as atmospheric.

The experiment starts with the micromodel being completely saturated with ethanol, in a way that air was completely expelled from the pore space. Then, water was introduced into the flow network for at least 10 pore volumes. As soon as ethanol was out of the pore space, as a result of the displacement process by the water, the flow was stopped and the inlet pressure was measured. We confirmed that the sensor readout corresponded to the hydrostatic pressure induced by the connecting tube at the inlet. This pressure was used as the calibration point for all further measurements of the same experimental cycle. Then, the boundary flux was increased to a certain value. As soon as the pressure reached a steady state, the flux was again increased further. Several incremental steps were taken, and we recorded both the actual flux value, and the corresponding pressures. The slope of the fitted line can then be used to estimate the hydraulic conductivity of the microfluidic model via Darcy's law. Furthermore, the experiment would stop if the measured pressure would exceed 25 mbar since above this value the pore space of the microfluidic chip expands significantly. As a consequence, the behaviour between flux and pressure is no longer linear as prescribed by Darcy's law and therefore not suitable anymore for the determination of the hydraulic conductivities. Proceeding, equivalent measurements with the same fluxes were done with a structure bearing with only the inlet and outlet of the microchip to obtain the corresponding pressures. Therefore, a subsequent calculation of the pressure drop occurring only in the porous medium is possible, excluding the influence of the inlet and the outlet, as presented in Sect. 4.3.1. Since the model with the porous medium and the porous medium including the fracture have the same inlet and outlet design, we only needed to measure the pressure drop for the corresponding fluxes for the inlet and outlet once. For the identification of the velocity field inside the fracture and the porous medium, we used PIV, cf. [1]. PIV is an optical technique used to measure the velocity and flow patterns of fluids. It works by seeding a fluid with small tracer particles and illuminating them with high intensity light. High-speed or dual shutter cameras capture images of the particles at different time intervals. The velocity fields can be calculated by analysing the displacement of particle groups between frames. The experimental setup for the determination of the velocity field was similar to the one used in Dastjerdi et al. [10]. A Cetoni[®] mid-pressure syringe pump and a 2.5 ml syringe were used for the application of the boundary flux conditions of 0.1 ml/min at the inlet of the microfluidic chip. The imaging setup is similar to the ones used in Dastjerdi et al. [10] and Karadimitriou et al. [26] with some modifications. The process was visualised with a Cyclone-5-700 Optronis GmbH monochrome camera. The camera was capable of recording 5 megapixel (Mpx) images at a frame rate of 693 frames per second (fps). After binning to an area of interest of $256 \times 8 \text{ px}^2$, the acquisition frame rate could go as high as 95K fps. Given the volume of information per second, a frame grabber is needed, and for this purpose, an Euresys Coaxlink Quad CXP-12 frame grabber was used. The PCI Express frame grabber was installed on a PC with an Intel[®] i9 processor and 128 GB of RAM. The images were recorded directly to the RAM, since the recording was too fast for the M.2 SSD hard disc drive to cope with. Recording and control of the camera took place with the use of StreamPix 9 from NorPix[®]. For the visualisation of flow and the identification of the velocity field, mono-disperse, polystyrene particles (with a mean diameter of 3.97 microns, a standard deviation of 0.06μ and density of 1040 kg/m^3 , from microparticles GmbH) were used as the tracers. The flow was illuminated with a Chrolis C1 LED source at a wavelength of 565 nm. The synergy between the light source and StreamPix allowed us to reduce the camera exposure time and increase the light intensity, so that the camera shutter remained open for a shorter time and sharp images of the particles were obtained at all times. The images were taken with a spatial resolution of 1μ per pixel and a maximum temporal resolution of 693 frames per second. This meant that an image was captured every 1.4 ms.

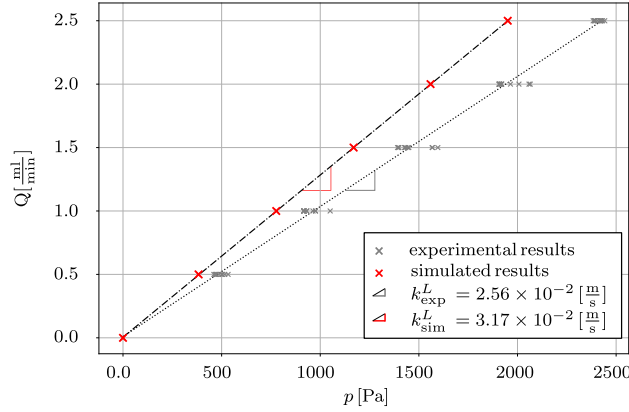
4.3 Experimental results and their adaption for the numerical model

4.3.1 Experimentally determined hydraulic conductivities of microfluidic chips

Since the hydraulic conductivity k_T^L of the complete microfluidic chip, cf. Fig. 14 (left), and the hydraulic conductivity k_i^L for two directly connected identical inlet and outlet domains, cf. Fig. 14 (right), were determined experimentally, the hydraulic conductivity for the porous domain k_p^L can be calculated in terms of a serial connection using the known pressure differences Δp_j . Therefore, applying Darcy's law (18) with neglected

Table 5 Experimentally determined hydraulic conductivities of the intact chip

$k_T^L \left(\frac{\text{m}}{\text{s}} \right)$	$k_i^L \left(\frac{\text{m}}{\text{s}} \right)$	$k_p^L \left(\frac{\text{m}}{\text{s}} \right)$
3.237×10^{-3}	8.721×10^{-3}	2.543×10^{-3}

**Fig. 15** Comparison of simulated and experimental inlet pressures for the microfluidic chip with embedded channel

gravitational forces, the following relation is found

$$Q_j = A_j \frac{k_j^L}{\gamma^{LR}} \text{grad } p_j, \quad \text{where} \quad \text{grad } p_j = \frac{\Delta p_j}{L_j} \quad \text{and} \quad j = \{T, i, p\}. \quad (22)$$

Therein, Q_j are the volume fluxes over the cross-sectional areas A_j and L_j the length of the considered sections, cf. Fig. 14. After rearranging (22) with respect to the pressure differences Δp_j and writing the total pressure difference Δp_T in terms of the sum of all pressure differences $\Delta p_p + 2\Delta p_i$, an expression for k_p^L is found as

$$k_p^L = \frac{L_p}{\left(\frac{L_T}{k_T^L} - \frac{2L_i}{k_i^L} \right)}. \quad (23)$$

Note that the volume fluxes Q_j cancel in the above equation due to continuity ($Q_T = Q_i = Q_p$). Furthermore, the cross-sectional areas A_j are assumed to be constant in $\mathbf{e}_1$ -direction (length direction), leading to linearity in the section-wise pressure drop. The results of the experimentally measured hydraulic conductivities and the calculated hydraulic conductivity k_p^L for the intact (unfractured) chip are given below in Table 5.

The experimentally determined hydraulic conductivity k_p^L for the intact (unfractured) chip is used as a base material parameter for the numerical simulation of the microfluidic chip with the embedded fracture (rectangular channel). According to the geometry of the microfluidic model shown in Fig. 3, a corresponding numerical model with a depth of $190 \mu\text{m}$ is considered as shown in Fig. 11. In the experiments, only the pressure at the inlet and the atmospheric pressure at the outlet are known. Therefore, the simulated and experimentally measured inlet pressures of the microfluidic chip containing the channel are presented for a range of fluxes Q in Fig. 15, showing a very good agreement in their general trends. This suggests that the model accurately captures the physical key processes and shows the predictive capability of the simulations. For the experiments, a linear fitting resulted in a coefficient of determination R^2 of 0.99 and above. The resulting slope, or using the linear flux–pressure relationship given by Darcy’s law, yields the global hydraulic conductivity, which is in the same order of magnitude but differs by approximately 19%. This slight deviation can be caused by the fact that several real-world properties of our experimental setting, as, for example, irregularities in surface roughness or local deviations of the depth of the microchip, are very difficult to be identified and, thus, cannot easily be considered in the numerical model. Furthermore, using multiple experimental setups to determine and compare the hydraulic conductivities for the numerical model adds onto this uncertainty. The later statement strongly motivates the use of different experimental designs which feature pressure measurements at discrete locations in the microchip, such that the in- and outlet domains can be completely neglected in numerical models.

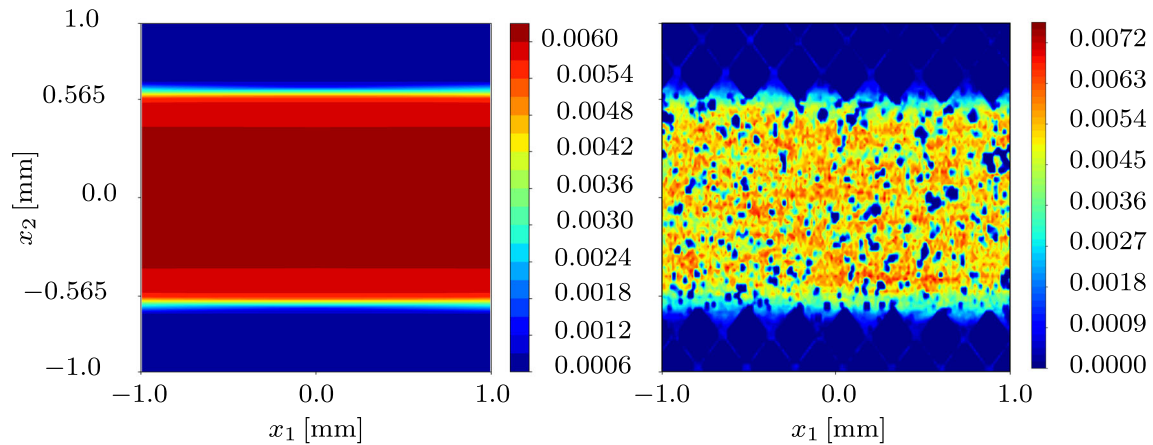


Fig. 16 Comparison of simulated (left) and experimental velocity fields (right)

4.3.2 Evaluation of PIV data and comparison to simulated flow velocities

The images obtained from the PIV are evaluated as mentioned in Sect. 4.2. However, focussed on the area of interest in the middle of the microchip, cf. the detail zoomed out in Fig. 3, contains regions with significantly different velocities in the channel and neighbouring porous domains. In order to capture the fast moving (free) flow in the channel, every consecutive pair of images is evaluated using the given time delay of 1.4 ms. For evaluating the porous-media flow in the neighbouring porous domains, every tenth image is used with a corresponding time delay of 14 ms. To keep the grid used for the evaluation consistent, the same search area size of 32 px was used for both PIV evaluations. Furthermore, an algorithm is used which averages the velocities in a point-wise manner considering non-consistent zero values. A non-consistent zero value can appear if, for example, no particles are present in a search area window for a given pair of images. In contrast, a consistent zero value would be at locations of the solid inclusion of the porous domain where no particles can physically be present. Given that point-wise averaging algorithm and using thresholds to eliminate outliers and finally superimposing both created velocity fields lead to the contour plot in Fig. 16 (right). As a result, it could be shown that the transition region from the faster (free) flow in the channel to the slower (porous-media) flow in the surrounding porous material is in fact occurring within the expected width w_r of roughly half of the unit cell's diagonal, as hypothesised in Sect. 2.2. Furthermore, the averaged field from the PIV can be compared with the velocity field in Fig. 16 (left) obtained from the numerical simulations, which is extracted in the middle of the chip and represents the maximum velocities in the channel. Note that in the three-dimensional simulations, the maximum velocity adjusts in the middle of the depth of the microchip. Since the velocity field obtained by the PIV measurements is already averaged over the depth (as a consequence of the experimental setup), the simulated velocity needs to be averaged over the depth as well. In the PIV measurements, the no-slip boundary conditions would manifest themselves in an agglomeration of particles on the top and bottom of the PDMS layer which is in reality typically not the case. To adopt this circumstance to the results of the numerical simulations, the influence of the (zero-valued) boundary nodes on the top and bottom walls is neglected accordingly in the averaging process. This leads to the red-coloured simulation curve in Fig. 17. To further consider the periodic properties of the studied microfluidic chip, all measured velocities are averaged over the x_1 -direction, leading to the blue-coloured experimental curve in Fig. 17. In conclusion, it could be shown that the numerically predicted velocity field is consistent with the experimentally measured velocities. Moreover, with the applied geometrically motivated choice of the length-scale parameter in Sect. 2.2, the correct slip-length and closely related the correct transition width could be predicted for the given experimental setup.

5 Conclusion

In this work, general theoretical as well as application-oriented aspects are discussed for flow through thin porous materials with an embedded free-flow channel (fracture). In a holistic study of the occurring phenomena, we investigated a combined numerical–experimental approach. For the experimental part of the study, microfluidic chips were used as a suitable choice to study phenomena relevant in sub-surface geo-engineering

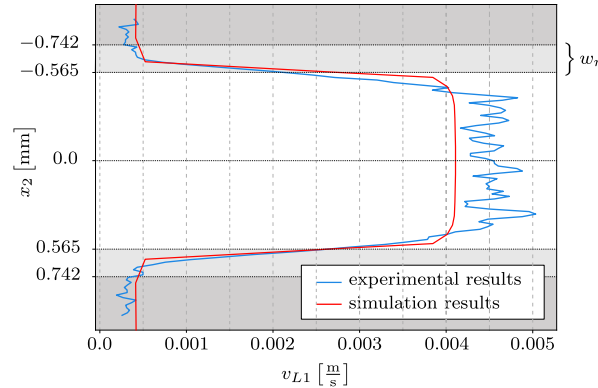


Fig. 17 Velocity profile from averaged velocity field. (Colour figure online)

applications.

At the beginning of this article, the theoretical framework of the biphasic TPM-phase-field model of Ehlers and Luo [13, 14] was introduced with regard to the fluid-flow behaviour in a porous material. Therein, we discussed the length-scale parameter ϵ which is responsible for the transition of the phase field. In this regard, we proposed a simple approach to estimate physically meaningful values based on the topological roughness of a material's fracture surface and proposed values for a range of rock materials. The verification of the estimated value was realised by tailored microfluidic experiments, where the experimentally observed transition region is exactly in line with the transition region obtained by the TPM-phase-field simulation. Note that this approach can also be used to determine a meaningful diffuse fracture interface for fracturing processes in single-phasic materials.

In a general study of flow through a thin porous plate containing a free-flow channel, we investigated and discussed in analogy to a thin microfluidic sample two different flow scenarios under different boundary conditions and hydraulic conductivities, mimicking sub-surface reservoir conditions. As a highlight arising from the general study, we found that the TPM-phase-field model is capable of capturing even very detailed effects, such as the velocity profile inversion phenomenon. This phenomenon is known from classical channel flow within impermeable walls. With the given model setup, we were able to study the fluid flow in a channel (fracture) with two opposing porous and therefore permeable walls (interfaces) and could show for the first time that this specific effect is increasing for flow into the channel and decreasing for flow out of the channel. To verify the model assumptions made for the length-scale parameter and to give an example of a real-world application of the TPM-phase-field model, we set up microfluidic experiments. As a result of preparatory numerical studies, we could show that the influence of drag or resistance of a channel embedded in a porous domain increases significantly with a decrease in thickness what was interpreted as an effect governed by a reduced distance of the top and bottom walls with a no-slip condition. This emphasises the necessity of full three-dimensional simulations to accurately capture the nature of physical processes and, furthermore, shows the need for the development of thicker microfluidic devices. For the devices used in this article, we were able to manufacture microfluidic chips with a thickness of roughly $200\ \mu\text{m}$, which is higher as conventional chips. Following that, we discussed the overall experimental setup and evaluation of the pressure and velocity measurements. Therein, the local velocity field for relevant sections of the microfluidic chips was determined using PIV.

For model verification, we compared the experimentally obtained data with the numerical results at the example of the microfluidic chip. In this regard, the estimation of the length-scale parameter and the experimentally determined hydraulic conductivities are used as material parameters. In particular, a comparison of discrete inlet pressures and the local velocity field in the middle of the chip showed to be in reasonable agreement. Therefore, the assumptions regarding the length-scale parameter are successfully validated using the velocity field. It was shown that the diffuse transition width and, closely related, the slip velocities at the porous walls (interfaces) are in good agreement with the experimental results. In conclusion, it has been proven that the TPM-phase-field approach provides an elegant and powerful single-domain approach for the simulation of coupled flow interactions in porous media.

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Data availability Data sets generated during the current study can be requested from the authors.

Declarations

Conflict of interest The authors declare no conflict of interest.

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