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RPPR Final Report
as of 11-Mar-2019

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STEM Degrees: 0 **STEM Participants:** 2

Major Goals: The major goal of the proposed project is to quantitatively examine the suspension flows over porous media and the related instabilities by developing and experimentally validating a new framework to model and understand the stability of the flow of particle-laden liquids in a rectangular channel in which one or two walls are coated with various porous media. The proposed concept, inspired by the nearly frictionless movement of red blood cells through tiny capillaries, involves covering the planar surfaces with a specific porous material with permeability K and porosity ?.
The specific objectives of the proposed project, described below, are aimed at achieving our major goal of developing and experimentally validating a new theoretical framework to model and understand this coupled flow and the causes of instability in the system.
In Objective# 1, we will consider pressure-driven channel flow of non-Brownian, non- colloidal particle-laden liquids at moderate to high concentrations (i.e., 0.05<?bulk<0.5) in which one or two walls is/are coated with various porous media. We will couple the Brinkman equation and the suspension balance model to understand the velocity profile and concentration field above the porous media and to define the steady-state (base state) solutions in the presence of the permeable media. Then, we will linearly perturb the coupled equations in the steady-state regime. The Chebyshev tau method will be utilized to determine the eigenmodes of perturbed equations. The PI plans to validate and calibrate the code by performing and reproducing the results of [2,11]. Finally, the stability of the system will be analyzed, the normalized amplitude of the stream function and concentration profiles, and the new families of stable/unstable modes will be determined. A phase diagram that summarizes the effect of Reynolds number and flow property, channel geometry, and physical property of the porous media on instability will be also introduced.
In Objective# 2, we will experimentally validate the theoretical predictions. We will design and construct an experimental test set-up and its supporting structures which will allow us to flow suspensions in a channel over surfaces coated with and without a porous layer and to investigate the onset of instability. The set-up will be fully instrumented to measure the steady-state velocity and concentration profiles in the channel over the porous layer at low to moderate Reynolds number. We plan to perform Osborne Reynolds experiment to define the onset of the instability in the system for dilute to concentrated suspensions. The slurry will be composed of poly(methyl methacrylate?) (PMMA) particles with a mean radius of 100–150 ?m. Particle concentrations of 1% to 50% will be tested. We will employ particle image velocimetry (PIV) measurements to characterize the flow, to define the velocity profiles, at dilute suspensions (i.e., ?bulk =1% and 5%). Magnetic resonance imaging (MRI) will be used to define the concentration distribution and velocity profiles for dilute to concentrated suspensions (i.e., ?bulk =1% and 50%). The data will be compared with the analytical calculations performed in Objective 1. Discrepancies will be noted, their potential sources will be investigated, and approaches to decreasing the errors will be explored.

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Accomplishments: The major activities of Year 1 have focused on achieving the objective (1), namely, investigating the instability in a coupled suspension-porous system. We first analyzed unperturbed (steady-state) solution of the coupled flow.
We considered a two-dimensional flow of noncolloidal suspensions of rigid, spherical particles in a Newtonian fluid with thickness 2L overlying a porous layer of thickness H, porosity ?, and permeability K. We assumed monodisperse suspensions of the spheres of radius r in the Newtonian solvent with viscosity ?. Also, both the Reynolds number based on the bulk flow definition and the particle Reynolds number is? sufficiently small that bulk inertia has little effect on the free flow as well as the flow inside the porous media. Furthermore, the pores of the porous media are much smaller than the size of the particles; thus, the particles are not going inside the porous medium. In these cases, the velocity, shear stress, and concentration profiles for unperturbed (base) solution can be calculated by coupling Brinkman equation with the suspension balance model. The outcomes have been submitted to the Journal of Fluid mechanics and also have been presented in conferences including APS-DFD 2017 and InterPore Annual Meeting 2018 and by the PI through invited talks.
In addition, we performed several experiments to study the characteristics of flow over random porous materials in which the porous media coated the lower surface of the channel. The void volume fraction (i.e., porosity) varied from 0.95 to 0.99. In all the experiments, the Reynolds number was kept low so that the flow was laminar. The PIV (particle image velocimetry) technique was used to obtain a detailed velocity profile over the porous media and at the interface between the porous media and the flow. The study provided only two-dimensional whole-field velocity component measurements in two planes (where changes of velocity distributions are most dramatic) for various porous media. Using the obtained measurements, the slip velocity was determined, and its variation with porosity, Reynolds number, and height of model porous medium relative to the channel height was studied. A coupled flow model over and inside the soft porous media was examined via experimental measurements; the proper experiments to determine the Darcy permeability for random porous media were also conducted.
These outcomes have been submitted to the Journal of Fluid mechanics and have also been published in the Physics of Fluids Journal. The results have been presented in conferences including APS-DFD 2017 and InterPore Annual Meeting 2018 as follows.

Training Opportunities: 1) The training and education of one female Ph.D. student and one female postdoctoral fellow.

2) Classroom instruction through the administration of a Graduate-level special topics course in Applied Fluid Mechanics, taught by the PI.

3)WeeklymeetingsofthePh.D.candidateandpostdoctoralfellowwiththePIhaveplaced an emphasis on professional communication of data (both oral and written).

4) Recruitment and participation of an undergraduate student during the Spring semester, supported partially by this grant. The opportunity allowed the undergraduate to participate in group meetings and weekly presentations related to research methods.

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Results Dissemination: Results have been disseminated locally, as well as nationally as follows.
1) High-school classroom visitation/instruction was carried out as the PI and her undergraduate researcher visited the Potsdam, NY Central School to present a 45 minutes presentation about the bio-inspired strategies and how they can be applied in the science and engineering applications. This presentation reached approximately 35 high school choral members that were predominantly female.

2) The PI presented her work as part of the 2018 Clarkson seminar series, which is a community outreach forum for researchers to present their findings. Approximately 70 individuals from the community attended the presentations related to the PI's research.

3) The PI has also presented her work as “invited talks” in the following conferences and universities;

a) 10th InterPore Annual Meeting and Jubilee, May 2018.
b) Department of Mechanical engineering, University of Las Vegas, Oct. 2017.
c) Department of Mechanical engineering, City College of New York, Feb. 2018.
d) Department of Mechanical and Industrial engineering, University of Illinois- Chicago, April 2018.
e) Department of Biomedical Engineering, University of Wisconsin-Milwaukee, April 2018.

4) The Ph.D. graduate student presented his work at the American Physical Society Division of Fluid Dynamics meeting.

5) Three journal articles have also been either in review or published. One paper has been published at the J. Physics of Fluids. There are two other manuscripts in the review at the Journal of Fluid Mechanics.

6)The Ph.D. graduate student also highlighted her research at the Fall and Spring Clarkson University open house for prospective students, reaching over 100 prospective students and parents.

Honors and Awards: Editorial Member of the Scientific Journal (Nature Journal community)

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Parisa Mirbod
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Eileen Ann Haffner
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Indika Udagedara
Person Months Worked: 5.00 **Funding Support:**

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Stephen Cardiff
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Conference Location: Denver, Colorado, USA
Paper Title: Instability of dilute suspensions in a channel coated with porous media
Authors: Parisa Mirbod, Zhenxing Wu
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
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Date Received: 08-Mar-2019 Conference Date: 14-May-2018 Date Published: 17-May-2018
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Paper Title: Flow and transport of particle-laden liquids over permeable surfaces; Theory and experiment
Authors: Parisa Mirbod
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
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Date Received: 08-Mar-2019 Conference Date: 18-Nov-2018 Date Published: 20-Nov-2018
Conference Location: Georgia World Congress Center. Atlanta, GA
Paper Title: Instability of dilute suspensions in a channel coated with porous media
Authors: Zhenxing Wu, Parisa Mirbod
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 11-Mar-2019

Final Report

Proposal; Understanding the instability of particle-laden liquids over soft porous media (Research area: b.1.I Fluid Dynamics)

Grant number; W911NF-70870-EG

What are the major goals of the project?

The **major goal** of the proposed project is to quantitatively examine the suspension flows over porous media and the related instabilities by developing and experimentally validating a new framework to model and understand the stability of the flow of particle-laden liquids in a rectangular channel in which one or two walls are coated with various porous media. The proposed concept, inspired by the nearly frictionless movement of red blood cells through tiny capillaries, involves covering the planar surfaces with a specific porous material with permeability K and porosity ε.

The **specific objectives** of the proposed project, described below, are aimed at achieving our major goal of developing and experimentally validating a new theoretical framework to model and understand this coupled flow and the causes of instability in the system.

In **Objective# 1**, we will consider pressure-driven channel flow of non-Brownian, non-colloidal particle-laden liquids at moderate to high concentrations (i.e., $0.05<\phi_{bulk}<0.5$) in which one or two walls is/are coated with various porous media. We will couple the Brinkman equation and the suspension balance model to understand the velocity profile and concentration field above the porous media and to define the steady-state (base state) solutions in the presence of the permeable media. Then, we will linearly perturb the coupled equations in the steady-state regime. The Chebyshev tau method will be utilized to determine the eigenmodes of perturbed equations. The PI plans to validate and calibrate the code by performing and reproducing the results of [2,11]. Finally, the stability of the system will be analyzed, the normalized amplitude of the stream function and concentration profiles, and the new families of stable/unstable modes will be determined. A phase diagram that summarizes the effect of Reynolds number and flow property, channel geometry, and physical property of the porous media on instability will be also introduced.

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Accomplished under Goals

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Plans for next reporting period

The PI and her students plan to perform the major activities of Year 2 as follows.

1) Focus on perturbing the governing equations of the coupled flow of suspensions and porous media by developing an analytical model to examine the velocity profiles, shear stress, and concentration profiles perturbed due to the motion of various concentration of suspensions over porous media.

2) Investigate the instability of the coupled flow using precise experimental set up such as PIV, and MRI.

3) Comparing the theoretical and experimental results and update the outcomes.

4) High-school outreach will be continued by visiting choral groups in school districts at Chicago, IL to improve female participation in the STEM disciplines by highlighting how a biological strategy can be resulted in advance science and engineering system and how that can be related to opportunities provided by a STEM education.

5) A dedicated website will be developed to disseminate research results, and data gathered will be provided to students, researchers, and collaborators with the ability to visualize the tests and perform data analysis remotely.

6) In addition to publishing our research in highly rated journals, we will present our results at the professional conferences.

Honors and Awards

Editorial Member of the Scientific Journal (Nature Journal community)

Technology Transfer (patent applications, inventions, licenses, interaction with DoD laboratories)

Participants

Last Name	First Name	Middle name	Actions

Eileen A. Haffner   Ph.D. Candidate (Clarkson)

Indika G. Udagedara   Postdoctoral fellow (Clarkson)

Stephen Cardiff   Undergraduate REU researcher (Clarkson)

Major Activities:

The major activities of Year 1 have focused on achieving objective (1), namely, investigating the flow over a porous medium by developing a framework to model flow of a Newtonian fluid in a channel where the lower surface was replaced by various porous media.

We considered the slow flow of noncolloidal suspensions of rigid, spherical particles in a Newtonian fluid with thickness 2L overlying a porous layer of thickness H, porosity ε, and permeability K. A schematic of the model is depicted in figure 1(a). We also considered monodisperse suspensions of the spheres of radius r in the Newtonian solvent with viscosity η. The velocity and shear stress profiles for a pure Newtonian fluid over porous media has been reported by (Mirbod et al. 2017).

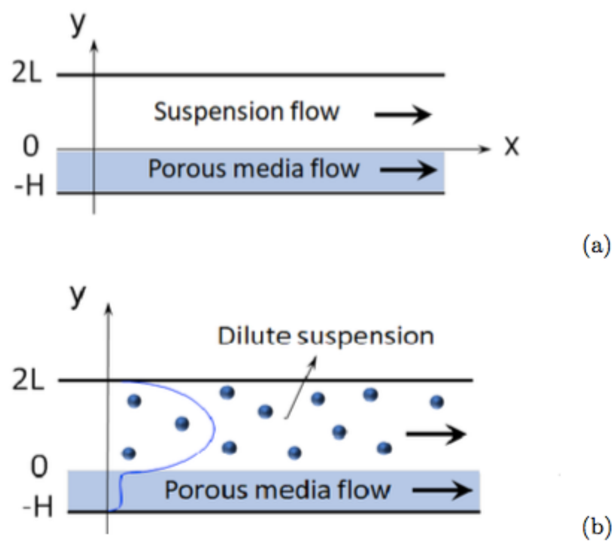


Figure 1. (a) A schematic of the model. (b) Fully developed velocity profile in the channel.

In these cases, the velocity and pressure profiles, for a given distribution of particles $\hat{\phi} = \hat{\phi}(\hat{x}, \hat{y})$ are found by solving the equations for linear momentum conservation and continuity as

$$\nabla \cdot \hat{\tau} + \nabla p = 0$$
$$\nabla \cdot V = 0, \qquad \textbf{(1)}$$

Furthermore, the steady-state concentration profile can be given by Phillips et al. (1992)

$$r^2 K_c \nabla \cdot \left(\hat{\phi}^2 \nabla \hat{\dot{\gamma}} + \hat{\phi}\hat{\dot{\gamma}} \nabla \hat{\phi}\right) + r^2 K_\eta \nabla \cdot \left(\hat{\dot{\gamma}} \hat{\phi}^2 \frac{1}{\eta} \frac{\partial \eta}{\partial \hat{\phi}} \nabla \hat{\phi}\right) = 0, \quad (2)$$

In these equations, V ($u^\wedge$, $v^\wedge$, $w^\wedge$) and p are the velocity and the pressure fields, respectively. $\tau^\wedge$ is the stress tensor, $\dot{\gamma}$ is the rate of strain tensor, $\eta = \eta(\phi)$ is the viscosity of the suspension, $\phi^\wedge$ is the volume fraction of the particles in the suspensions flow, and K_c, K_η are phenomenological parameters that must be determined using experimental measurements of the particle distribution.

In addition, the flow through the porous medium using the continuity and Darcy- Brinkman equations can be described as (Durlofsky & Brady 1987)

$$\nabla \cdot V = 0$$
$$\frac{\eta_e}{\epsilon} \nabla^2 V - \frac{\eta_s}{K} V - \nabla p = 0, \quad \textbf{(3)}$$

As a first step, to define the unperturbed (steady-state) solutions of the coupled flow of suspensions and porous media, the above equations and the corresponding boundary conditions can be non-dimensionalized through a selection of appropriate scales. We selected half of the thickness of the suspension region L, the velocity of the working fluid at the half of the suspension channel $q = -(dp/dx^\wedge)L^2$, and the suspending fluid viscosity η_s, as the repeating variables. We then introduced non-dimesionalized parameters as

$$x = \frac{\hat{x}}{L}, y = \frac{\hat{y}}{L}, y_0 = \frac{\hat{y}_0}{L}, u = \frac{\hat{u}}{q}, \dot{\gamma} = \frac{\hat{\dot{\gamma}}}{q/L}, \tau = \frac{\hat{\tau}}{\eta_s q/L} \quad \textbf{(4)}$$

Also, $\alpha^2 = L^2/K$ is the permeability parameter and $M = \eta_e/\eta_s$ is the viscosity ratio which relates the ratio between the viscosity of suspending fluid penetrating inside the porous media to the viscosity of the suspending fluid. The thickness ratio is δ=H/L.

Specific Objectives and results:

The primary objectives were to define the unperturbed solutions and examine the dimensionless parameters in the coupled flow system. Key findings of this research are as follows;

1) Figure 2 shows the normalized velocity, the corresponding shear stress, and the normalized concentration profiles at different values of α for a bulk concentration, ϕ_a= 1%. As can be seen from Fig. 1(a), for ϕ_a= 1% and in the large α limit (α>10), the velocity profile inside the suspension region is parabolic except near the interface, where the velocity approaches very small values. Also, for large α values fluid shear stress in the

porous layer decreases to zero. This is because as the permeability decreases, the bulk of the shear stress is sustained by the fibers in the porous layer, which results in very small velocity and fluid shear stress (Fig. 2(b)). The normalized concentration profiles and their variation with the α values has also been calculated in Fig. 2(c).

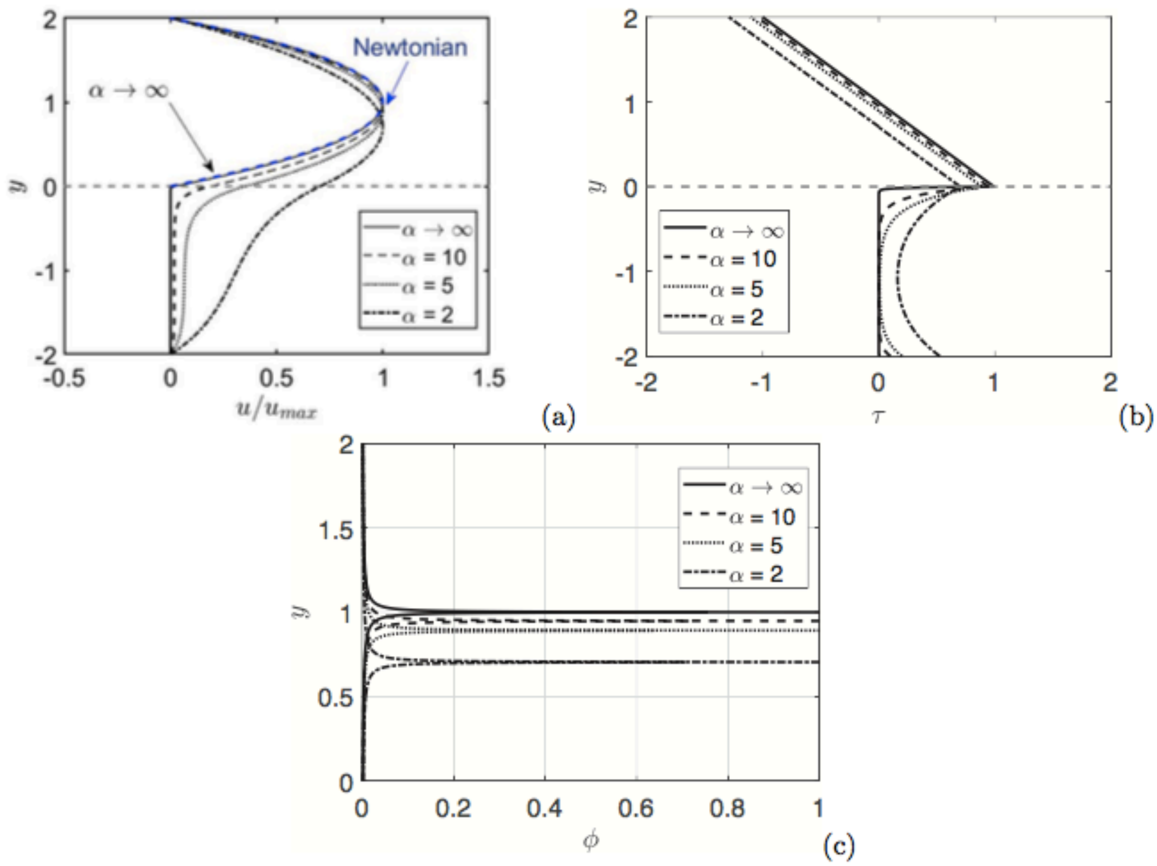


Figure 2. The validation of the results for 1% of the bulk volume concentration. (a) The normalized velocity profiles, (b) the normalized shear stress profiles, and (c) the normalized concentration profiles for different values of α. The gray dashed line denotes the suspension-porous interface. The velocity and shear stress profiles at $\alpha \to \infty$, $\alpha = 10$, $\alpha = 5$, and $\alpha = 2$ are shown in black solid, dashed, dotted, and dotted dash, respectively. For all cases, the thickness ratio is $\delta = 2$.

2) The dimensionless velocity and the shear stress profiles in the channel for 50% initial particle concentration, the thickness ratio $\delta = 2$ and different α values are also shown in Figure 3. As can be seen in Figure 3(a), for all values of α, a blunted velocity profile can be seen inside the suspension region where $y = y_0$ (which is a value function of both α and δ). In addition, in our model $\alpha \propto 1$; therefore, increasing α results in decreasing the permeability of the K porous medium.

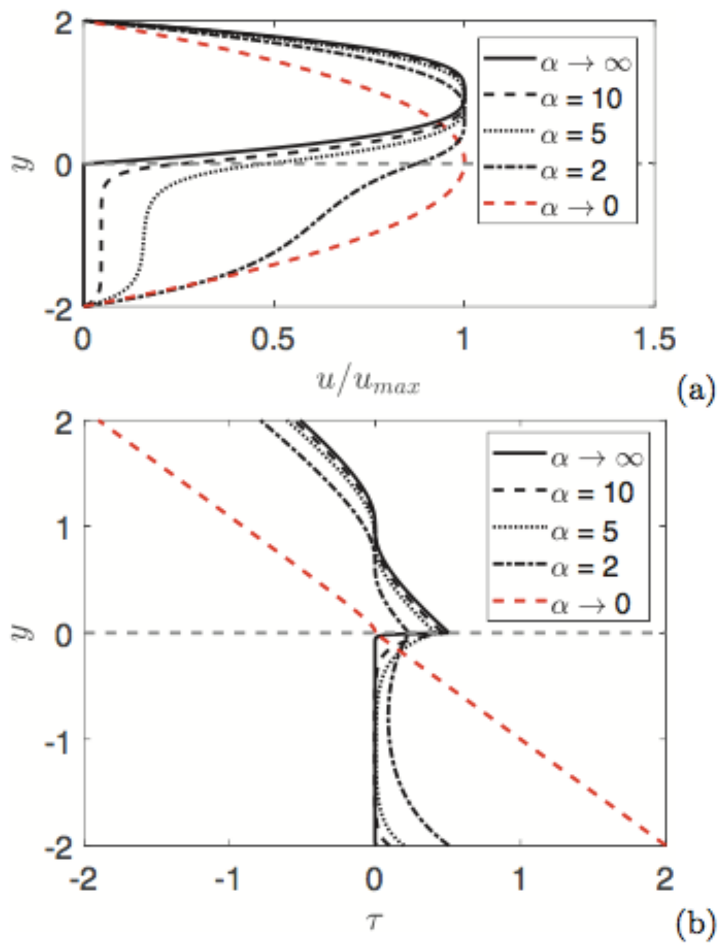


Figure 3. (a) Normalized velocity profile and (b) normalized shear stress profile for the coupled flow for different values of α. For all cases, the initial concentration of the particles is 50% and the thickness ratio is 2.

3) Figure 4 shows the normalized velocity profile and the corresponding shear stress for four different bulk particle volume fractions ϕ_a. In both figures, we included the profiles where ϕ_a = 1% in order to compare the results with pure Newtonian fluid Mirbod et al. (2017). For all cases, the maximum velocity occurs at the same location and the variation in the bulk concentration will not change the velocity profile. A similar observation can be seen in the shear stress profile in the 4 (b) where for all four cases presented in the figure, the shear stress is zero at the plane $y = y_0$. In addition, by increasing the bulk concentration ϕ_a the velocity at the interface of the suspension-fluid region (i.e., slip velocity at the interface) builds up.

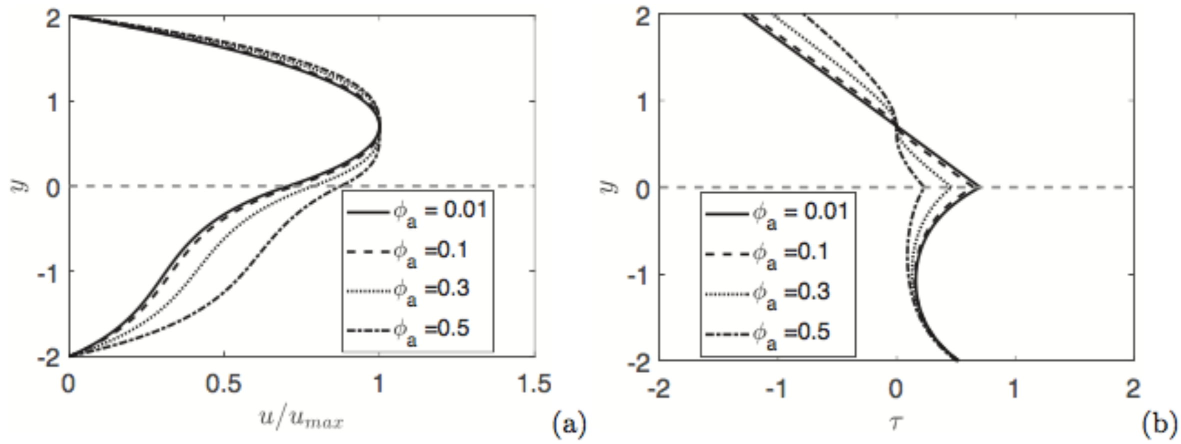


Figure 4. (a) The normalized velocity profiles and (b) the shear stress profiles in the channel as a function of dimensionless thickness of the channel at different bulk concentration. α = 2 and δ = 2 are used for the calculations.

4) To study the linear stability of this problem, we then derived the perturbation equations for dilute suspension flows over porous media by introducing the perturbed forms $u = \tilde{u} + \bar{u},\ v = \tilde{v} + \bar{v},\ p = \tilde{p} + \bar{p},\ u_m = \tilde{u}_m + \bar{u}_m, v_m = \tilde{v}_m + \bar{v}_m,\ p_m = \tilde{p}_m + \bar{p}_m$. We then changed our normalization parameters by defining d and $\boldsymbol{\beta}$**.** By comparing the effect of the new depth ratio d=L/H and the new permeability parameter $\boldsymbol{\beta} = \frac{\boldsymbol{H}}{\sqrt{\boldsymbol{K}}}$ on the instability system, we found there is always a neutral curve with a critical value of $\boldsymbol{\beta} = \frac{\boldsymbol{H}}{\sqrt{\boldsymbol{K}}}$ or d, which has identical minimal Reynolds number in both fluid branch and the porous branch. This phenomenon has not been addressed before. We then defined a new parameter γ which relates $\boldsymbol{\beta}$ and d as

$$\gamma = \boldsymbol{\beta} \times d = \frac{L}{\sqrt{K}}$$

Fig. 5 shows the neutral curves for $\boldsymbol{\beta} = \frac{\boldsymbol{H}}{\sqrt{\boldsymbol{K}}} = 2.5, 3.16, 4$ at $M = 1, \varepsilon = 0.8$. For each $\boldsymbol{\beta}$, we have chosen two groups of $\boldsymbol{\beta}$ and d values. As can be seen in Fig. 5, $\boldsymbol{\beta} = \boldsymbol{\beta}_c = 3.16$ is a critical value where the minimum value of the Reynolds number in both the fluid and the porous branch are the same. Thus, specifically for $M = 1, \varepsilon = 0.8$, when $\boldsymbol{\beta}$ is less than $\boldsymbol{\beta}_c$, where the instability is dominated by the porous region, the system becomes more stable and when $\boldsymbol{\beta}$ is greater than $\boldsymbol{\beta}_c$, the instability is dominated by the fluid branch, the values of the critical Reynolds number decays, and the system becomes unstable.

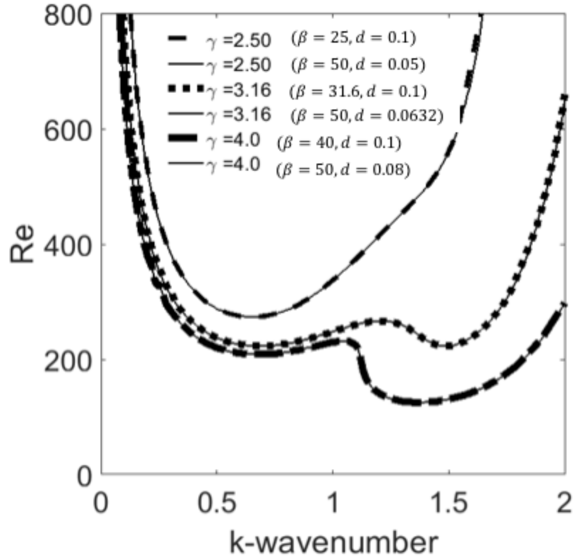


Fig. 5. The neutral curves for $\gamma = 2.5, 3.16$, 4 at $M = 1, \varepsilon = 0.8$.

5) To demonstrate how various porosities and the thickness of the random permeable layer modify the velocity profile from the corresponding one in an empty channel, we performed experiments using PIV (particle image velocimetry) as can be seen in Fig. 6.

   It can be seen that one of the effects of the porous layer is to shift the location of the maximum velocity towards the upper wall of the channel. In addition, the values of velocity at the interface ($y/h_p=0$) for h_p =5.5 mm and 11 mm are very different (h_p is the porous thickness)– they are around 2% and 10% of the maximum velocity, respectively.

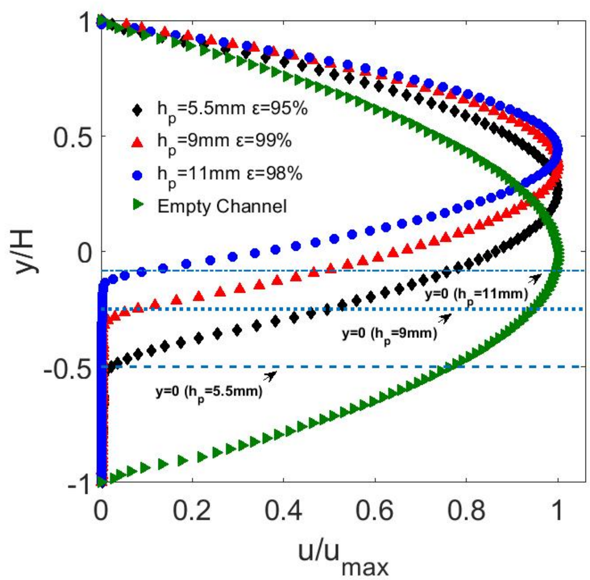


Fig. 6. Normalized Velocity fields u(y) obtained from the PIV for various porosities and porous layer thicknesses through and above the porous media and comparison with the velocity profile obtained in an empty channel for Re = 2.5.

6) Fig. 7 also shows the variation of the normalized average velocity in the smaller test window, obtained from the PIV, where $y/h_p=0$ corresponds to the fluid-porous interface. As can be observed from the plots, the velocity decreases from the value at the interface to a constant value inside the porous media. In addition, the slip velocity appears to be higher as the porosity increases. This is because the lower resistance in the porous material with higher porosity.

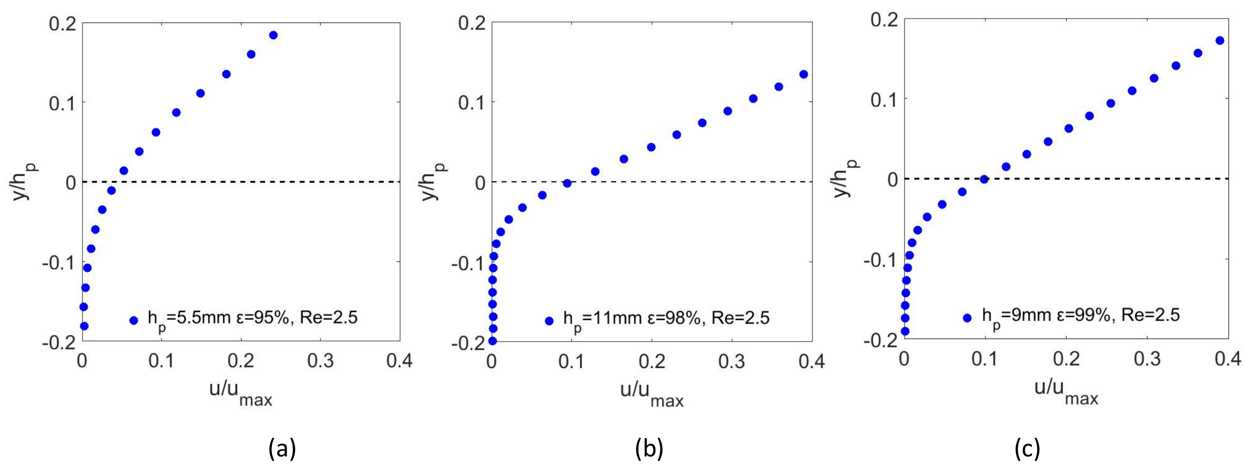
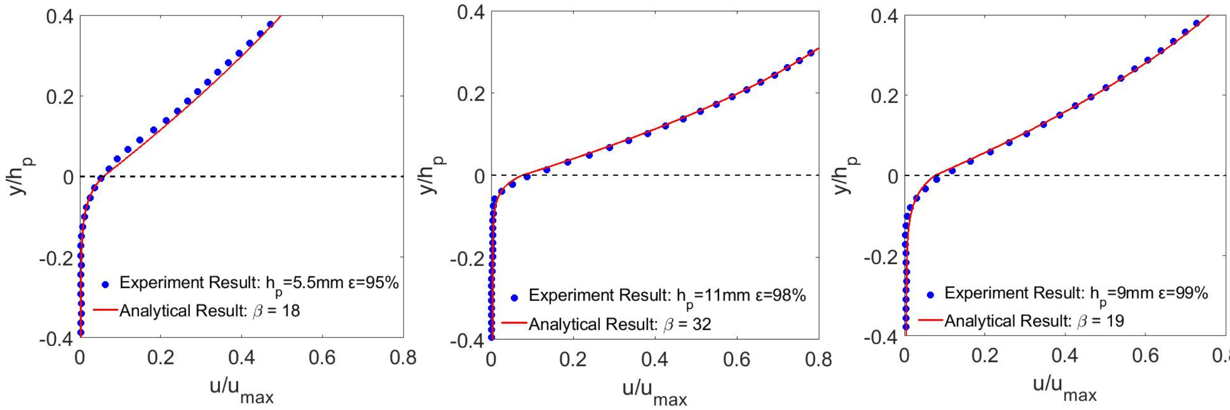


Fig. 7. Normalized velocity u(y) profiles near the fluid-porous interface at various porosities of the porous media for Re=2.5. (a) ε =95%, h_p=5.5mm, (b) ε =98%, h_p=11mm, and (c) ε =99%, h_p=9mm.

7) We then evaluated our theoretical model for pure Newtonian fluid by comparing it with the experimental results of the current study for different porous media. The velocity measurements and model prediction are shown in Fig. 8. The value of $\beta=\frac{\boldsymbol{hp}}{\sqrt{\boldsymbol{K}}}$ is determined to perform the best fit between the experimental and coupled analytical methods for each porous medium, that is, β=18, β=32, β=19 for porosity of 0.95, 0.98, and 0.99, respectively. First, we defined the value of β for each porous media using the fitting of the interfacial velocity. This fitted value of β then has been used to perform a prediction of the remaining data set. As can be seen from the figure, the values of β are different depending on the porous material and the thickness of the permeable layer. Thus, one can define the velocity profile over and inside each porous medium using our analytical model when the porous medium property and the thickness of the layer are known.

Consequently, we calculated permeability K for each random porous medium from the fitted velocity profile and $K=\frac{h_p^2}{M\beta^2}$, then compared them with the experimentally measured values of the permeability of each porous medium using Darcy's law. The details are reported in table I.



(a) (b) (c)

Fig. 8. Comparison between experimental velocity measurements and model predictions for different porous media. (a) ε =95%, h_p=5.5mm, (b) ε =98%, h_p=11mm, and (c) ε =99%, h_p=9mm.

TABLE I. The comparison of analytical fitted permeability and tested permeability.

Porosity ε	h_p (mm)	K_fitted (mm^2)	K_tested (mm^2)
95%	5.5	0.074	0.083
98%	11	0.087	0.105
99%	9	0.120	0.140

Key outcomes or other achievements:

1) We presented a detailed analysis of unperturbed (steady-state) velocity and shear stress profiles of particle-laden liquids over porous media.
2) The model was validated at a low bulk concentration of suspensions. At low bulk concentration, the velocity and shear stress profiles and those of the pure Newtonian fluid are similar as has been reported in our previous work Mirbod et al. (2017).
3) We have also presented the asymptotic solutions of the velocity and concentration profiles in the coupled flow in the limits when both α=$\frac{L}{\sqrt{K}}$ and δ=$\frac{H}{L}$ approaches to either 0 or ∞. For instance, the results show that, in dilute suspensions, as α=$\frac{L}{\sqrt{K}}$ approaches to ∞ for δ =$\frac{H}{L}$= 2 value, the velocity and shear stress profiles asymptotically approach to the outcomes of the pressure-driven flow in a channel with solid smooth walls and a height of 2L.
4) Further, we examined the Instability of dilute particle-laden liquids overlying porous surfaces and found that the instability depends strongly on

$$\boldsymbol{Re} = \frac{\rho VL}{\mu},\ \boldsymbol{Re_m} = \frac{\rho V_m H}{\mu}, \boldsymbol{d} = \frac{L}{H},\ \boldsymbol{M} = \frac{\eta_e}{\eta},\ \boldsymbol{\varepsilon},\ \boldsymbol{\beta} = \frac{H}{\sqrt{K}},\ \boldsymbol{\phi_{bulk}}$$

5) For dilute suspensions, depending on $\boldsymbol{\beta}$, $\boldsymbol{d}$, and $\boldsymbol{\varepsilon}$ the dominant mode of the instability is found either on the suspension region or porous region;

6) For porous media with high porosity and low permeability, decreasing $\boldsymbol{d}$ at some point stabilizes the flow results in increasing the critical Reynolds number;

7) The two extreme values of $\boldsymbol{\beta}$ (0 and∞) correspond to plane Poiseuille flow;

Related Journal Articles, Conference Papers and Presentations:

Journal Articles

1. Zhenxing Wu, Parisa Mirbod, Flow near a boundary of a random soft porous medium, *Physics of Fluids,* **30**, 047103, 2018. (Manuscript attached)
2. Indika G. Udagedara, Parisa Mirbod, Drag reduction of particle-laden liquids over porous media, *In review.* (Manuscript attached)
3. Zhenxing Wu, Parisa Mirbod, inastability of the flow between two parallel paltes where the bottom one coated with porous media, *In review.* (Manuscript attached)

Conference Presentations

1. Parisa Mirbod, "Flow and transport of particle-laden liquids over permeable surfaces; Theory and experiment", 10th InterPore Annual Meeting and Jubilee, May 14-17, 2018, New Orleans, Louisiana, USA. *(Invited Talk)* (Abstract attached)
2. Parisa Mirbod, Zhenxing Wu, Goodarz Ahmadi, "Laminar drag reduction on a soft porous material", APS March Meeting, March 5-9, 2018, Los Angeles, California, USA. (Abstract attached)
3. Zhenxing Wu, Parisa Mirbod "Flow near the boundary of random soft porous media", 70th Annual Meeting of the Division of Fluid Dynamics, November 19-21, 2017, Denver, Colorado, USA. (Abstract attached)