INTERPORE

French InterPore Chapter

SUPERFLUID AND QUANTUM TURBULENCE IN POROUS MEDIA

-

A tribute to Michel Quintard

-

April 15-16, 2019 - Bordeaux

-

Cyprien Soulaine, Hervé Allain, Michel Quintard, Marc Prat, Bertrand Baudouy, Rob Van Weelderen

www.cypriensoulaine.com

INTERPORE
French InterPore Chapter

SUPERFLUID AND QUANTUM TURBULENCE IN POROUS MEDIA

-

A tribute to Michel Quintard

-

April 15-16, 2019 - Bordeaux

-

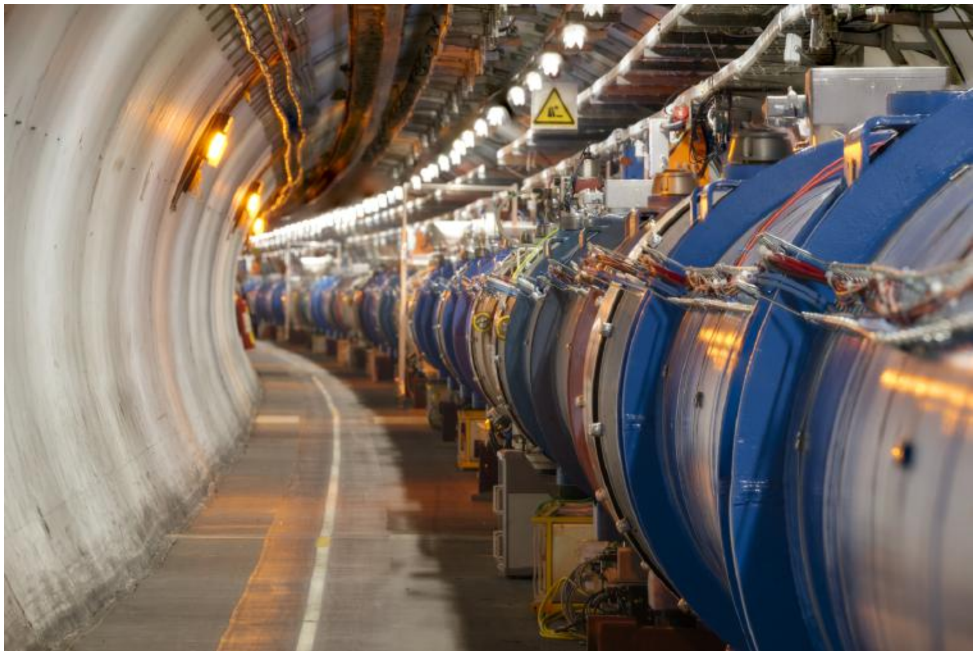
Cyprien Soulaine, Hervé Allain, Michel Quintard, Marc Prat, Bertrand Baudouy, Rob Van Weelderen

www.cypriensoulaine.com



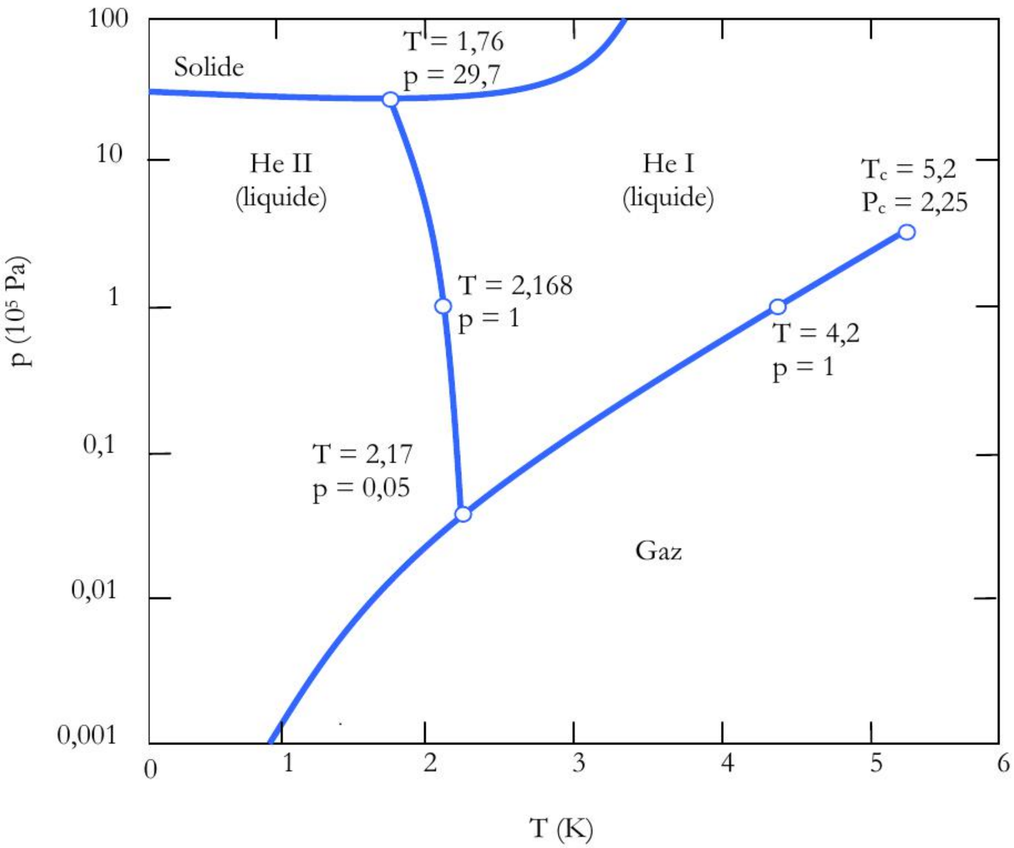
cea CERN IMFT INSTITUT DE MÉCANIQUE DES FLUIDES DE TOULOUSE

Background

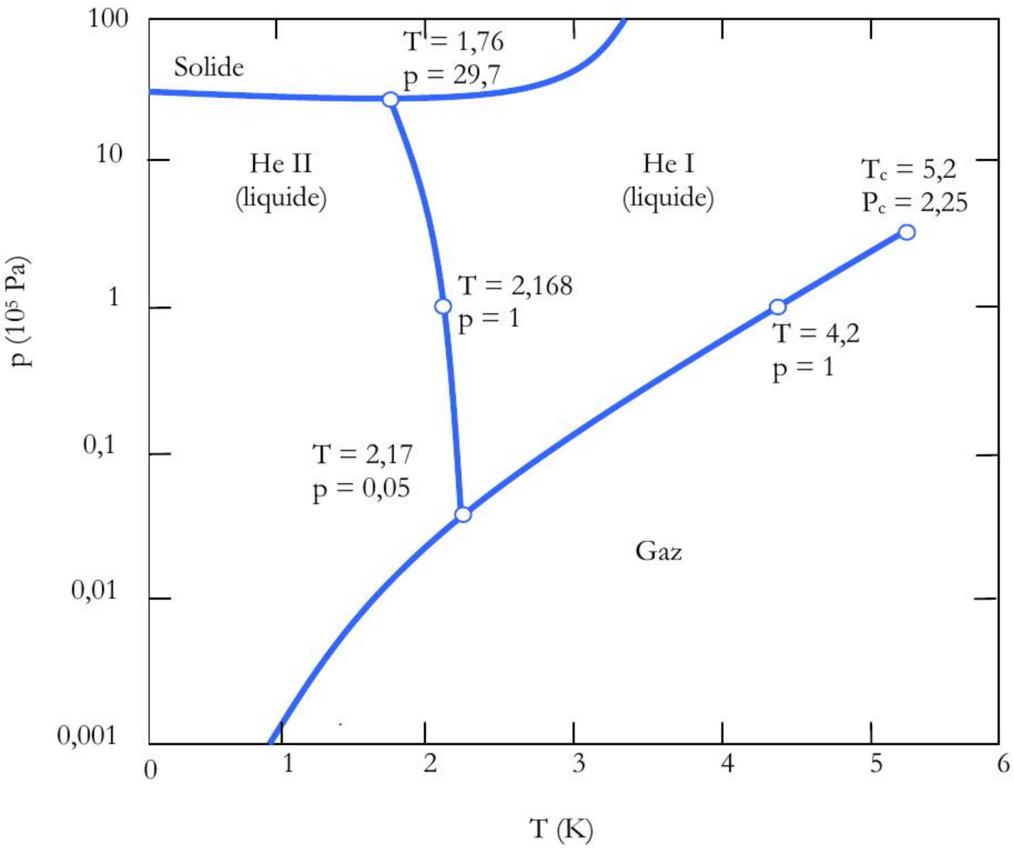


- The LHC’s magnets are made by repeatedly winding a superconducting cable into long coils.
- Superconducting magnets of the Large Hadron Collider (LHC) operate at 1.9K,
- These coils are encased inside a superfluid helium cryogenic system to keep the magnet at the operating temperature.
- Superfluid helium is a very efficient coolant
- The coils seen as porous materials, we are looking for a theory of helium superfluid in porous media to predict heat tranfer.

Helium phase diagram and superfluid transition



Helium phase diagram and superfluid transition

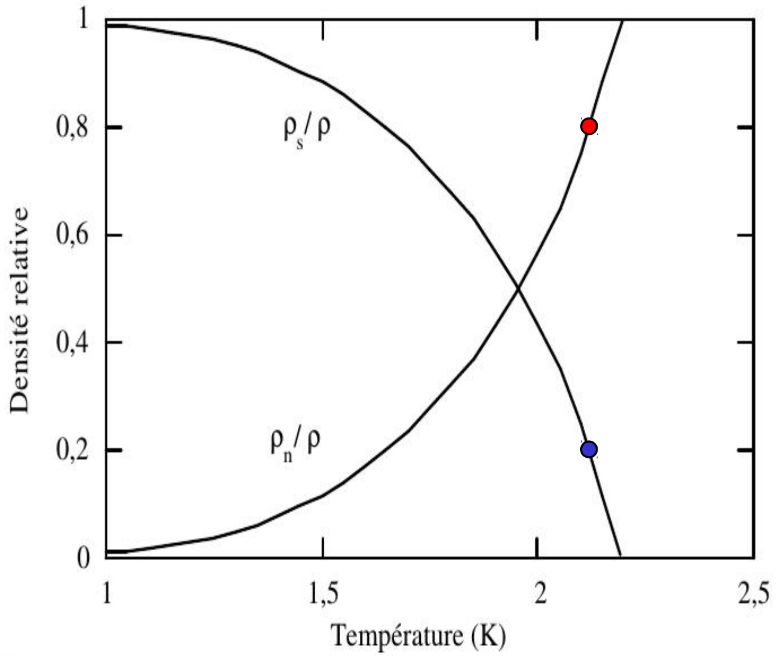


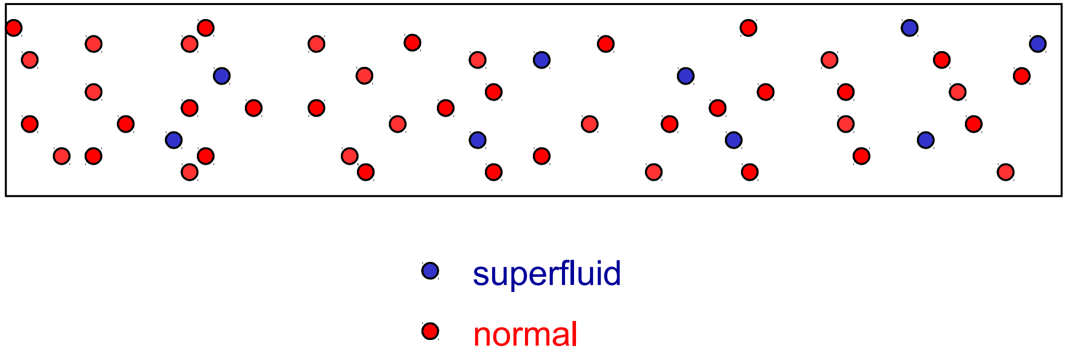
Alfred Leitner - Liquid Helium II the Superfluid
(www.alfredleitner.com or on youtube)

- Bottom of the beaker made of a porous membrane with pore-throat smaller than 1 micron,
- Above 2.17K, liquid helium (He I) is viscous and does not flow through the membrane,
- Below 2.17K, He II pours out. The flow rate is even faster at lower temperature.

Superfluid helium modeling

- He II can be thought as two interpenetrating fluids that are fully miscible and have temperature dependent densities[1],
  - The normal fluid component with a density ρ_n and a velocity v_n,
  - The superfluid component with a density ρ_s and a velocity v_s,

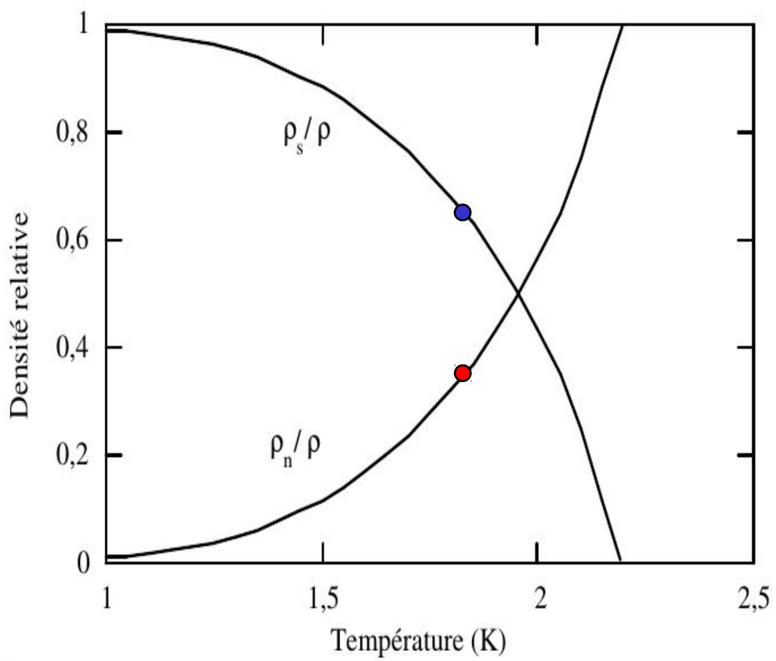


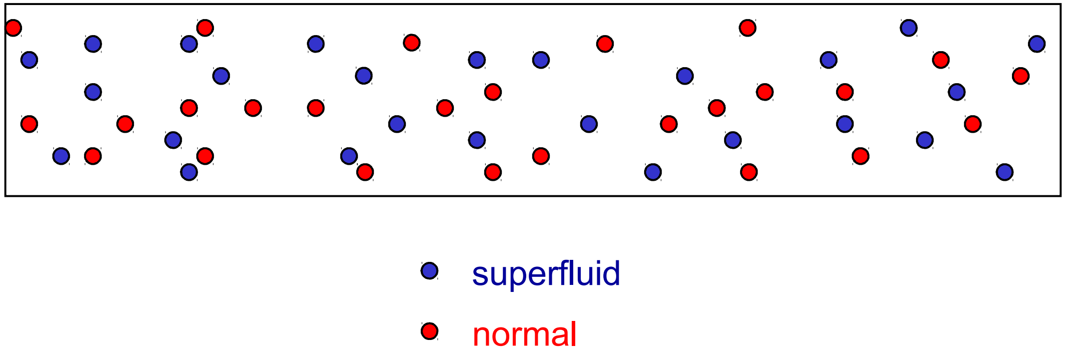


[1]Landau, L., Aug 1941. *Theory of the superfluidity of Helium II*. Phys. Rev. 60, 356–358.

Superfluid helium modeling

- He II can be thought as two interpenetrating fluids that are fully miscible and have temperature dependent densities[1],
  - The normal fluid component with a density ρ_n and a velocity v_n,
  - The superfluid component with a density ρ_s and a velocity v_s,

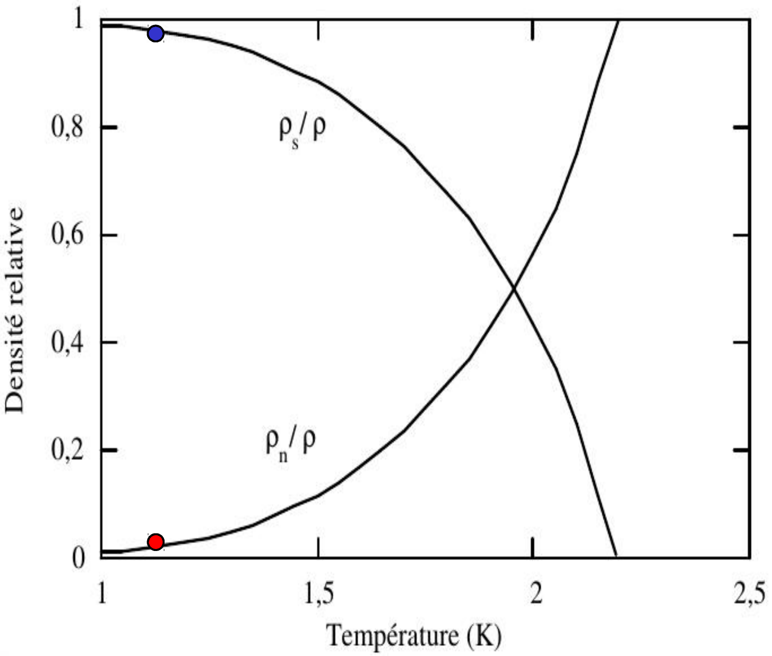


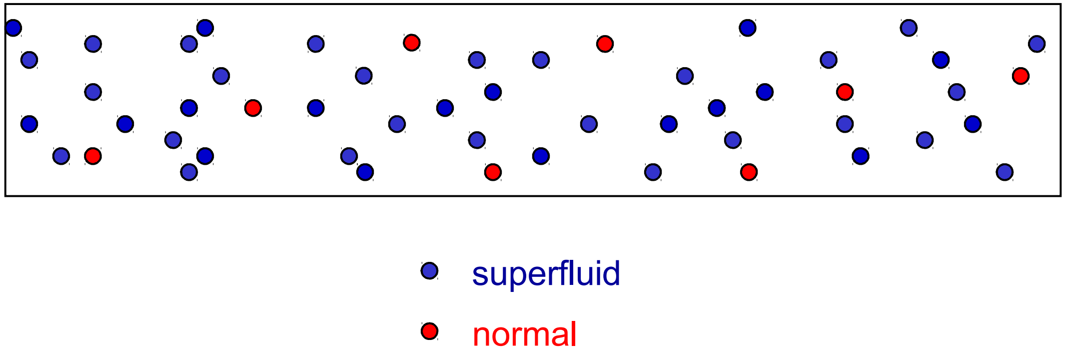


[1]Landau, L., Aug 1941. *Theory of the superfluidity of Helium II*. Phys. Rev. 60, 356–358.

Superfluid helium modeling

- He II can be thought as two interpenetrating fluids that are fully miscible and have temperature dependent densities[1],
  - The normal fluid component with a density ρ_n and a velocity v_n,
  - The superfluid component with a density ρ_s and a velocity v_s,

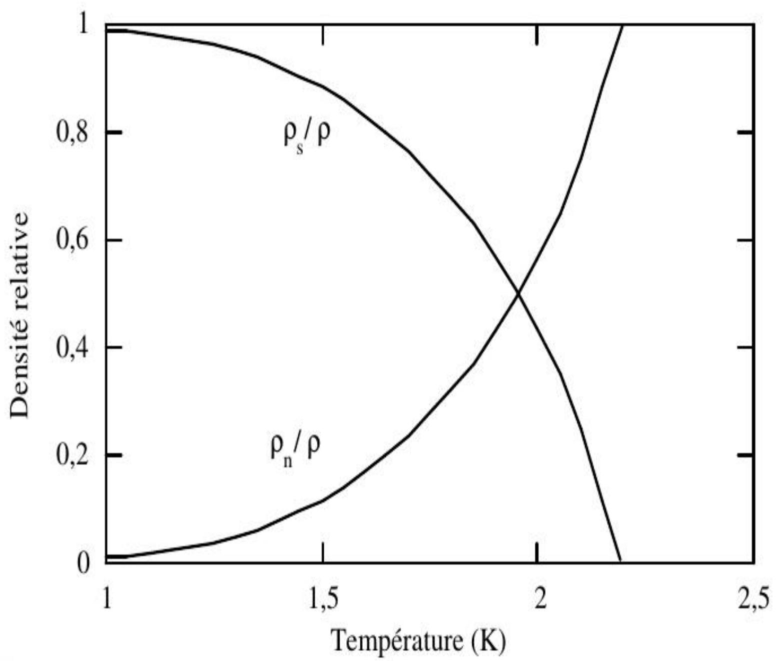


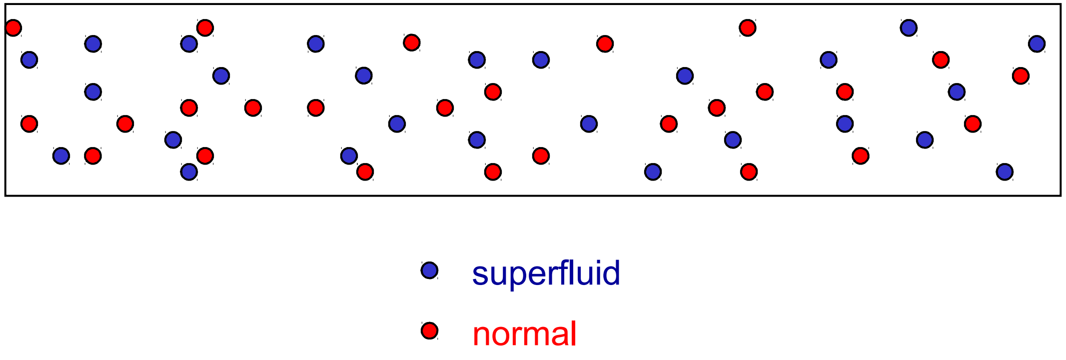


[1]Landau, L., Aug 1941. *Theory of the superfluidity of Helium II*. Phys. Rev. 60, 356–358.

Superfluid helium modeling

- He II can be thought as two interpenetrating fluids that are fully miscible and have temperature dependent densities[1],
  - The normal fluid component with a density ρ_n and a velocity v_n,
  - The superfluid component with a density ρ_s and a velocity v_s,
- The superfluid component carries no entropy and has no viscosity,
- The heat is carried by the normal component only,

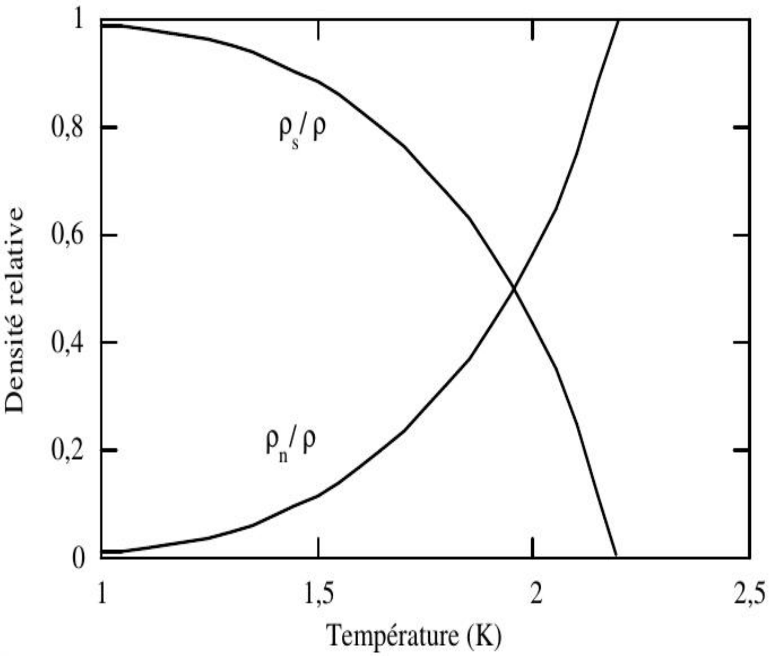


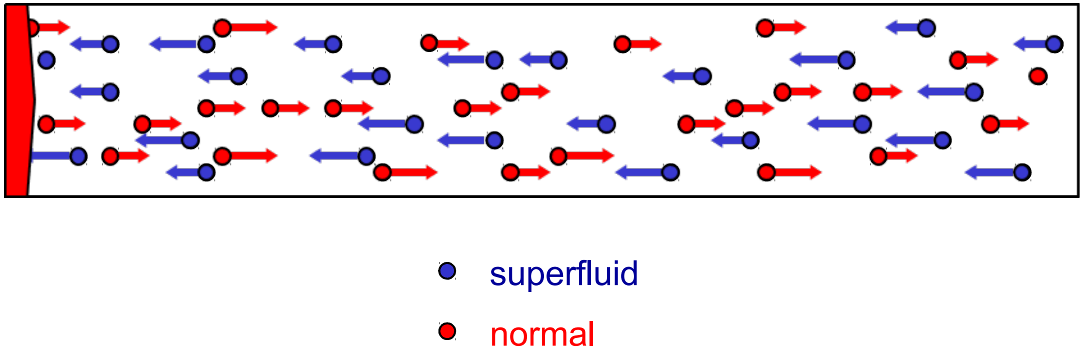


[1]Landau, L., Aug 1941. *Theory of the superfluidity of Helium II*. Phys. Rev. 60, 356–358.

Superfluid helium modeling

- He II can be thought as two interpenetrating fluids that are fully miscible and have temperature dependent densities[1],
  - The normal fluid component with a density ρ_n and a velocity v_n,
  - The superfluid component with a density ρ_s and a velocity v_s,
- The superfluid component carries no entropy and has no viscosity,
- The heat is carried by the normal component only,
- The two components flow at countercurrent when a temperature gradient is applied,

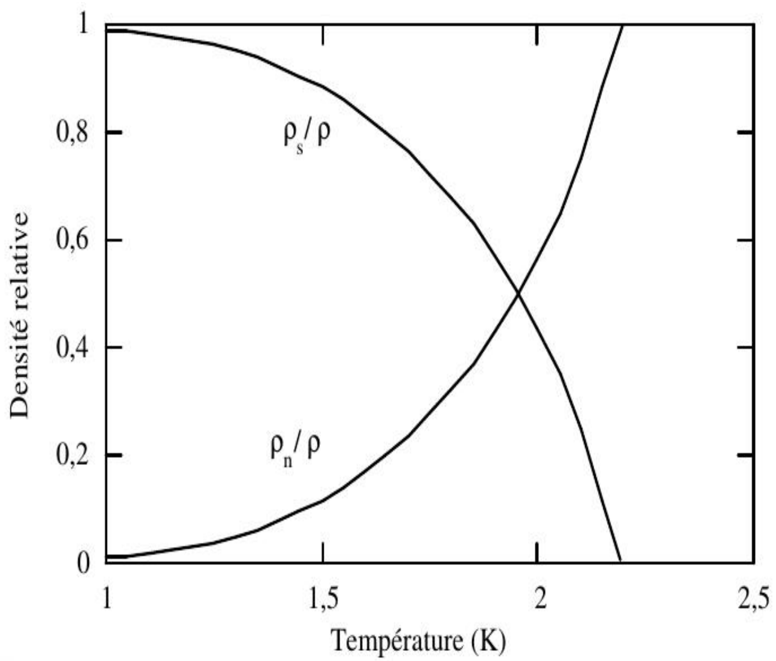


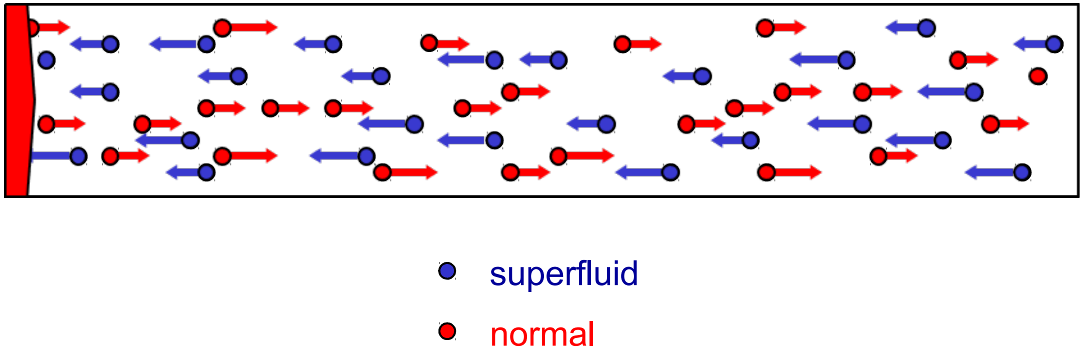


[1]Landau, L., Aug 1941. *Theory of the superfluidity of Helium II*. Phys. Rev. 60, 356–358.

Superfluid helium modeling

- He II can be thought as two interpenetrating fluids that are fully miscible and have temperature dependent densities[1],
  - The normal fluid component with a density ρ_n and a velocity v_n,
  - The superfluid component with a density ρ_s and a velocity v_s,
- The superfluid component carries no entropy and has no viscosity,
- The heat is carried by the normal component only,
- The two components flow at countercurrent when a temperature gradient is applied,
- Above a critical velocity, quantum turbulence arises.





[1]Landau, L., Aug 1941. *Theory of the superfluidity of Helium II*. Phys. Rev. 60, 356–358.

He II two-fluid model[1]

- Continuity equation for the total mass of fluid

$$\frac{\partial \rho}{\partial t} + \nabla \boldsymbol{\cdot} (\rho_n \mathbf{v}_n + \rho_s \mathbf{v}_s) = 0$$

[1]Landau, L., Aug 1941. *Theory of the superfluidity of Helium II*. Phys. Rev. 60, 356–358.
[2]Gorter, C., Mellink, J., 1949. *On the irreversible processes in liquid Helium-II*. Physica 15 (3-4), 285–304.
[3]Gorter, C., Kasteleijn, P., Mellink, J., 1950. *Discussion of the properties of Helium-II on the basis of the two fluid model*. Physica 16 (2), 113–121.

He II two-fluid model[1]

- Continuity equation for the total mass of fluid

$$\frac{\partial \rho}{\partial t} + \nabla . (\rho_n \mathbf{v}_n + \rho_s \mathbf{v}_s) = 0$$

- Momentum equation for the normal component

$$\frac{\partial \rho_n \mathbf{v}_n}{\partial t} + \nabla . (\rho_n \mathbf{v}_n \mathbf{v}_n) = -\frac{\rho_n}{\rho} \nabla p - \rho_s s \nabla T + \nabla . (\mu_n \nabla \mathbf{v}_n)$$

Thermo-mechanical force

- Momentum equation for the superfluid component

$$\frac{\partial \rho_s \mathbf{v}_s}{\partial t} + \nabla . (\rho_s \mathbf{v}_s \mathbf{v}_s) = -\frac{\rho_s}{\rho} \nabla p + \rho_s s \nabla T$$

[1]Landau, L., Aug 1941. *Theory of the superfluidity of Helium II*. Phys. Rev. 60, 356–358.
[2]Gorter, C., Mellink, J., 1949. *On the irreversible processes in liquid Helium-II*. Physica 15 (3-4), 285–304.
[3]Gorter, C., Kasteleijn, P., Mellink, J., 1950. *Discussion of the properties of Helium-II on the basis of the two fluid model*. Physica 16 (2), 113–121.

He II two-fluid model[1]

- Continuity equation for the total mass of fluid

$$\frac{\partial \rho}{\partial t} + \nabla . \left(\rho_n \mathbf{v}_n + \rho_s \mathbf{v}_s \right) = 0$$

- Momentum equation for the normal component

$$\frac{\partial \rho_n \mathbf{v}_n}{\partial t} + \nabla . (\rho_n \mathbf{v}_n \mathbf{v}_n) = -\frac{\rho_n}{\rho} \nabla p - \rho_s s \nabla T + \nabla . \left(\mu_n \nabla \mathbf{v}_n \right)$$

Thermo-mechanical force

- Momentum equation for the superfluid component

$$\frac{\partial \rho_s \mathbf{v}_s}{\partial t} + \nabla . (\rho_s \mathbf{v}_s \mathbf{v}_s) = -\frac{\rho_s}{\rho} \nabla p + \rho_s s \nabla T$$

- Entropy equation

$$\frac{\partial \rho s}{\partial t} + \nabla . (\rho s \mathbf{v}_n) = \nabla . \left(\frac{k_n}{T} \nabla T \right)$$

[1] Landau, L., Aug 1941. *Theory of the superfluidity of Helium II*. Phys. Rev. 60, 356–358.
[2] Gorter, C., Mellink, J., 1949. *On the irreversible processes in liquid Helium-II*. Physica 15 (3-4), 285–304.
[3] Gorter, C., Kasteleijn, P., Mellink, J., 1950. *Discussion of the properties of Helium-II on the basis of the two fluid model*. Physica 16 (2), 113–121.

He II two-fluid model[1]

- Continuity equation for the total mass of fluid

$$\frac{\partial \rho}{\partial t} + \nabla . (\rho_n \mathbf{v}_n + \rho_s \mathbf{v}_s) = 0$$

- Momentum equation for the normal component

$$\frac{\partial \rho_n \mathbf{v}_n}{\partial t} + \nabla . (\rho_n \mathbf{v}_n \mathbf{v}_n) = -\frac{\rho_n}{\rho} \nabla p - \rho_s s \nabla T + \nabla . (\mu_n \nabla \mathbf{v}_n)$$

Thermo-mechanical force

- Momentum equation for the superfluid component

$$\frac{\partial \rho_s \mathbf{v}_s}{\partial t} + \nabla . (\rho_s \mathbf{v}_s \mathbf{v}_s) = -\frac{\rho_s}{\rho} \nabla p + \rho_s s \nabla T$$

- Entropy equation

$$\frac{\partial \rho s}{\partial t} + \nabla . (\rho s \mathbf{v}_n) = \nabla . \left(\frac{k_n}{T} \nabla T \right)$$

- Slip conditions at walls for superfluid particles. No-slip for normal particles.

[1]Landau, L., Aug 1941. *Theory of the superfluidity of Helium II*. Phys. Rev. 60, 356–358.
[2]Gorter, C., Mellink, J., 1949. *On the irreversible processes in liquid Helium-II*. Physica 15 (3-4), 285–304.
[3]Gorter, C., Kasteleijn, P., Mellink, J., 1950. *Discussion of the properties of Helium-II on the basis of the two fluid model*. Physica 16 (2), 113–121.

He II two-fluid model[1]

- Continuity equation for the total mass of fluid

$$\frac{\partial \rho}{\partial t} + \nabla . (\rho_n \mathbf{v}_n + \rho_s \mathbf{v}_s) = 0$$

- Momentum equation for the normal component

$$\frac{\partial \rho_n \mathbf{v}_n}{\partial t} + \nabla . (\rho_n \mathbf{v}_n \mathbf{v}_n) = -\frac{\rho_n}{\rho} \nabla p - \rho_s s \nabla T + \nabla . (\mu_n \nabla \mathbf{v}_n) - A \rho_n \rho_s |\mathbf{v}_n - \mathbf{v}_s|^2 (\mathbf{v}_n - \mathbf{v}_s)$$

Thermo-mechanical force

Gorter-Mellink mutual friction term[2,3]

- Momentum equation for the superfluid component

$$\frac{\partial \rho_s \mathbf{v}_s}{\partial t} + \nabla . (\rho_s \mathbf{v}_s \mathbf{v}_s) = -\frac{\rho_s}{\rho} \nabla p + \rho_s s \nabla T + A \rho_n \rho_s |\mathbf{v}_n - \mathbf{v}_s|^2 (\mathbf{v}_n - \mathbf{v}_s)$$

- Entropy equation

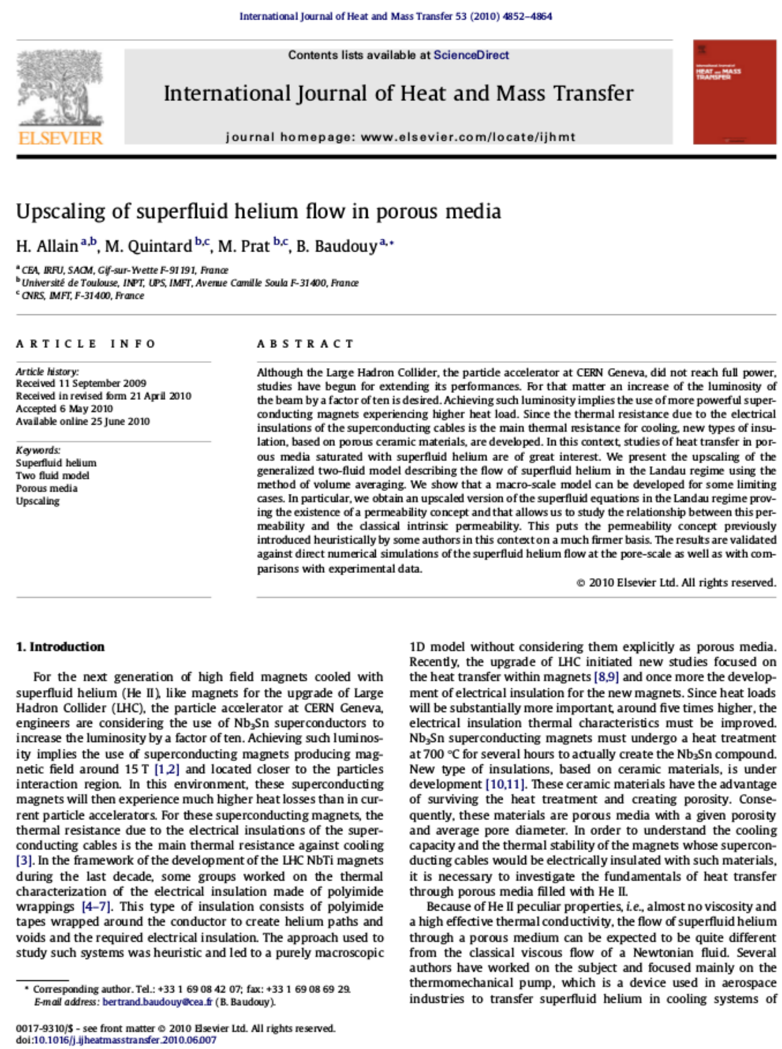
$$\frac{\partial \rho s}{\partial t} + \nabla . (\rho s \mathbf{v}_n) = \nabla . \left(\frac{k_n}{T} \nabla T \right) + \frac{A \rho_n \rho_s |\mathbf{v}_n - \mathbf{v}_s|^4}{T}$$

- Slip conditions at walls for superfluid particles. No-slip for normal particles.

[1]Landau, L., Aug 1941. *Theory of the superfluidity of Helium II*. Phys. Rev. 60, 356–358.
[2]Gorter, C., Mellink, J., 1949. *On the irreversible processes in liquid Helium-II*. Physica 15 (3-4), 285–304.
[3]Gorter, C., Kasteleijn, P., Mellink, J., 1950. *Discussion of the properties of Helium-II on the basis of the two fluid model*. Physica 16 (2), 113–121.

Upscaling superfluid helium flow in porous media

- Upscaling of superfluid helium flow in porous media in the Laudau regime[1]



International Journal of Heat and Mass Transfer 53 (2010) 4852–4864

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Upscaling of superfluid helium flow in porous media

H. Allain [a,b], M. Quintard [b,c], M. Prat [b,c], B. Baudouy [a,*]

[a] CEA, IRFU, SACM, Gif-sur-Yvette F-91191, France
[b] Université de Toulouse, INPT, UPS, IMFT, Avenue Camille Soula F-31400, France
[c] CNRS, IMFT, F-31400, France

A R T I C L E I N F O

Article history:
Received 11 September 2009
Received in revised form 21 April 2010
Accepted 6 May 2010
Available online 25 June 2010

Keywords:
Superfluid helium
Two fluid model
Porous media
Upscaling

A B S T R A C T

Although the Large Hadron Collider, the particle accelerator at CERN Geneva, did not reach full power, studies have begun for extending its performances. For that matter an increase of the luminosity of the beam by a factor of ten is desired. Achieving such luminosity implies the use of more powerful superconducting magnets experiencing higher heat load. Since the thermal resistance due to the electrical insulations of the superconducting cables is the main thermal resistance for cooling, new types of insulation, based on porous ceramic materials, are developed. In this context, studies of heat transfer in porous media saturated with superfluid helium are of great interest. We present the upscaling of the generalized two-fluid model describing the flow of superfluid helium in the Landau regime using the method of volume averaging. We show that a macro-scale model can be developed for some limiting cases. In particular, we obtain an upscaled version of the superfluid equations in the Landau regime proving the existence of a permeability concept and that allows us to study the relationship between this permeability and the classical intrinsic permeability. This puts the permeability concept previously introduced heuristically by some authors in this context on a much firmer basis. The results are validated against direct numerical simulations of the superfluid helium flow at the pore-scale as well as with comparisons with experimental data.

1. Introduction

For the next generation of high field magnets cooled with superfluid helium (He II), like magnets for the upgrade of Large Hadron Collider (LHC), the particle accelerator at CERN Geneva, engineers are considering the use of Nb_3Sn superconductors to increase the luminosity by a factor of ten. Achieving such luminosity implies the use of superconducting magnets producing magnetic field around 15 T [1,2] and located closer to the particles interaction region. In this environment, these superconducting magnets will then experience much higher heat losses than in current particle accelerators. For these superconducting magnets, the thermal resistance due to the electrical insulations of the superconducting cables is the main thermal resistance against cooling [3]. In the framework of the development of the LHC NbTi magnets during the last decade, some groups worked on the thermal characterization of the electrical insulation made of polyimide wrappings [4–7]. This type of insulation consists of polyimide tapes wrapped around the conductor to create helium paths and voids and the required electrical insulation. The approach used to study such systems was heuristic and led to a purely macroscopic 1D model without considering them explicitly as porous media. Recently, the upgrade of LHC initiated new studies focused on the heat transfer within magnets [8,9] and once more the development of electrical insulation for the new magnets. Since heat loads will be substantially more important, around five times higher, the electrical insulation thermal characteristics must be improved. Nb_3Sn superconducting magnets must undergo a heat treatment at 700 °C for several hours to actually create the Nb_3Sn compound. New type of insulations, based on ceramic materials, is under development [10,11]. These ceramic materials have the advantage of surviving the heat treatment and creating porosity. Consequently, these materials are porous media with a given porosity and average pore diameter. In order to understand the cooling capacity and the thermal stability of the magnets whose superconducting cables would be electrically insulated with such materials, it is necessary to investigate the fundamentals of heat transfer through porous media filled with He II.

Because of He II peculiar properties, *i.e.*, almost no viscosity and a high effective thermal conductivity, the flow of superfluid helium through a porous medium can be expected to be quite different from the classical viscous flow of a Newtonian fluid. Several authors have worked on the subject and focused mainly on the thermomechanical pump, which is a device used in aerospace industries to transfer superfluid helium in cooling systems of

* Corresponding author. Tel.: +33 1 69 08 42 07; fax: +33 1 69 08 69 29.
E-mail address: bertrand.baudouy@cea.fr (B. Baudouy).

0017-9310/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2010.06.007

[1]Allain et al., *Upscaling of superfluid helium flow in porous media*, International Journal of Heat and Mass Transfer 53 (2010), 4852-4864

Upscaling superfluid helium flow in porous media

- Upscaling of superfluid helium flow in porous media in the Laudau regime[1]
- In presence of quantum turbulence (i.e. in most of the operating situations), the mutual friction terms have to be average and closed...

$$\left\langle A\rho_n\rho_s\left|\mathbf{v}_n-\mathbf{v}_s\right|^2\left(\mathbf{v}_n-\mathbf{v}_s\right)\right\rangle$$

$$\left\langle \frac{A\rho_n\rho_s\left|\mathbf{v}_n-\mathbf{v}_s\right|^4}{T}\right\rangle$$

International Journal of Heat and Mass Transfer 53 (2010) 4852–4864

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Upscaling of superfluid helium flow in porous media

H. Allain [a,b], M. Quintard [b,c], M. Prat [b,c], B. Baudouy [a,*]

[a] CEA, IRFU, SACM, Gif-sur-Yvette F-91191, France
[b] Université de Toulouse, INPT, UPS, IMFT, Avenue Camille Soula F-31400, France
[c] CNRS, IMFT, F-31400, France

ARTICLE INFO

Article history:
Received 11 September 2009
Received in revised form 21 April 2010
Accepted 6 May 2010
Available online 25 June 2010

Keywords:
Superfluid helium
Two fluid model
Porous media
Upscaling

ABSTRACT

Although the Large Hadron Collider, the particle accelerator at CERN Geneva, did not reach full power, studies have begun for extending its performances. For that matter an increase of the luminosity of the beam by a factor of ten is desired. Achieving such luminosity implies the use of more powerful superconducting magnets experiencing higher heat load. Since the thermal resistance due to the electrical insulations of the superconducting cables is the main thermal resistance for cooling, new types of insulation, based on porous ceramic materials, are developed. In this context, studies of heat transfer in porous media saturated with superfluid helium are of great interest. We present the upscaling of the generalized two-fluid model describing the flow of superfluid helium in the Landau regime using the method of volume averaging. We show that a macro-scale model can be developed for some limiting cases. In particular, we obtain an upscaled version of the superfluid equations in the Landau regime proving the existence of a permeability concept and that allows us to study the relationship between this permeability and the classical intrinsic permeability. This puts the permeability concept previously introduced heuristically by some authors in this context on a much firmer basis. The results are validated against direct numerical simulations of the superfluid helium flow at the pore-scale as well as with comparisons with experimental data.

1. Introduction

For the next generation of high field magnets cooled with superfluid helium (He II), like magnets for the upgrade of Large Hadron Collider (LHC), the particle accelerator at CERN Geneva, engineers are considering the use of Nb_3Sn superconductors to increase the luminosity by a factor of ten. Achieving such luminosity implies the use of superconducting magnets producing magnetic field around 15 T [1,2] and located closer to the particles interaction region. In this environment, these superconducting magnets will then experience much higher heat losses than in current particle accelerators. For these superconducting magnets, the thermal resistance due to the electrical insulations of the superconducting cables is the main thermal resistance against cooling [3]. In the framework of the development of the LHC NbTi magnets during the last decade, some groups worked on the thermal characterization of the electrical insulation made of polyimide wrappings [4–7]. This type of insulation consists of polyimide tapes wrapped around the conductor to create helium paths and voids and the required electrical insulation. The approach used to study such systems was heuristic and led to a purely macroscopic 1D model without considering them explicitly as porous media. Recently, the upgrade of LHC initiated new studies focused on the heat transfer within magnets [8,9] and once more the development of electrical insulation for the new magnets. Since heat loads will be substantially more important, around five times higher, the electrical insulation thermal characteristics must be improved. Nb_3Sn superconducting magnets must undergo a heat treatment at 700 °C for several hours to actually create the Nb_3Sn compound. New type of insulations, based on ceramic materials, is under development [10,11]. These ceramic materials have the advantage of surviving the heat treatment and creating porosity. Consequently, these materials are porous media with a given porosity and average pore diameter. In order to understand the cooling capacity and the thermal stability of the magnets whose superconducting cables would be electrically insulated with such materials, it is necessary to investigate the fundamentals of heat transfer through porous media filled with He II.

Because of He II peculiar properties, *i.e.*, almost no viscosity and a high effective thermal conductivity, the flow of superfluid helium through a porous medium can be expected to be quite different from the classical viscous flow of a Newtonian fluid. Several authors have worked on the subject and focused mainly on the thermomechanical pump, which is a device used in aerospace industries to transfer superfluid helium in cooling systems of

* Corresponding author. Tel.: +33 1 69 08 42 07; fax: +33 1 69 08 69 29.
E-mail address: bertrand.baudouy@cea.fr (B. Baudouy).

0017-9310/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2010.06.007

[1]Allain et al., *Upscaling of superfluid helium flow in porous media*, International Journal of Heat and Mass Transfer 53 (2010), 4852-4864

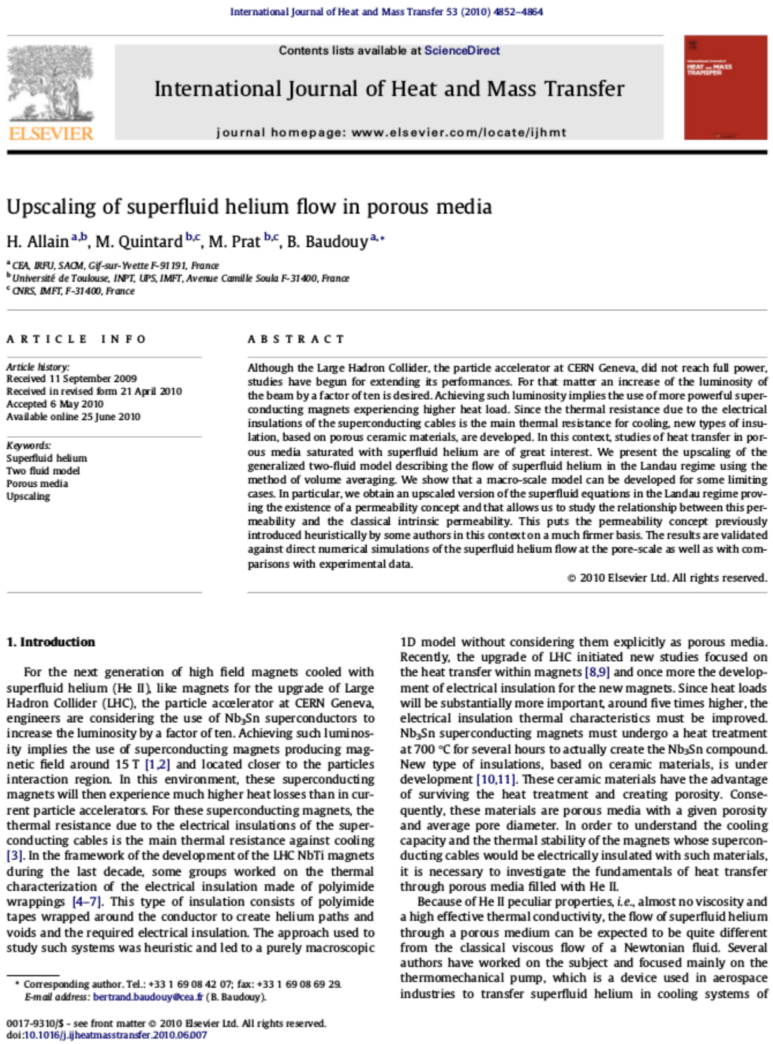
Upscaling superfluid helium flow in porous media

- Upscaling of superfluid helium flow in porous media in the Laudau regime[1]
- In presence of quantum turbulence (i.e. in most of the operating situations), the mutual friction terms have to be average and closed...

$$\left\langle A\rho_n\rho_s \left|\mathbf{v}_n - \mathbf{v}_s\right|^2 (\mathbf{v}_n - \mathbf{v}_s) \right\rangle$$

$$\left\langle \frac{A\rho_n\rho_s \left|\mathbf{v}_n - \mathbf{v}_s\right|^4}{T} \right\rangle$$

- Solve the physics at the pore-scale to get new insights into the quantum turbulence patterns.



International Journal of Heat and Mass Transfer 53 (2010) 4852–4864

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

ELSEVIER

Upscaling of superfluid helium flow in porous media

H. Allain [a,b], M. Quintard [b,c], M. Prat [b,c], B. Baudouy [a,*]

[a] CEA, IRFU, SACM, Gif-sur-Yvette F-91191, France
[b] Université de Toulouse, INPT, UPS, IMFT, Avenue Camille Soula F-31400, France
[c] CNRS, IMFT, F-31400, France

A R T I C L E I N F O

Article history:
Received 11 September 2009
Received in revised form 21 April 2010
Accepted 6 May 2010
Available online 25 June 2010

Keywords:
Superfluid helium
Two fluid model
Porous media
Upscaling

A B S T R A C T

Although the Large Hadron Collider, the particle accelerator at CERN Geneva, did not reach full power, studies have begun for extending its performances. For that matter an increase of the luminosity of the beam by a factor of ten is desired. Achieving such luminosity implies the use of more powerful superconducting magnets experiencing higher heat load. Since the thermal resistance due to the electrical insulations of the superconducting cables is the main thermal resistance for cooling, new types of insulation, based on porous ceramic materials, are developed. In this context, studies of heat transfer in porous media saturated with superfluid helium are of great interest. We present the upscaling of the generalized two-fluid model describing the flow of superfluid helium in the Landau regime using the method of volume averaging. We show that a macro-scale model can be developed for some limiting cases. In particular, we obtain an upscaled version of the superfluid equations in the Landau regime proving the existence of a permeability concept and that allows us to study the relationship between this permeability and the classical intrinsic permeability. This puts the permeability concept previously introduced heuristically by some authors in this context on a much firmer basis. The results are validated against direct numerical simulations of the superfluid helium flow at the pore-scale as well as with comparisons with experimental data.

1. Introduction

For the next generation of high field magnets cooled with superfluid helium (He II), like magnets for the upgrade of Large Hadron Collider (LHC), the particle accelerator at CERN Geneva, engineers are considering the use of Nb_3Sn superconductors to increase the luminosity by a factor of ten. Achieving such luminosity implies the use of superconducting magnets producing magnetic field around 15 T [1,2] and located closer to the particles interaction region. In this environment, these superconducting magnets will then experience much higher heat losses than in current particle accelerators. For these superconducting magnets, the thermal resistance due to the electrical insulations of the superconducting cables is the main thermal resistance against cooling [3]. In the framework of the development of the LHC NbTi magnets during the last decade, some groups worked on the thermal characterization of the electrical insulation made of polyimide wrappings [4–7]. This type of insulation consists of polyimide tapes wrapped around the conductor to create helium paths and voids and the required electrical insulation. The approach used to study such systems was heuristic and led to a purely macroscopic 1D model without considering them explicitly as porous media. Recently, the upgrade of LHC initiated new studies focused on the heat transfer within magnets [8,9] and once more the development of electrical insulation for the new magnets. Since heat loads will be substantially more important, around five times higher, the electrical insulation thermal characteristics must be improved. Nb_3Sn superconducting magnets must undergo a heat treatment at 700 °C for several hours to actually create the Nb_3Sn compound. New type of insulations, based on ceramic materials, is under development [10,11]. These ceramic materials have the advantage of surviving the heat treatment and creating porosity. Consequently, these materials are porous media with a given porosity and average pore diameter. In order to understand the cooling capacity and the thermal stability of the magnets whose superconducting cables would be electrically insulated with such materials, it is necessary to investigate the fundamentals of heat transfer through porous media filled with He II.

Because of He II peculiar properties, *i.e.*, almost no viscosity and a high effective thermal conductivity, the flow of superfluid helium through a porous medium can be expected to be quite different from the classical viscous flow of a Newtonian fluid. Several authors have worked on the subject and focused mainly on the thermomechanical pump, which is a device used in aerospace industries to transfer superfluid helium in cooling systems of

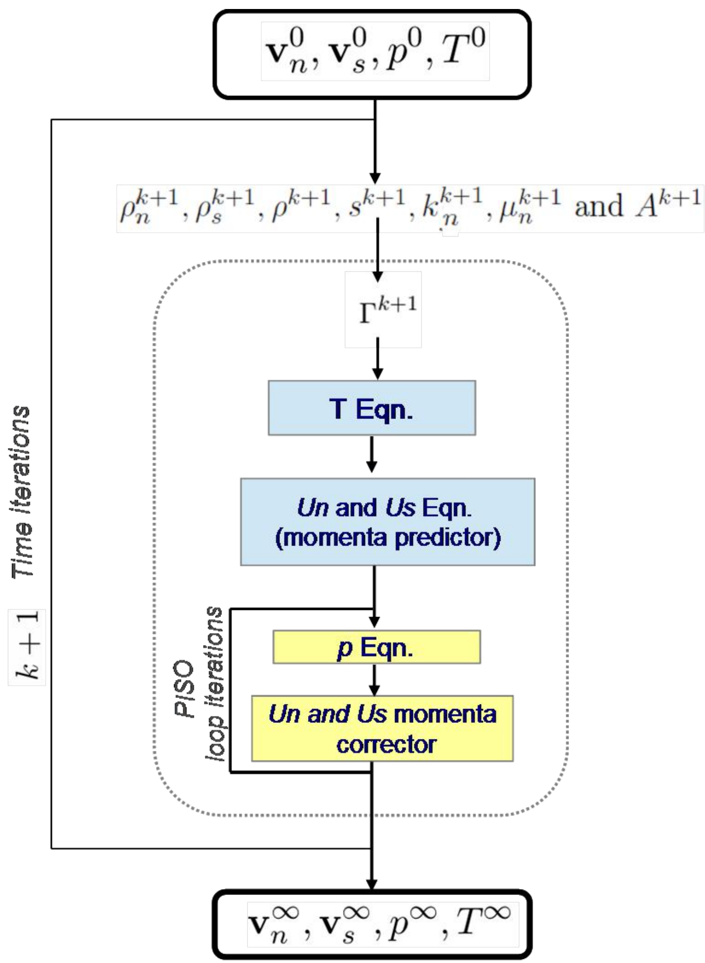
* Corresponding author. Tel.: +33 1 69 08 42 07; fax: +33 1 69 08 69 29.
E-mail address: bertrand.baudouy@cea.fr (B. Baudouy).

0017-9310/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2010.06.007

[1]Allain et al., *Upscaling of superfluid helium flow in porous media*, International Journal of Heat and Mass Transfer 53 (2010), 4852-4864

HeIIFOAM: superfluid helium flow simulator

HeIIFOAM = Superfluid Helium (He II) modeling with OpenFOAM®

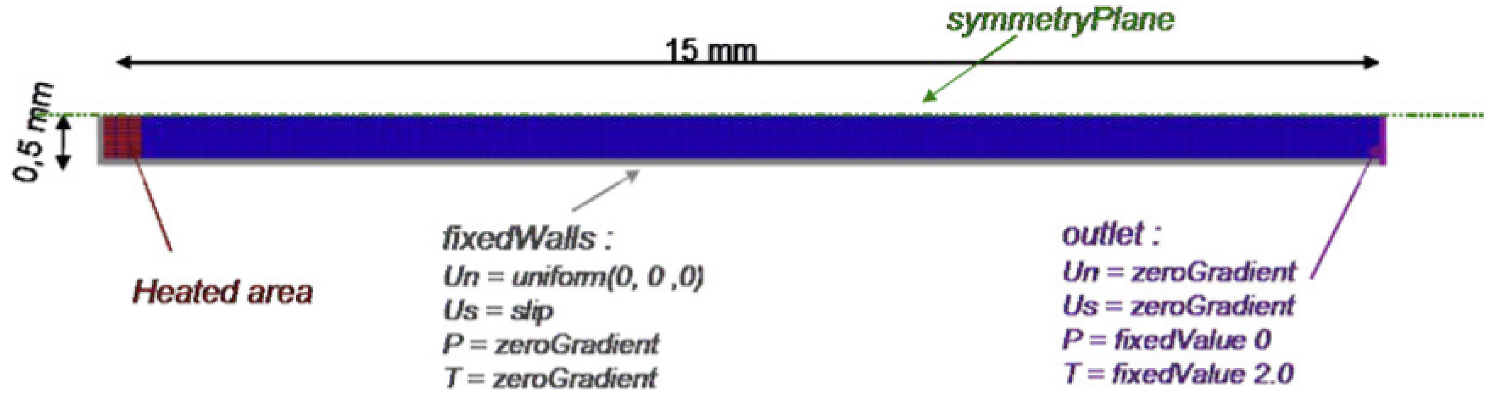


- Segregated approach for the Temperature-Pressure-Velocities coupling using the Super-PISO algorithm*.
- The pressure equation is formed by combining the momentum equations and the mass balance equation.
- The physical properties are function of the temperature.
- The heater is modeled by a volumic source term in the energy equation.
- Benefit of all the OpenFOAM features (3D, unstructured meshes, parallel simulations…)
- Public release of the code :

https://github.com/csoulain/HeIIFOAM

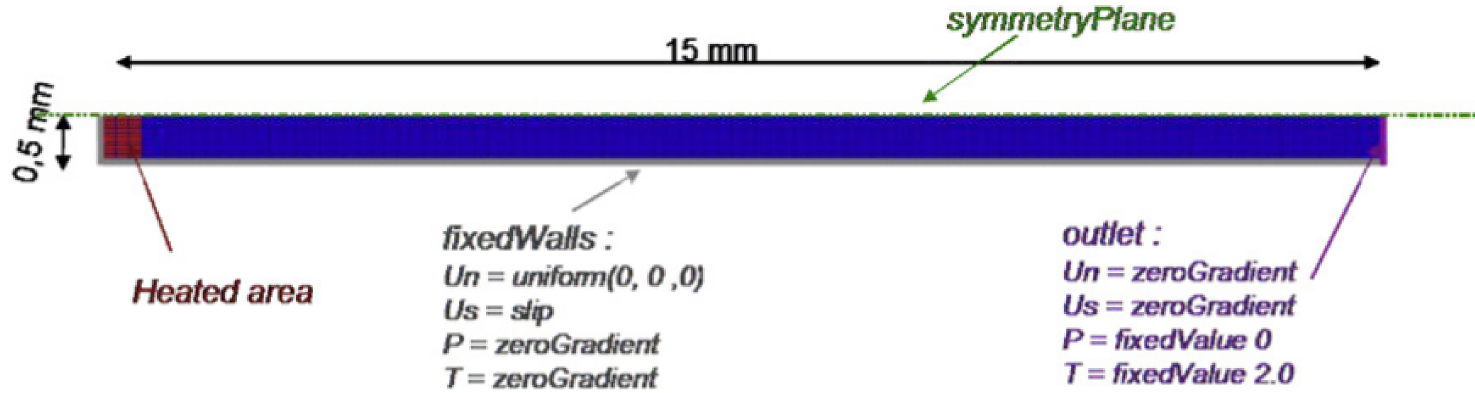
[1]Soulaine et al., *A PISO-like algorithm to simulate superfluid helium flow with the two-fluid model*, Computer Physics Communications 187 (2015), 20-28

Superfluid helium flow in a capillary tube

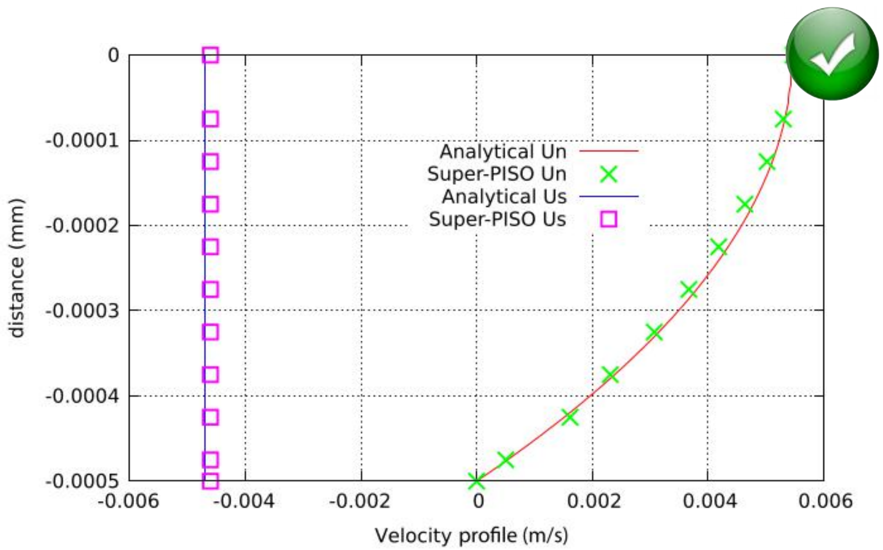


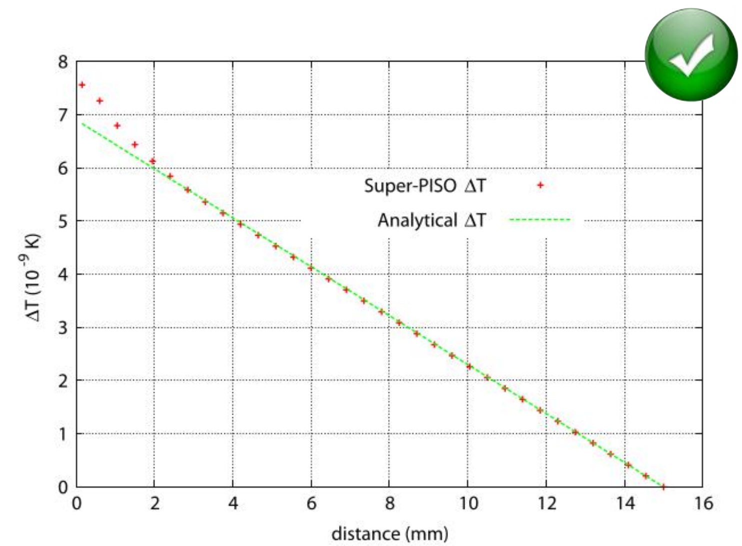
[1]Soulaine et al., *A PISO-like algorithm to simulate superfluid helium flow with the two-fluid model*, Computer Physics Communications 187 (2015), 20-28

Superfluid helium flow in a capillary tube



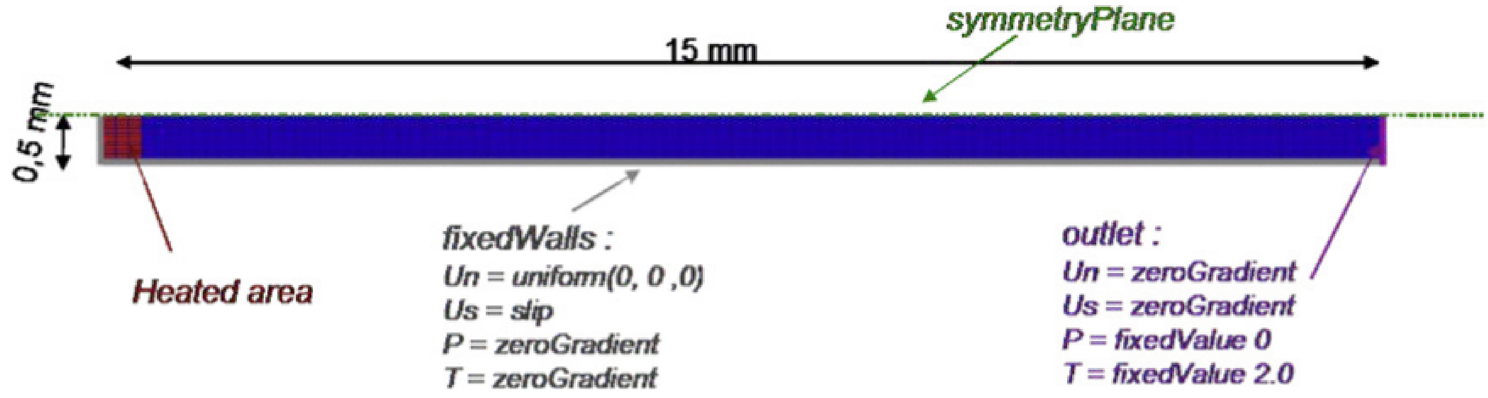
Without quantum turbulence
$q = 1\ kW/m^2$
(Landau regime)



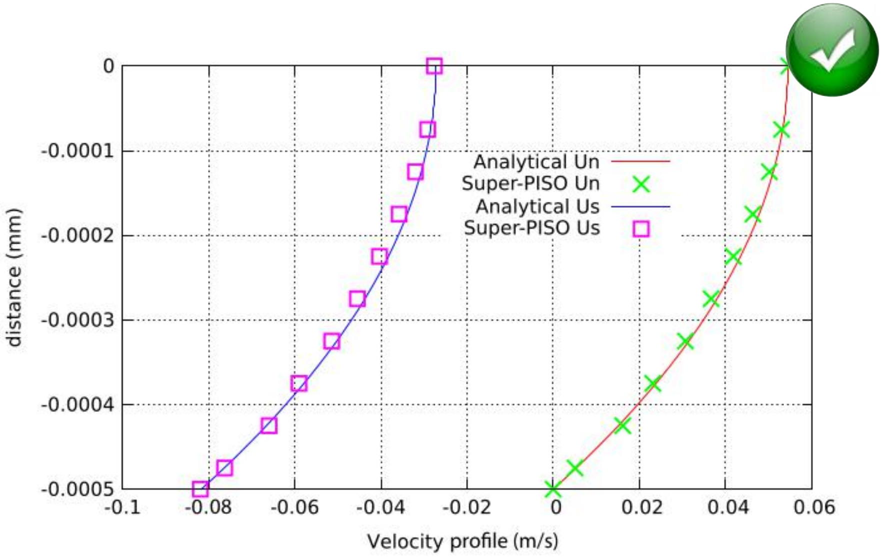


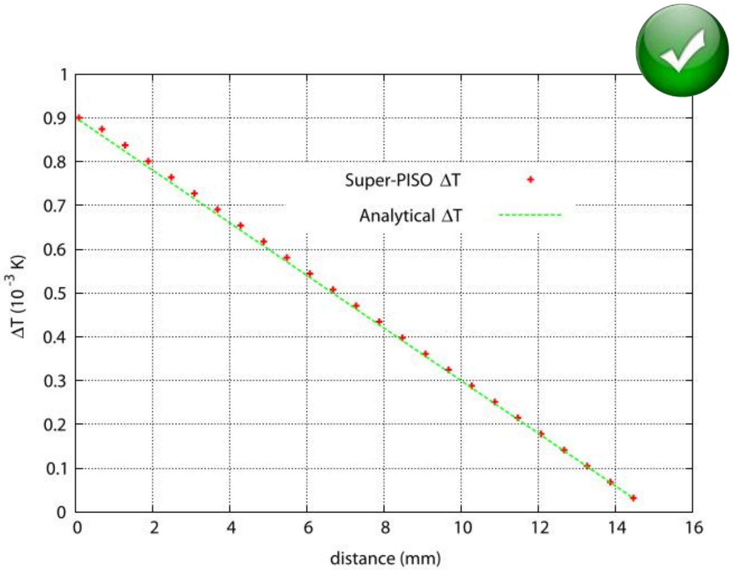
[1]Soulaine et al., *A PISO-like algorithm to simulate superfluid helium flow with the two-fluid model*, Computer Physics Communications 187 (2015), 20-28

Superfluid helium flow in a capillary tube



With quantum turbulence
q= 10 kW/m²
(Gorter-Mellink regime)

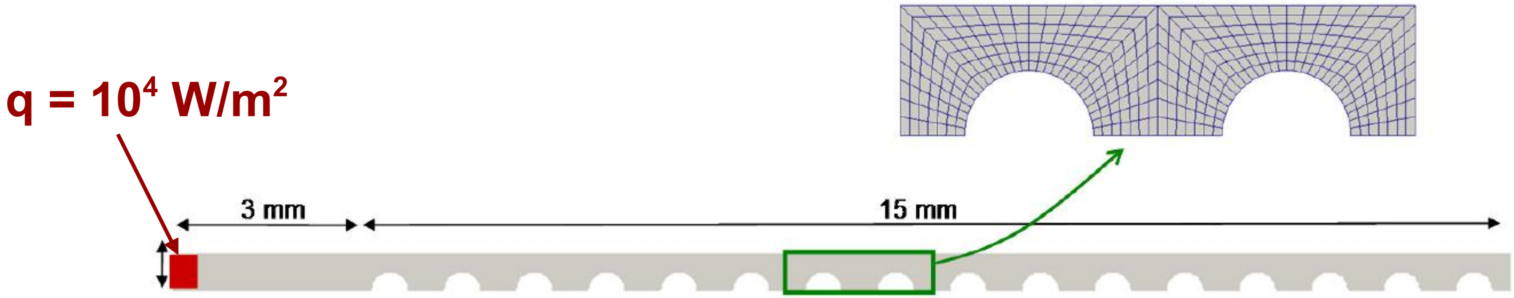




[1]Soulaine et al., *A PISO-like algorithm to simulate superfluid helium flow with the two-fluid model*, Computer Physics Communications 187 (2015), 20-28

Superfluid helium flow in a model porous medium[1]

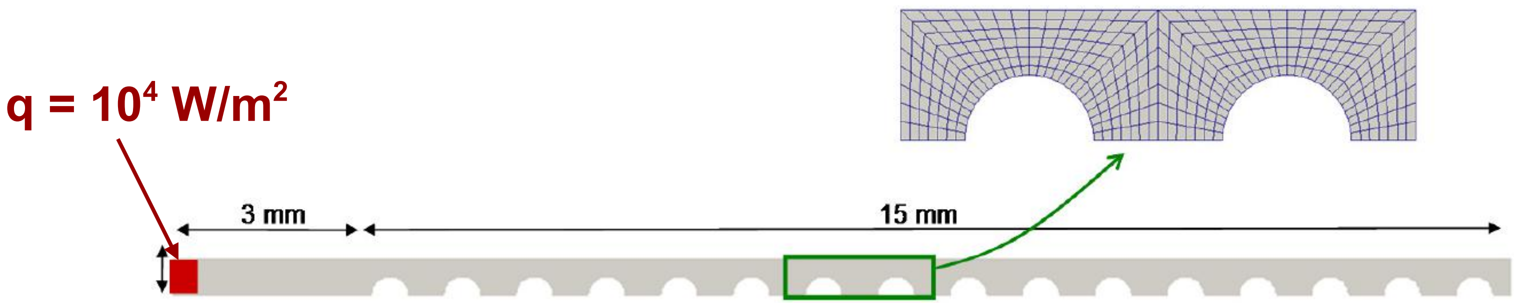
Objective: Investigate the superfluid flow in porous media in the Gorter-Mellink regime



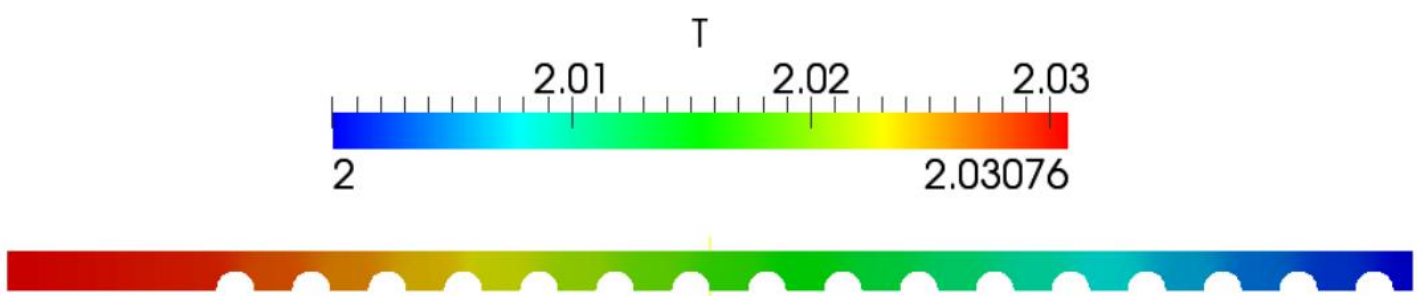
[1]Soulaine et al., *A PISO-like algorithm to simulate superfluid helium flow with the two-fluid model*, Computer Physics Communications 187 (2015), 20-28

Superfluid helium flow in a model porous medium[1]

Objective: Investigate the superfluid flow in porous media* in the Gorter-Mellink regime



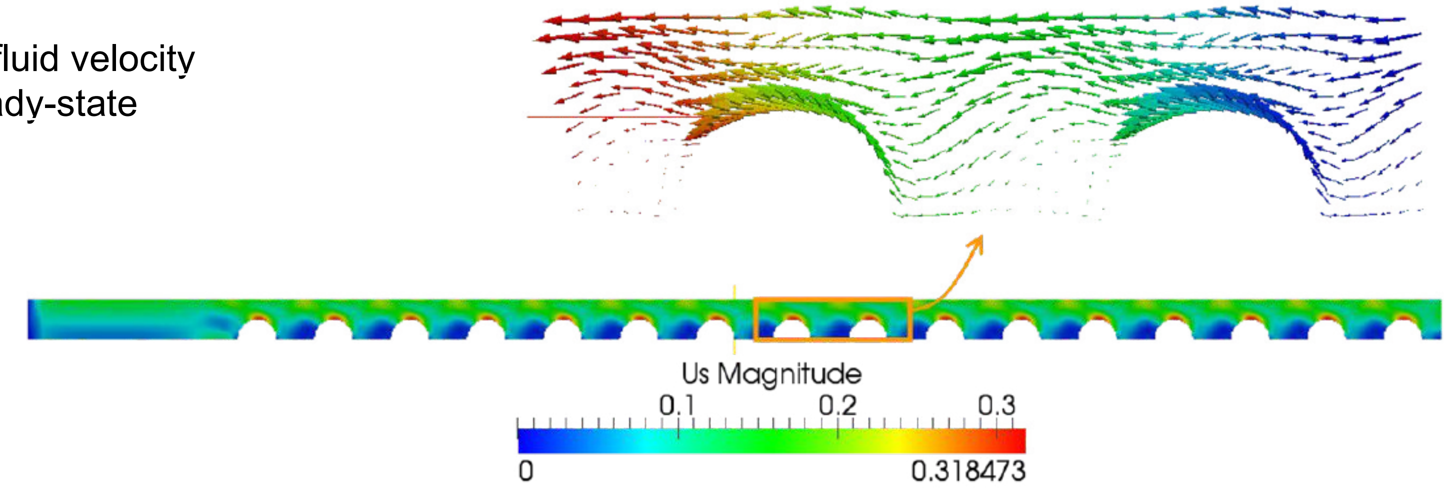
Temperature profile at steady-state



[1]Soulaine et al., *A PISO-like algorithm to simulate superfluid helium flow with the two-fluid model*, Computer Physics Communications 187 (2015), 20-28

Superfluid helium flow in a model porous medium[1]

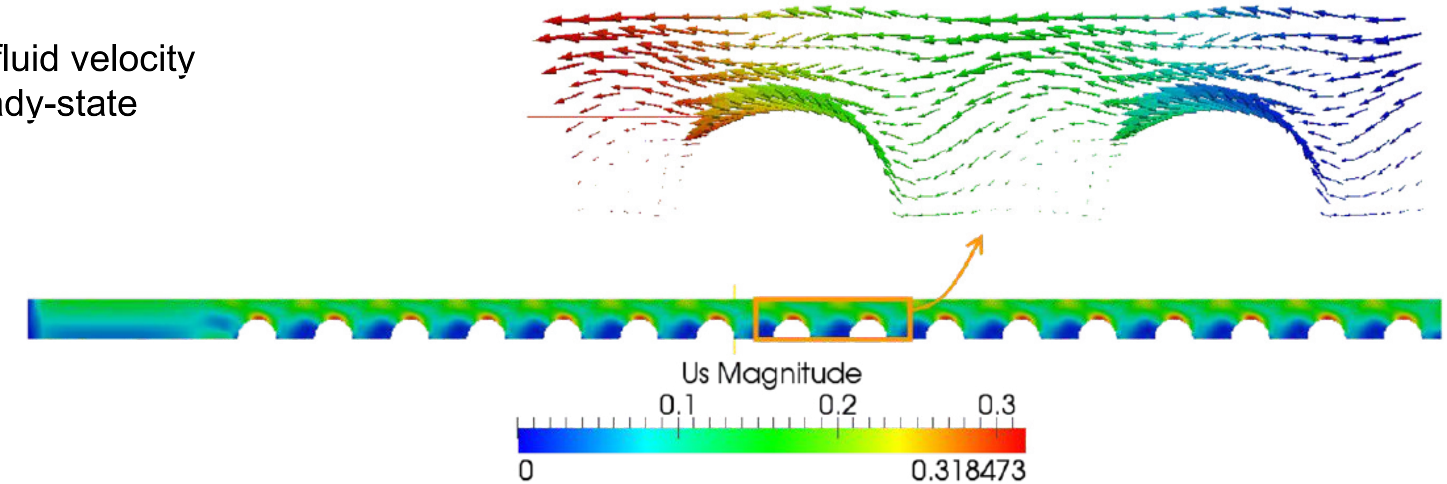
Superfluid velocity
at steady-state



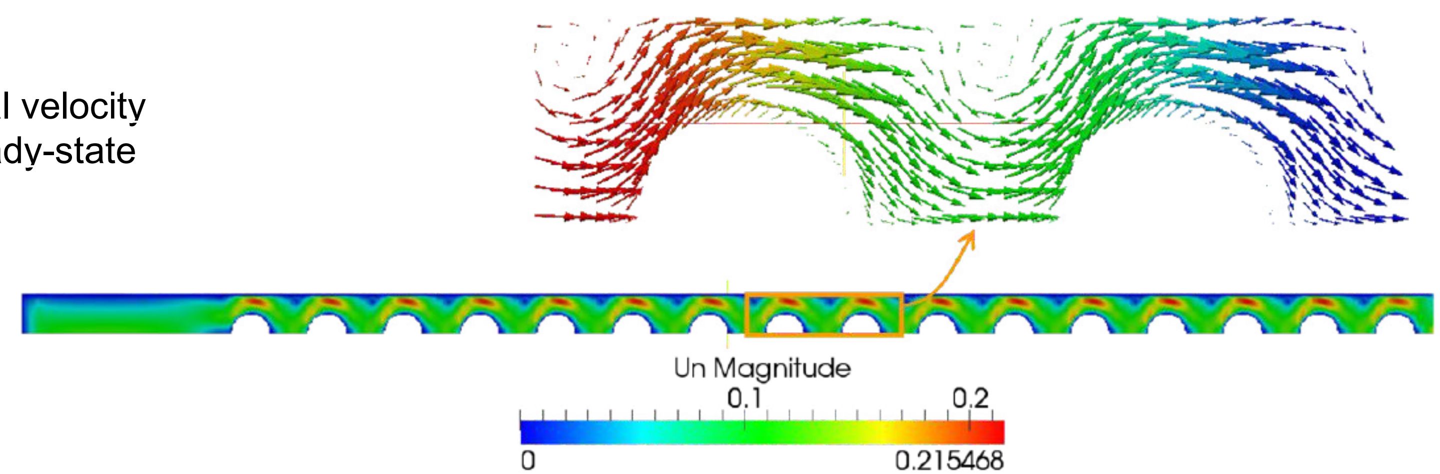
[1]Soulaine et al., *A PISO-like algorithm to simulate superfluid helium flow with the two-fluid model*, Computer Physics Communications 187 (2015), 20-28

Superfluid helium flow in a model porous medium[1]

Superfluid velocity
at steady-state



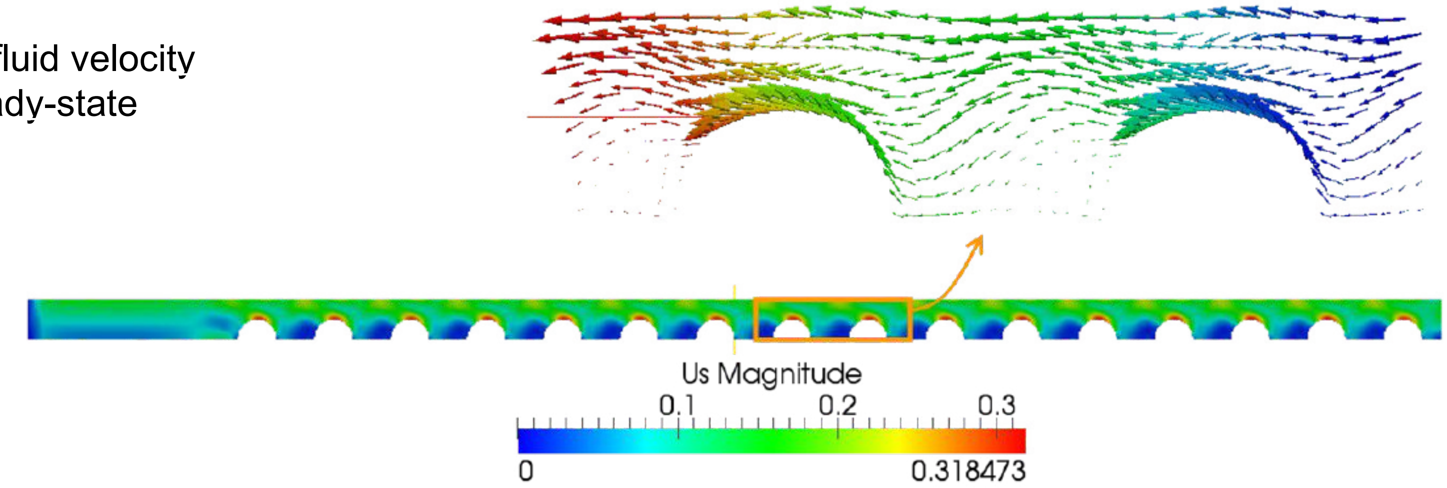
Normal velocity
at steady-state



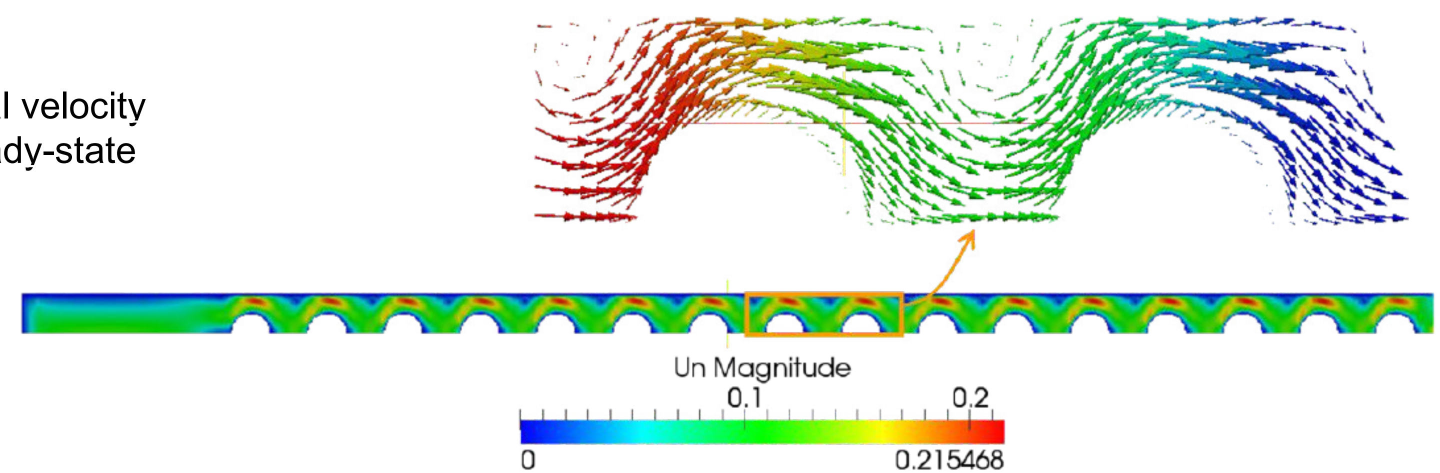
[1]Soulaine et al., *A PISO-like algorithm to simulate superfluid helium flow with the two-fluid model*, Computer Physics Communications 187 (2015), 20-28

Superfluid helium flow in a model porous medium[1]

Superfluid velocity
at steady-state

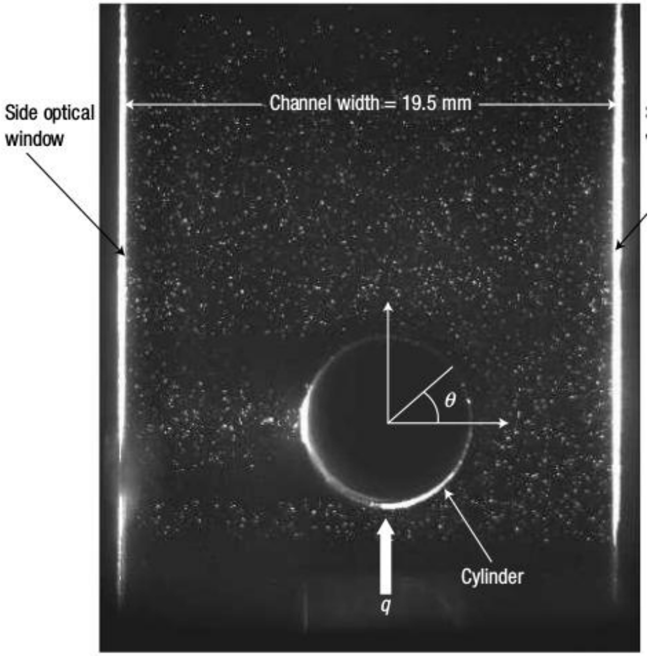


Normal velocity
at steady-state



[1]Soulaine et al., *A PISO-like algorithm to simulate superfluid helium flow with the two-fluid model*, Computer Physics Communications 187 (2015), 20-28

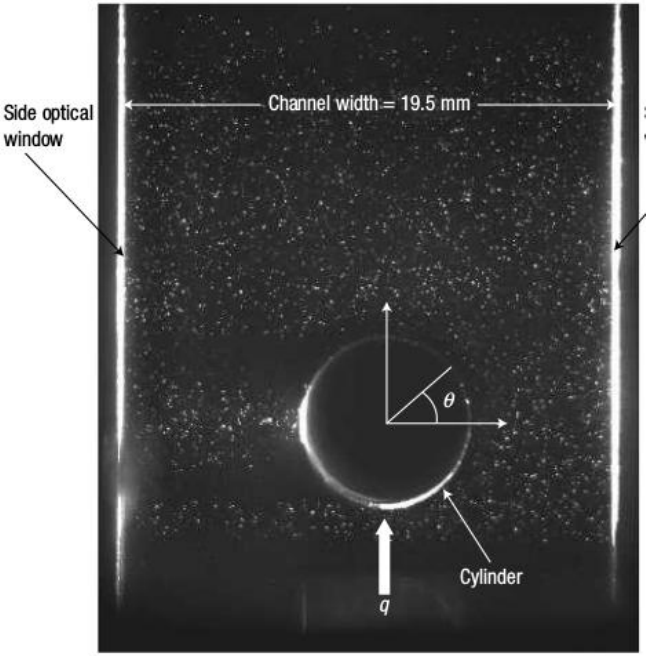
Flow past a cylinder: Zhang's experiment[1]

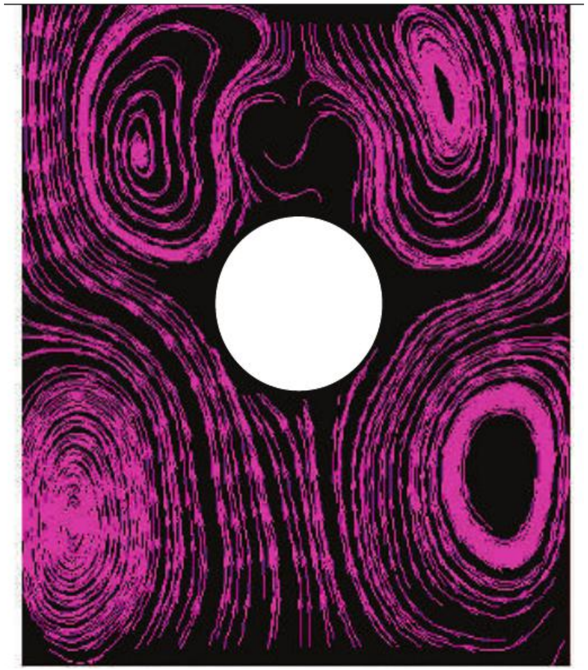


- PIV measurement of the flow of normal particles past a cylinder,

[1]Zhang T, Van Sciver SW, 2005. *Large scale turbulent flow around a cylinder in counterflow superfluid ^{4}He (He II)*. Nat Phys 1:36–38.

Flow past a cylinder: Zhang's experiment[1]



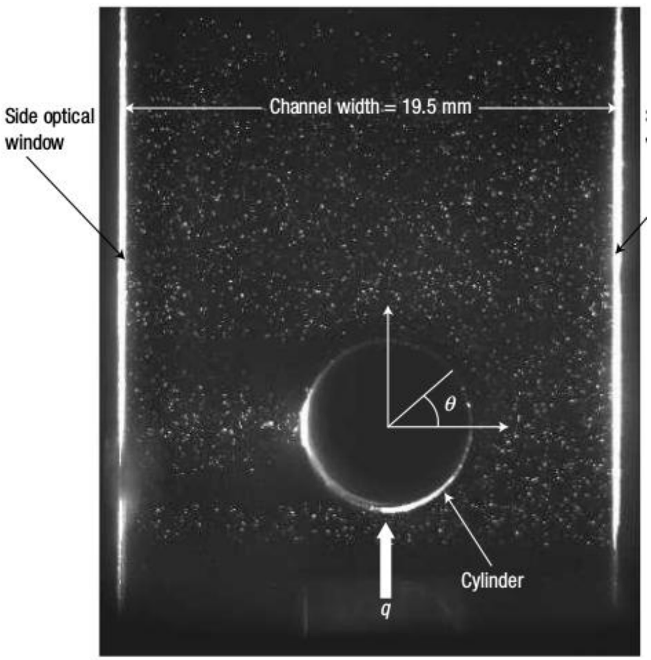


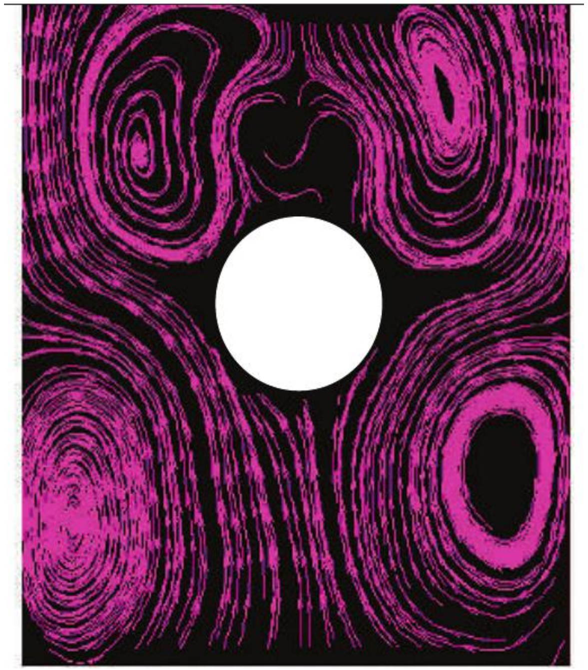
$q = 11.2\ \mathrm{kW\ m^{-2}}$ at $T = 2.03$ K corresponding to $\mathrm{Re}_D = 21{,}000$

- PIV measurement of the flow of normal particles past a cylinder,
- Unexpected eddies upstream the cylinder (results confirmed by other experiments),

[1]Zhang T, Van Sciver SW, 2005. *Large scale turbulent flow around a cylinder in counterflow superfluid ⁴He (He II)*. Nat Phys 1:36–38.

Flow past a cylinder: Zhang's experiment[1]





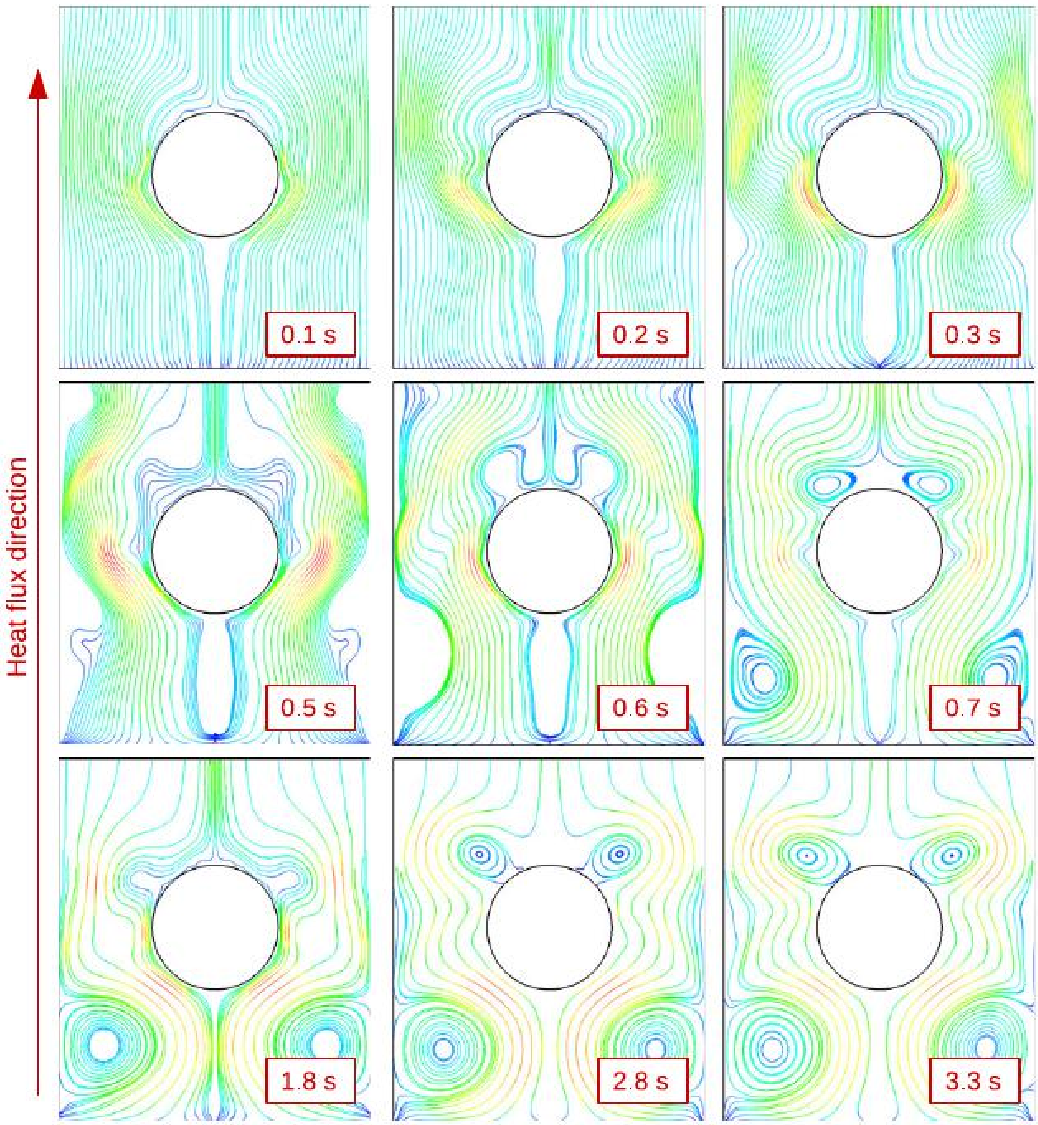
$q = 11.2\ \mathrm{kW\ m^{-2}}$ at $T = 2.03$ K corresponding to $\mathrm{Re_D} = 21{,}000$

$q = 4\ \mathrm{kW\ m^{-2}}$ at $T = 1.6$ K corresponding to $\mathrm{Re_D} = 41{,}000$

- PIV measurement of the flow of normal particles past a cylinder,
- Unexpected eddies upstream the cylinder (results confirmed by other experiments),
- The Reynolds number is not adequate to quantify the downstream vortices as in classic fluid dynamics.

[1]Zhang T, Van Sciver SW, 2005. *Large scale turbulent flow around a cylinder in counterflow superfluid ⁴He (He II)*. Nat Phys 1:36–38.

Numerical Investigation of Thermal Counterflow of He-II Past Cylinders



- Simulation of the thermal counterflow of superfluid helium past a cylinder including quantum turbulence with HellFOAM[1],
- At the early times, the streamlines (normal particles) follows the solid obstacles,
- Frictions at the walls (cylinder and channel) between the superfluid and normal particles that flow at countercurrent trigger recirculations both upstream and downstream,
- In agreement with experimental evidences, we obtain two large and very stable vortices upstream the cylinder and two vortices downstream,
- Downstream vortices are subject to fluctuations.
- All simulation reach a quasi-steady-state at about 3-4 seconds.

[1]Soulaine et al., *Numerical Investigation of Thermal Counterflow of He-II Past Cylinders*, Physical Review Letters 118, 074506 (2017)

Quantification of the quantum vortices

- Density ratio

$$a = (\rho_s^0/\rho_n^0)$$

- Reynolds number

$$\Re = (\rho_n^0 v_n^0 d/\mu_n^0)$$

- Dimensionless number that quantifies the mutual friction over inertia

$$\gamma = A^0\mu_n^0 \frac{(1+a)^3}{a^2}\Re$$

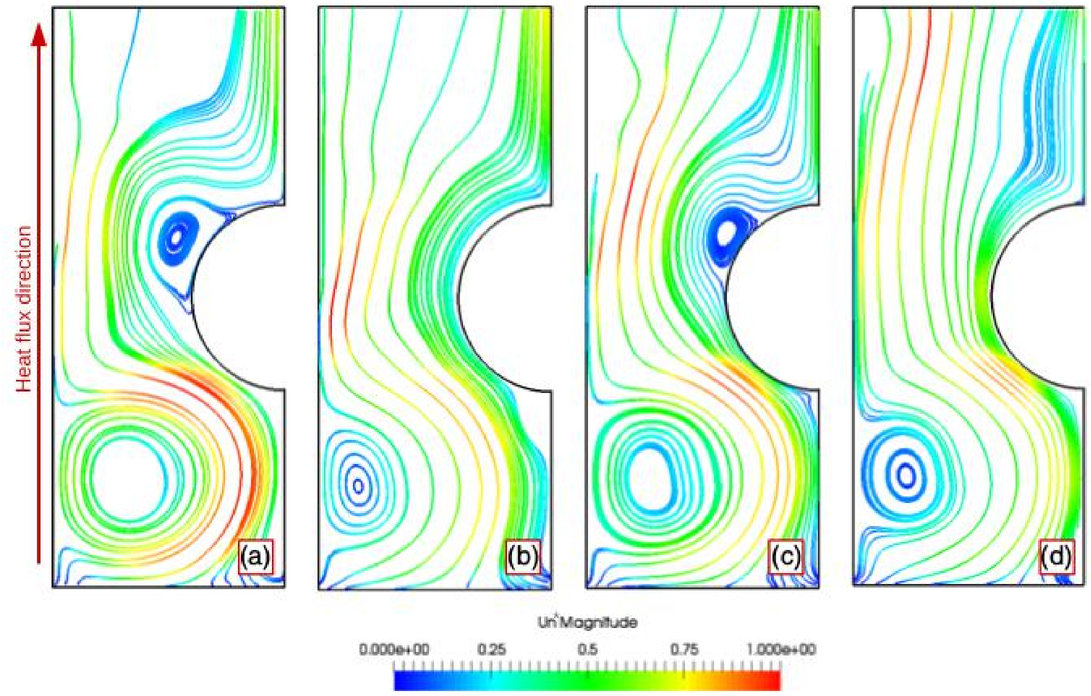
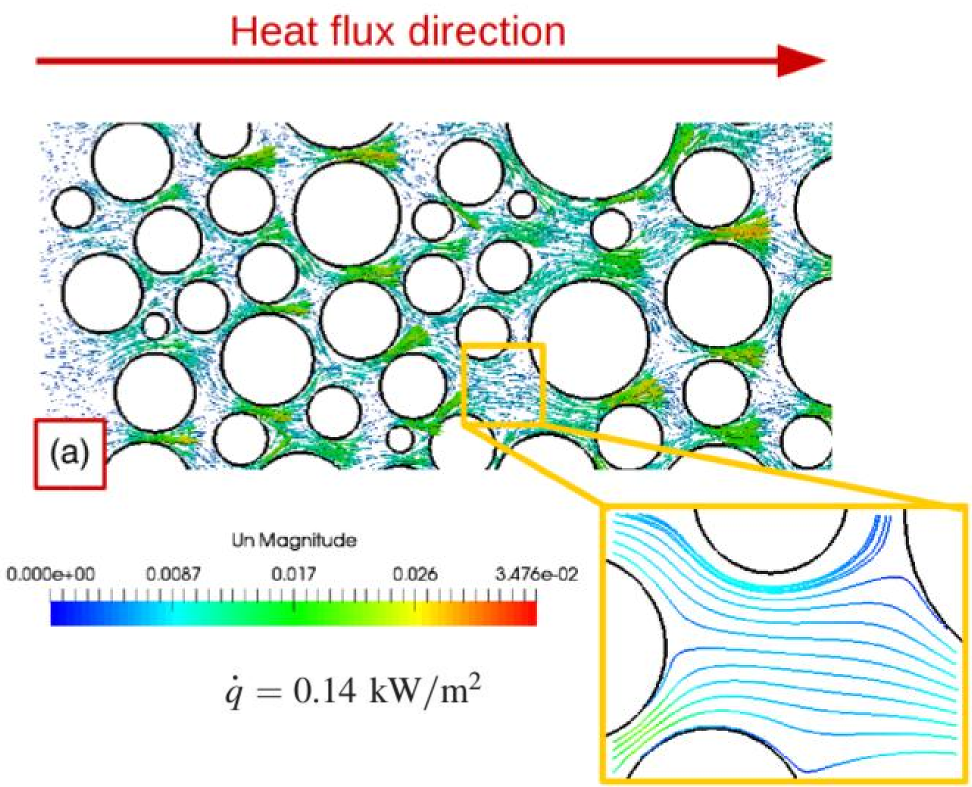


FIG. 3. Streamlines of the normal fluid component. (a) $T_b = 2.0$ K, $\dot{q} = 25$ kW/m^2, $\gamma = 620$, $a = 0.68$; (b) $T_b = 1.8$ K, $\dot{q} = 25$ kW/m^2, $\gamma = 300$, $a = 1.88$; (c) $T_b = 1.9$ K, $\dot{q} = 37$kW/m^2, $\gamma = 633$, $a = 0.97$; (d) $T_b = 1.6$ K, $\dot{q} = 25$ kW/m^2, $\gamma = 288$, $a = 3.1$.

- Multiple simulations are run to cover a large parameters space (bath temperature and heat flux).
- The size of the upstream eddies increases with increasing γ.
- The downstream eddies persist only if a<1 (normal fluid density > superfluid density)

[1]Soulaine et al., *Numerical Investigation of Thermal Counterflow of He-II Past Cylinders*, Physical Review Letters 118, 074506 (2017)

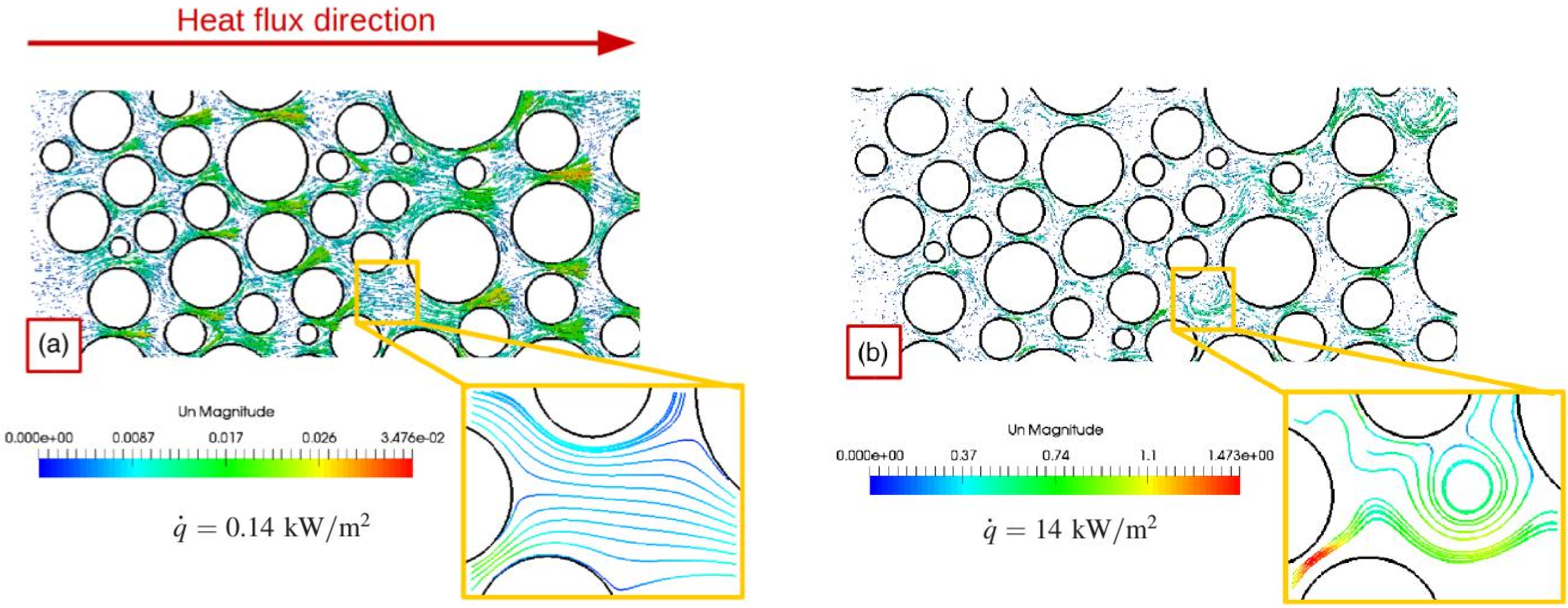
Pore-scale simulation of superfluid helium counterflow



- 6x17 mm^2 porous medium with 30% porosity and $K=10^{-9}\ m^2$,
- Heater on the left-hand side. Right-hand side connected to a He II bath at 1.6K. Initially filled with He II at 1.6K.
- In absence of quantum turbulence (Landau regime, a), the streamlines are similar to classic fluids. Allain et al. demonstrated that Darcy's law can be used for the normal component[2].

[1]Soulaine et al., *Numerical Investigation of Thermal Counterflow of He-II Past Cylinders*, Physical Review Letters 118, 074506 (2017)
[2]Allain et al., *Upscaling of superfluid helium flow in porous media*, Int. J. Heat Mass Transfer 53, 4852 (2010).

Pore-scale simulation of superfluid helium counterflow



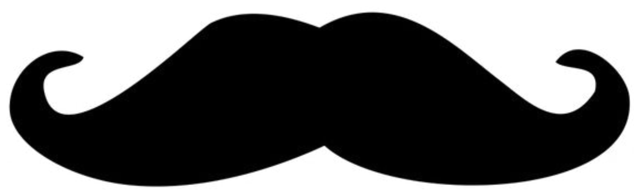
- 6x17 mm^2 porous medium with 30% porosity and $K=10^{-9}\ m^2$,
- Heater on the left-hand side. Right-hand side connected to a He II bath at 1.6K. Initially filled with He II at 1.6K.
- In absence of quantum turbulence (Landau regime, a), the streamlines are similar to classic fluids. Allain et al. demonstrated that Darcy's law can be used for the normal component[2].
- In presence of quantum turbulence (b), numerous eddies in the pores.

[1]Soulaine et al., *Numerical Investigation of Thermal Counterflow of He-II Past Cylinders*, Physical Review Letters 118, 074506 (2017)
[2]Allain et al., *Upscaling of superfluid helium flow in porous media*, Int. J. Heat Mass Transfer 53, 4852 (2010).

Summary

- We are looking for a theory of superfluid flow in porous media,
- We adopt a bottom-up strategy starting at the pore-scale,
- We have developed and validated *HellFOAM*, a superfluid helium simulator with OpenFOAM® based on the *Super-PISO* algorithm,
- Investigation of the thermal counterflow of He II in a micro-tube and past a cylinder,
- The numerical simulations match analytical solutions in both the Landau and Gorter-Mellink regime,
- The numerical model captures the complex flow patterns past a cylinder,
- Illustration of the complexity to build a comprehensive theory of superfluid flow in porous media including quantum turbulence.

Thank you for your attention
Questions?



H. Allain, **M. Quintard**, M. Prat and B. Baudouy, *Upscaling of superfluid helium flow in porous media*, **Int. J. Heat Mass Transfer** 53 (2010), 4852-4864

H. Allain, R. Van Weelderen, B. Baudouy, **M. Quintard**, M. Prat and C. Soulaine, *Investigation of suitability of the method of volume averaging for the study of heat transfer in superconducting magnet cooled by superfluid helium*, **Cryogenics** 53 (2013), 128-134

H. Allain, B. Baudouy, **M. Quintard** and M. Prat, *Experimental investigation of heat transfer through porous media in superfluid helium*, **Cryogenics** 66 (2015), 53-62

C. Soulaine, **M. Quintard**, H. Allain, B. Baudouy and R. Van Weelderen, *A PISO-like algorithm to simulate superfluid helium flow with the two-fluid model*, **Computer Physics Communications** 187 (2015), 20-28

C. Soulaine, **M. Quintard**, B. Baudouy and R. Van Weelderen, *Numerical Investigation of Thermal Counterflow of He-II Past Cylinders*, **Physical Review Letters** 118, 074506 (2017)

www.cypriensoulaine.com

Nondimensionalization of superfluid equations

- Density ratio

$$a = (\rho_s^0/\rho_n^0)$$

- Reynolds number

$$\Re = (\rho_n^0 v_n^0 d/\mu_n^0)$$

- Dimensionless number that quantifies the mutual friction

$$\gamma = A^0 \mu_n^0 \frac{(1+a)^3}{a^2} \Re$$

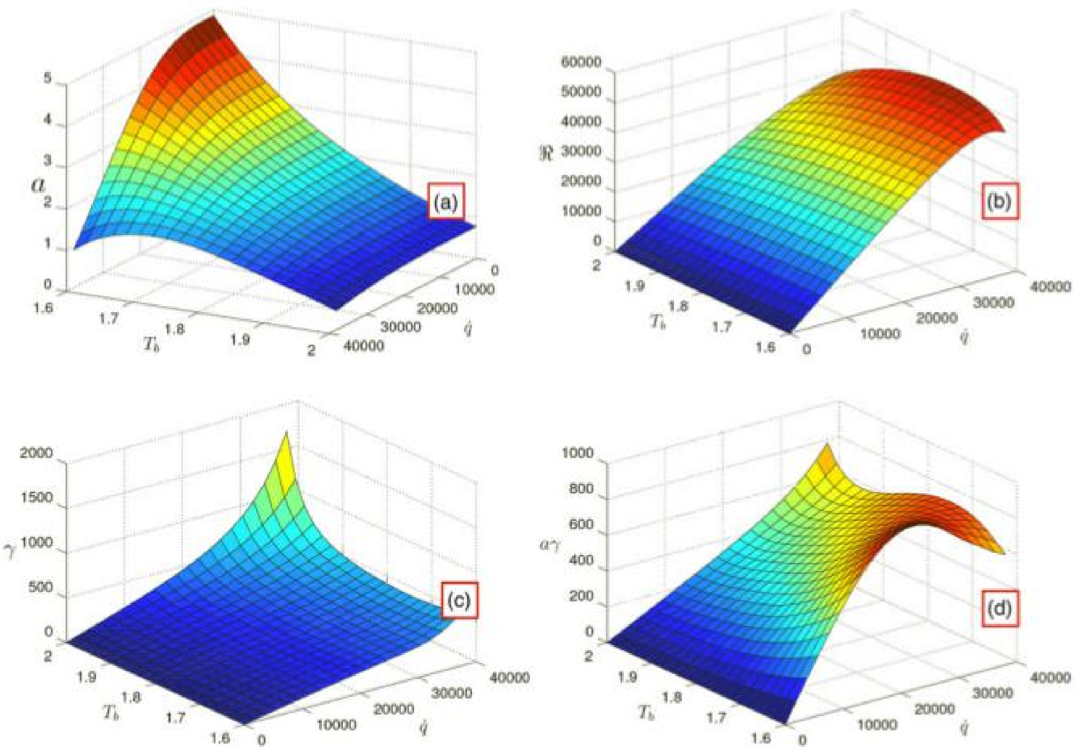


FIG. 1. Variation of the dimensionless numbers with heat flux and bath temperature, (a) densities ratio a, (b) Reynolds number $\Re$, (c) mutual friction over the advection of the normal component γ, and (d) mutual friction over the advection of the superfluid component $a\gamma$.

[1]Soulaine et al., *Numerical Investigation of Thermal Counterflow of He-II Past Cylinders*, Physical Review Letters 118, 074506 (2017)

Dimensionless superfluid equations

$$\left(\frac{\partial \rho_n' \mathbf{v}_n'}{\partial t'} + \nabla'.\left(\rho_n' \mathbf{v}_n' \mathbf{v}_n'\right)\right) = -\frac{1}{a}\frac{\rho_n'}{\rho'}\nabla' p' - \rho_s' s' \nabla' T' + \frac{1}{\Re}\nabla'.\left(\mu_n' \nabla' \mathbf{v}_n'\right) - \gamma A' \rho_n' \rho_s' \left|\mathbf{v}_n' - \mathbf{v}_s'\right|^2 \left(\mathbf{v}_n' - \mathbf{v}_s'\right), \tag{14}$$

$$\left(\frac{\partial \rho_s' \mathbf{v}_s'}{\partial t'} + \nabla'.\left(\rho_s' \mathbf{v}_s' \mathbf{v}_s'\right)\right) = \frac{\rho_s'}{\rho'}\nabla' p' + a\rho_s' s' \nabla' T' + a\gamma A' \rho_n' \rho_s' \left|\mathbf{v}_n' - \mathbf{v}_s'\right|^2 \left(\mathbf{v}_n' - \mathbf{v}_s'\right), \tag{15}$$

and

$$\left(\frac{\partial \rho' s'}{\partial t'} + \nabla.\left(\rho' s' \mathbf{v}_n'\right)\right) = \gamma \frac{A' \rho_n' \rho_s' \left|\mathbf{v}_n' - \mathbf{v}_s'\right|^4}{T'}. \tag{16}$$

$$a = \left(\rho_s^0 / \rho_n^0\right) \qquad \gamma = A^0 \rho_s^0 \left(1 + \frac{\rho_n^0}{\rho_s^0}\right)^3 v_n^0 d = A^0 \mu_n^0 \frac{(1+a)^3}{a^2}\Re$$

Heat transfer in superfluid helium flow in porous media

Cryogenics 53 (2013) 128–134

Contents lists available at SciVerse ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Investigation of suitability of the method of volume averaging for the study of heat transfer in superconducting accelerator magnet cooled by superfluid helium

Hervé Allain [a,*], Rob Van Weelderen [a], Bertrand Baudouy [b], Michel Quintard [c,d], Marc Prat [c,d], Cyprien Soulaine [c]

[a] CERN, TE-CRG, 1211, Geneva 23, Switzerland
[b] CEA, IRFU, SACM, F-91191 Gif-sur-Yvette, France
[c] Université de Toulouse, INPT, UPS, IMFT, Avenue Camille Soula, F-31400 Toulouse, France
[d] CNRS, IMFT, F-31400 Toulouse, France

A R T I C L E I N F O

Article history:
Available online 15 July 2012

Keywords:
Superconducting accelerator magnet
Liquid helium
Porous media
Method of volume averaging

A B S T R A C T

In the field of applied superconductivity, there is a growing need to better understand heat transfers in superconducting accelerator magnets. Depending on the engineering point of view looked at, either 0-D, 1-D, 2D or 3D modeling may be needed. Because of the size of these magnets, alone or coupled together, it is yet, impossible to study this numerically for computational reasons alone without simplification in the description of the geometry and the physics. The main idea of this study is to consider the interior of a superconducting accelerator magnet as a porous medium and to apply methods used in the field of porous media physics to obtain the equations that model heat transfers of a superconducting accelerator magnet in different configurations (steady-state, beam losses, quench, etc.) with minimal compromises to the physics and geometry. Since the interior of a superconducting magnet is made of coils, collars and yoke filled with liquid helium, creating channels that interconnect the helium inside the magnet, an upscaling method provides models that describe heat transfer at the magnet scale and are suitable for numerical studies. This paper presents concisely the method and an example of application for superconducting accelerator magnet cooled by superfluid helium in the steady-state regime in considering the thermal point of view.

1. Introduction

CERN, with the support from the European community and the international high energy particle accelerator community, currently researches and develops next generation (very) high field magnets based on Nb_3Sn and/or HTS superconductors, necessary for the LHC collimation upgrades and HL-LHC (High Luminosity LHC). These magnets will be at the forefront of technology and shall operate in a thermally very challenging environment where they will be subject to high doses of high-energy particle-showers. Analysis of steady state and transient heat flow and temperature and pressure distributions in these new magnet designs are a necessary ingredient for the success of these R&D efforts. These magnets will function either in sub-cooled, pressurized superfluid helium, in supercritical helium or in saturated normal helium. Due to the size of these magnets, it is yet, impossible to study this directly numerically for computational reasons alone with reasonable computing time and without simplification in the description of the geometry and the physics, especially if we consider several coupled magnets. For that reason a mathematical description, suitable for numerical modeling, which preserves as much as possible the geometrical information and the physics, is needed. In this framework, the development, and later-on application, of a generic method to numerically simulate the behavior of aforementioned complex systems is required.

In the field of porous media, it is also often impossible to simulate directly all the physical phenomena that arise in the microstructure and researchers currently use upscaling methods to model the physical behavior of porous media in some average sense. These techniques (method of volume averaging [1], homogenization [2] for instance) consider the physical problem at the pore scale and apply mathematical techniques to derive the equations that model the porous medium behavior at the porous media scale, for some Representative Elementary Volume (REV). The main idea of this study is to consider the interior of a superconducting magnet as a porous medium and to apply the method of volume averaging in order to get the equations that model the behavior of the magnet at the magnet scale; i.e. suitable for numerical simulation. Since the interior of a superconducting accelerator magnet is made of coils, collars and yoke filled with liquid helium creating channels that interconnect the helium inside the magnet, the magnet can be seen as a particular

* Corresponding author. Tel.: +41 22 767 41 78; fax: +41 22 767 88 85.
E-mail address: herve.allain@cern.ch (H. Allain).

0011-2275/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cryogenics.2012.07.001

[1]Allain et al., *Investigation of suitability of the method of volume averaging for the study of heat transfer in superconducting magnet cooled by superfluid helium*, Cryogenics 53 (2013), 128-134