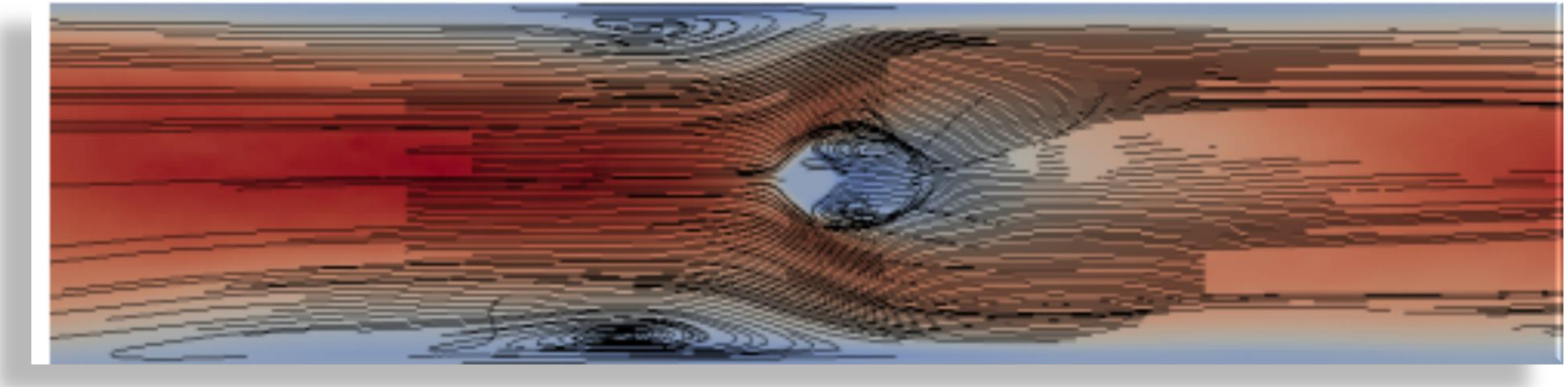
Large-scale vortical motions in thermal counterflow around an obstacle

Workshop on Interpretation of measurements in He^4 superfluid turbulence, Saclay sept. 2015

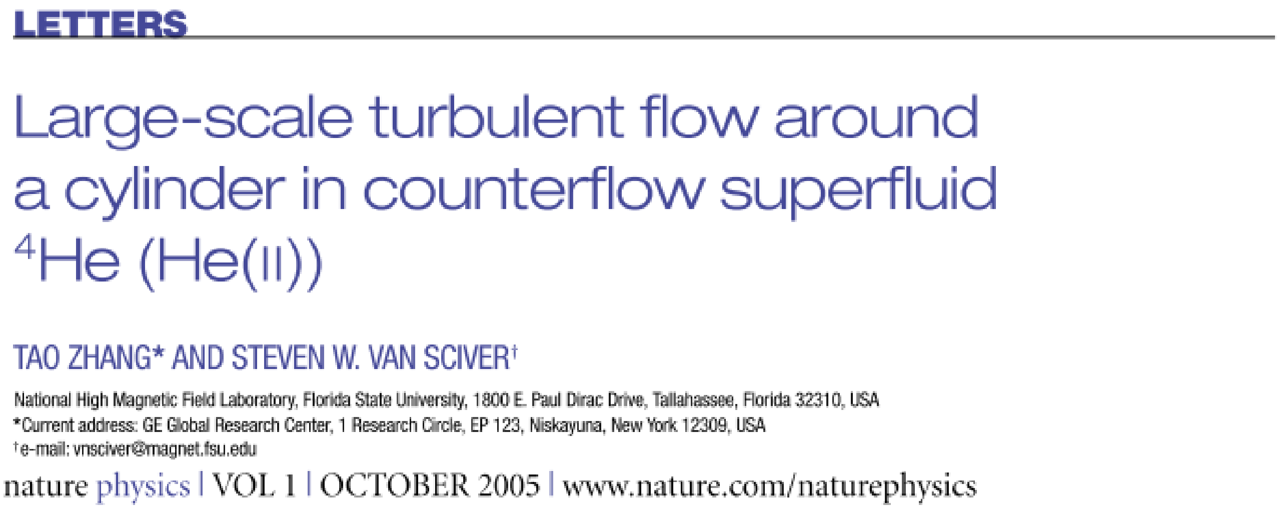
Jonathan Bertolaccini (PhD student)
Lab. de Physique, Ens de Lyon & CNRS, Lyon

Emmanuel Lévêque
Lab. de Physique, Ens de Lyon & CNRS, Lyon
Lab. Mécanique des Fluides et d'Acoustique, Ec-Lyon & CNRS, Lyon

Philippe-E. Roche
Institut Néel, CNRS & UJF, Grenoble



Motivations



LETTERS

Large-scale turbulent flow around a cylinder in counterflow superfluid ^{4}He (He(II))

TAO ZHANG* AND STEVEN W. VAN SCIVER†

National High Magnetic Field Laboratory, Florida State University, 1800 E. Paul Dirac Drive, Tallahassee, Florida 32310, USA
*Current address: GE Global Research Center, 1 Research Circle, EP 123, Niskayuna, New York 12309, USA
†e-mail: vnsciver@magnet.fsu.edu

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PIV measurements

$T=1.6K$
$Re_D=41000$

$T=2.03K$
$Re_D=21000$

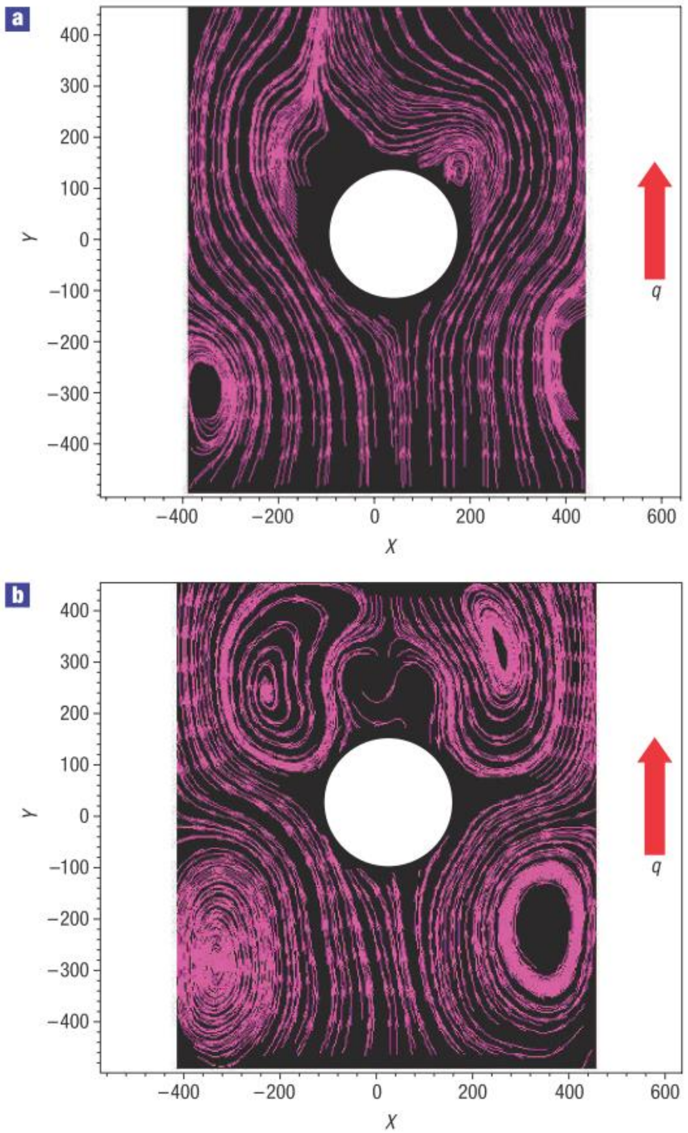


Figure 3 **Computed streamlines for particle motion for the two heat flux cases in Fig. 2. a**, $q = 4$ kW m^{-2} at $T = 1.6$ K corresponding to $Re_D = 41,000$ and $L_0 = 1 \times 10^{10}$ m m^{-3}. **b**, $q = 11.2$ kW m^{-2} at $T = 2.03$ K corresponding to $Re_D = 21,000$ and $L_0 = 2.6 \times 10^{10}$ m m^{-3}.

The current results indicate that both components may be undergoing a kind of flow separation as they pass over the cylinder

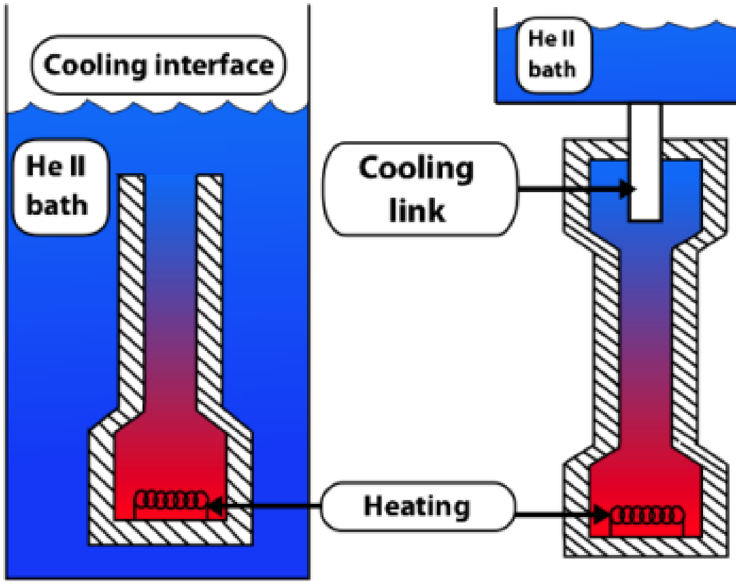
It is worth noting that for classical fluids at $Re_D > 10,000$ considerably different flow structures are normally present downstream of a cylinder

There is a need to understand the two-way coupling between the normal-fluid and the superfluid component !

… investigation by numerical simulations

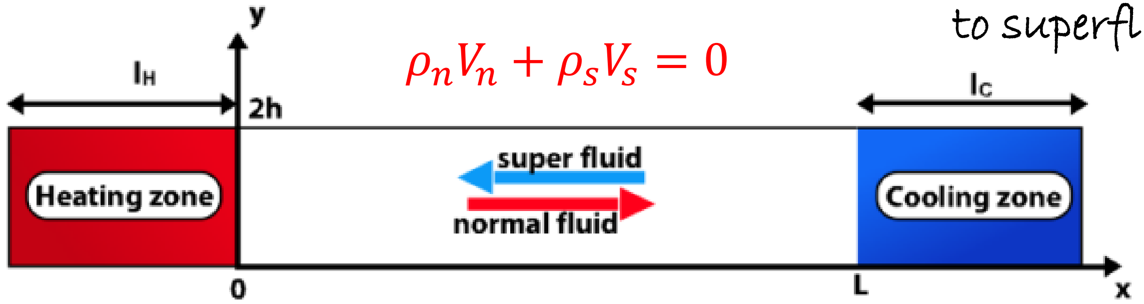
Numerical modeling of thermal counterflow

Geometry of simulations:



Sketch of experimental set-up

conversion normal fluid
to superfluid



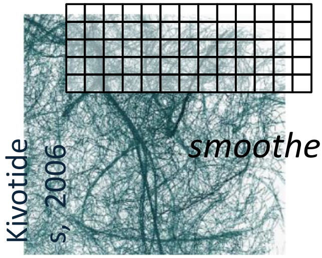
$$\rho_n V_n + \rho_s V_s = 0$$

conversion superfluid
to normal fluid

Sketch of numerical configuration
2d and 3d

Ingredients of the physical modeling (at macroscopic level):

★ Two-fluid model (Landau & Tisza)


Kivotides, 2006

smoothed superfluid velocity field

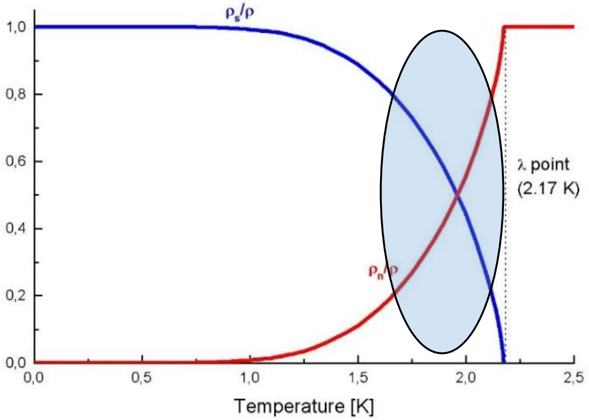
★ Boussinesq-type approximation

$$\nabla p_n = \frac{\rho_n}{\rho} \nabla P + \rho_s \, s \, \nabla T \qquad \nabla p_s = \frac{\rho_s}{\rho} \nabla P - \rho_s \, s \, \nabla T$$

- Thermo-mechanical effect is encapsulated in a generalized partial pressure
- isothermal and incompressible approximations:
  - Temperature T is a parameter (not a variable) of the system
  - $\rho_n = \rho_n(T)$ and $\rho_s = \rho_s(T)$: $\nabla . \mathrm{v_n} = 0$ and $\nabla . \mathrm{v_s} = 0$

$$\cancel{\rho = \rho(P,T)}$$

$$\rho_n \frac{Dv_n}{Dt} = -\nabla p_n + F_{ns} + \nu \Delta v_n \qquad \rho_s \frac{Dv_s}{Dt} = -\nabla p_s - F_{ns}$$



★ HVBK approximation for mutual coupling

$$F_{ns} \approx -\frac{B \rho_s \rho_n}{2\rho} \widehat{\omega_s} \times (\omega_s \times (v_s - v_n)) + \frac{B' \rho_s \rho_n}{2\rho} (\omega_s \times (v_s - v_n))$$

mutual friction — Magnus effect

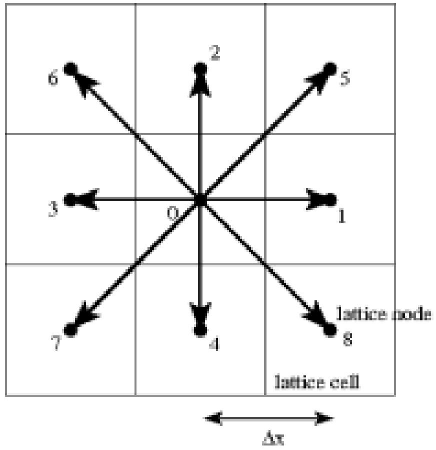
… dynamics is integrated numerically at a mesoscopic level by the Lattice Boltzmann method

Lattice Boltzmann method - key ingredients only:

He-II is viewed as populations of normal-fluid and superfluid particles that propagate and collide on a lattice

The Lattice Boltzmann scheme expresses the dynamics of these propulations on the lattice

★ In the bulk :



$f_\alpha(x,t)$ is the number of particles moving in the direction **α** in (x,t):

$$\mathrm{f}_\alpha(\mathbf{x}+\mathbf{c}_\alpha\Delta t, t+\Delta t) = \mathrm{f}_\alpha(\mathbf{x},t) \;-\frac{1}{\tau}\left(\mathrm{f}_\alpha(\mathbf{x},t) - \mathrm{f}_\alpha^{\mathrm{eq}}(\mathrm{p},\mathbf{v},\mathbf{F}_{\mathrm{hvbk}})(\mathbf{x},t)\right)$$

$$\mathrm{f}_\alpha^{eq}(\rho,\mathbf{v},\mathbf{F}_{\mathrm{hvbk}}) = w_\alpha\left(A + \frac{\mathbf{B}\cdot\mathbf{c}_\alpha}{c_s^2} + \frac{\mathbf{C}:(\mathbf{c}_\alpha\mathbf{c}_\alpha - c_s^2\mathbf{I})}{2c_s^4}\right)$$

$$A = \mathrm{p}/c_s^2$$

$$\mathbf{B} = \rho\mathbf{v} + \nu/c_s^2\ \mathbf{F}_{\mathrm{hvbk}}$$

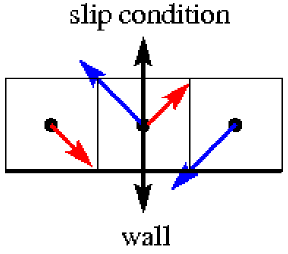
$$\mathbf{C} = \rho\mathbf{v}\mathbf{v} + 2\nu/c_s^2\ \mathbf{F}_{\mathrm{hvbk}}\mathbf{v}$$

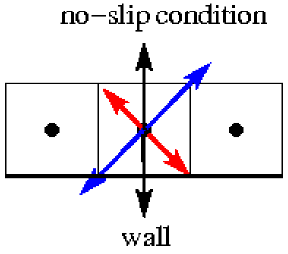
$$\mathrm{p} = \sum_\alpha f_\alpha c_s^2$$ « particles carry pressure »

$$\rho\mathbf{v} = \sum_\alpha f_\alpha\mathbf{c}_\alpha + \Delta t/2\ \mathbf{F}_{\mathrm{hvbk}}.$$

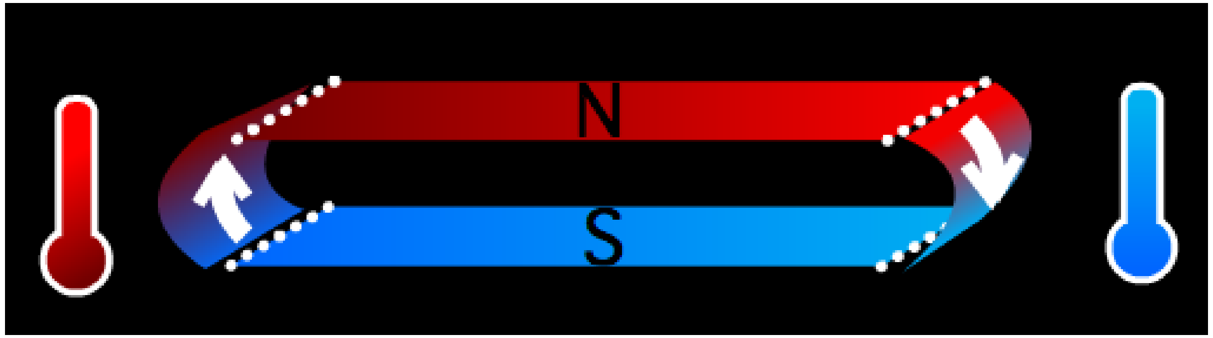
Note that for the sake of numerical stability, a very small artificial viscosity is affected to the superfluid : $\boldsymbol{\nu_s/\nu_n} = \frac{\mathbf{1}}{\mathbf{25}}$

★ At solid boundaries:





★ How to drive the thermal flow (at a mesoscopic level) ?



conversion superfluid to normal fluid

conversion normal fluid to superfluid

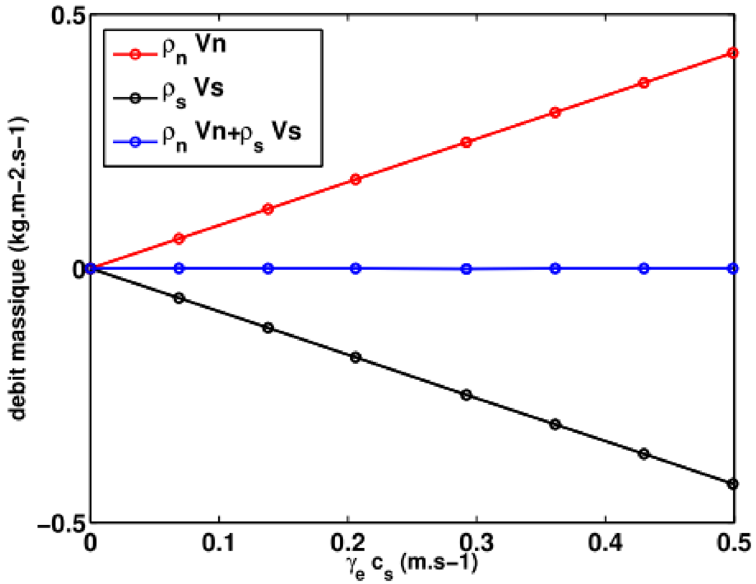
Exchange coefficient γ_e similar to heat power

Thermostats are coupled so that the total number of particles of each component is conserved

As a result, a counterflow naturally establishes between the two thermostats :

$$\rho_n V_n + \rho_s V_s = 0$$

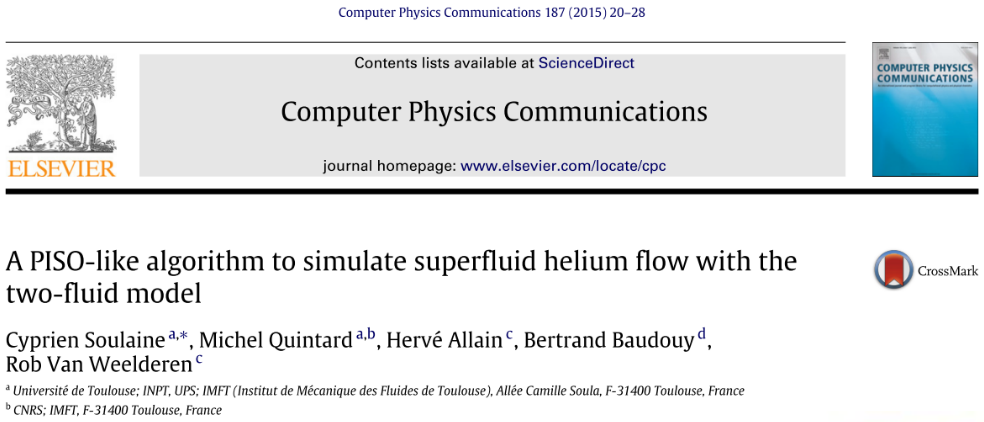
$V_n \propto \gamma_e$ is here equivalent to the heating law $V_n \propto \dot{q}$



T=1.5K

Existing simulations of thermal counterflow simulations (two-way coupling) :

The knowledge of cooling characteristics of He II is indispensable
to design superconducting magnets !



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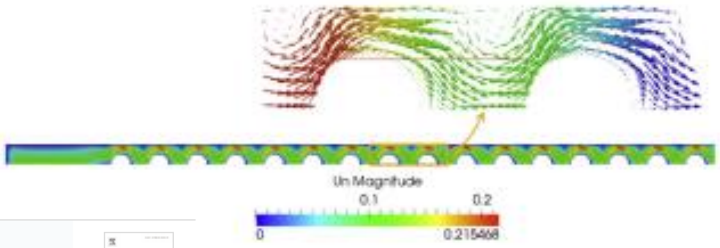
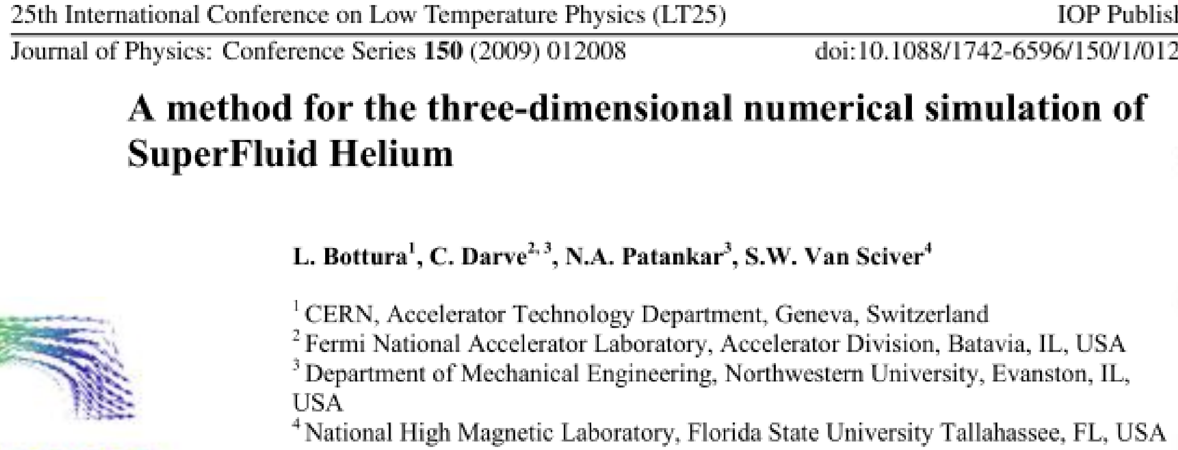
A PISO-like algorithm to simulate superfluid helium flow with the two-fluid model

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

[a] Université de Toulouse; INPT, UPS; IMFT (Institut de Mécanique des Fluides de Toulouse), Allée Camille Soula, F-31400 Toulouse, France
[b] CNRS; IMFT, F-31400 Toulouse, France
[c] CERN, TE-CRG, 1211 Geneva 23, Switzerland
[d] CEA Saclay, Irfu/SACM, F-91191 Gif-sur-Yvette, France



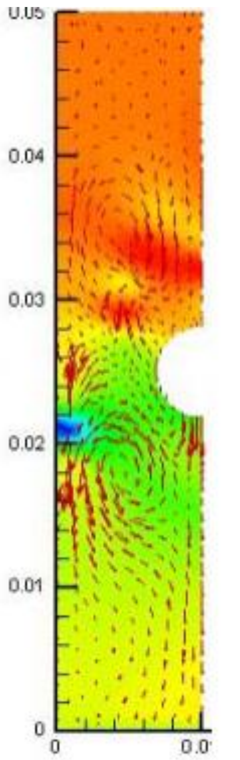


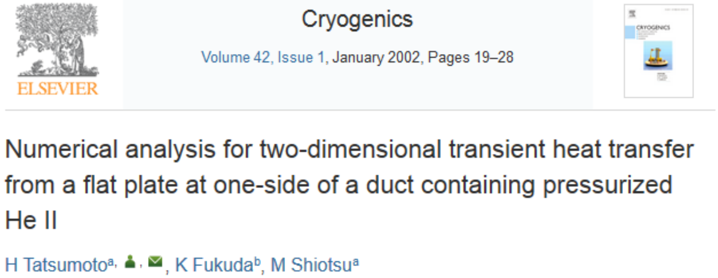
25th International Conference on Low Temperature Physics (LT25) IOP Publishing
Journal of Physics: Conference Series **150** (2009) 012008 doi:10.1088/1742-6596/150/1/012008

A method for the three-dimensional numerical simulation of SuperFluid Helium

L. Bottura[1], C. Darve[2,3], N.A. Patankar[3], S.W. Van Sciver[4]

[1] CERN, Accelerator Technology Department, Geneva, Switzerland
[2] Fermi National Accelerator Laboratory, Accelerator Division, Batavia, IL, USA
[3] Department of Mechanical Engineering, Northwestern University, Evanston, IL, USA
[4] National High Magnetic Laboratory, Florida State University Tallahassee, FL, USA



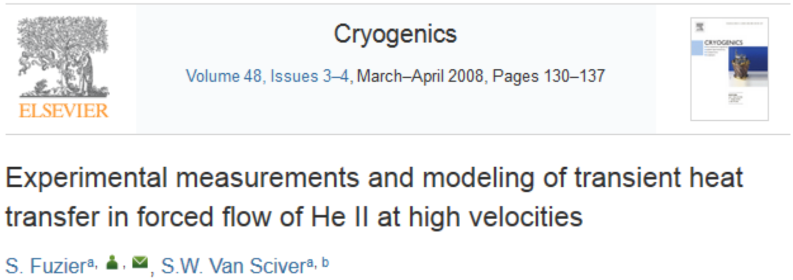


Cryogenics

Volume 42, Issue 1, January 2002, Pages 19–28

Numerical analysis for two-dimensional transient heat transfer from a flat plate at one-side of a duct containing pressurized He II

H Tatsumoto[a], K Fukuda[b], M Shiotsu[a]



Cryogenics

Volume 48, Issues 3–4, March–April 2008, Pages 130–137

Experimental measurements and modeling of transient heat transfer in forced flow of He II at high velocities

S. Fuzier[a], S.W. Van Sciver[a, b]

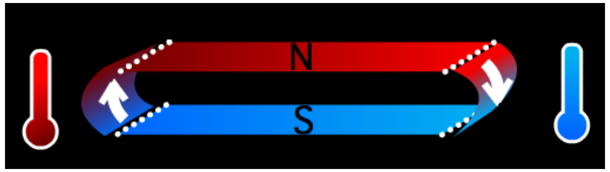
3-D NUMERICAL ANALYSIS FOR HEAT TRANSFER FROM A FLAT PLATE IN A DUCT WITH CONTRACTIONS FILLED WITH PRESSURIZED HE II

D. Doi[1], Y. Shirai[1] and M. Shiotsu[1]

+ VIEW AFFILIATIONS

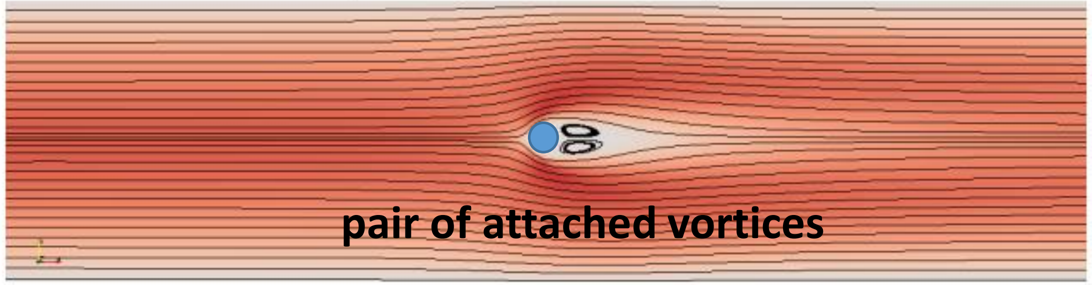
AIP Conf. Proc. **985**, 648 (2008); http://dx.doi.org/10.1063/1.2908617
Conference date: 16–20 July 2007
Location: Chattanooga (Tennessee)

Counterflow without mutual coupling



$T=1.96K$
$\rho_n \approx \rho_s$

composante normale $Re_n = 19$

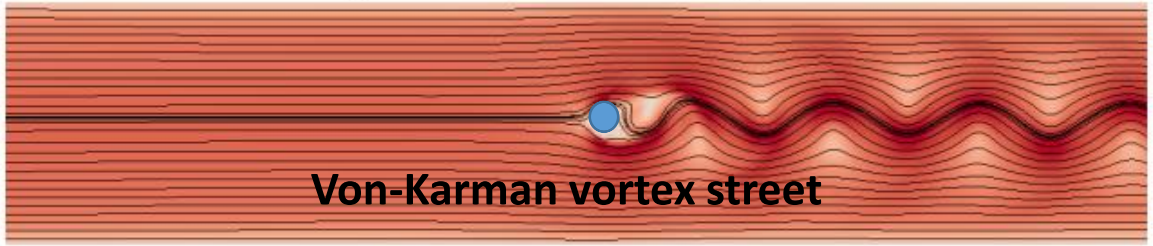


pair of attached vortices

composante superfluide $Re_s = 475$

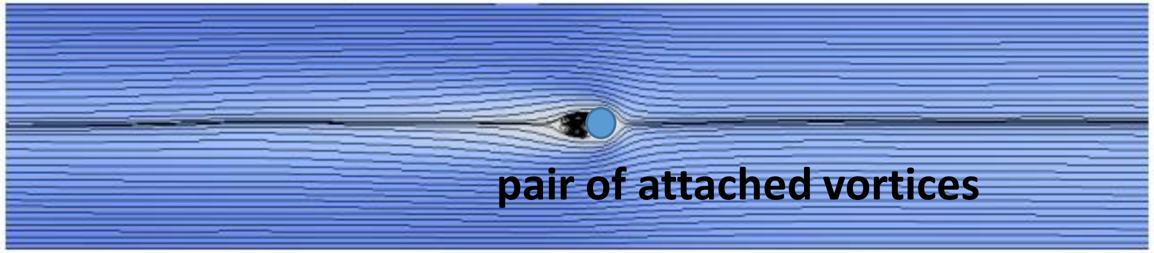
Von-Karman vortex street

composante normale $Re_n = 475$

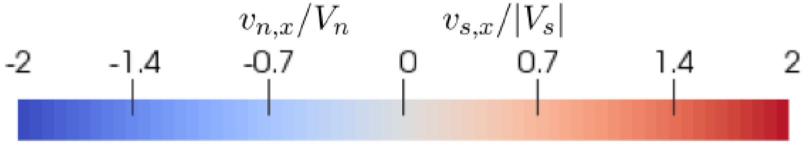


Von-Karman vortex street

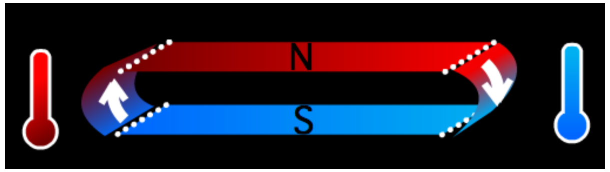
composante superfluide $Re_s = 19$



pair of attached vortices



Turning on mutual coupling at low Reynolds number

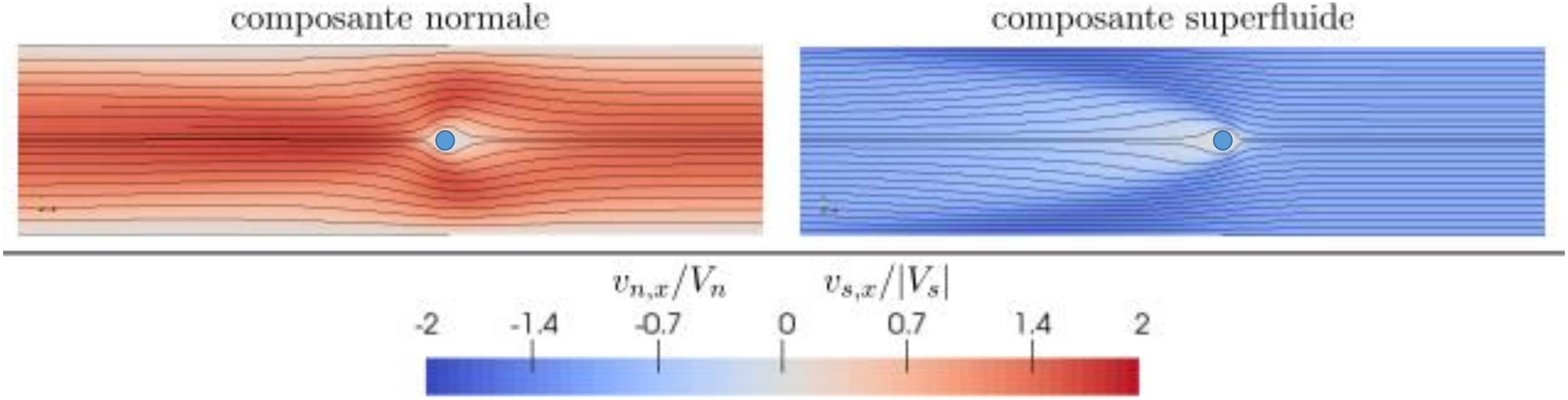


T=1.96K

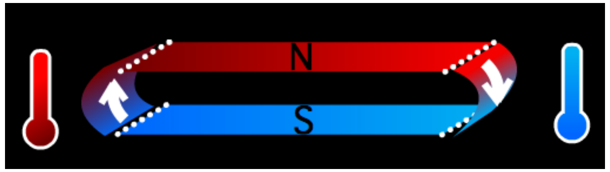
$\rho_n \approx \rho_s \longrightarrow V_n \approx -V_s$

$Re_s \approx 25\, Re_n$

Very low Reynolds number for normal fluid: $Re_n = 2$

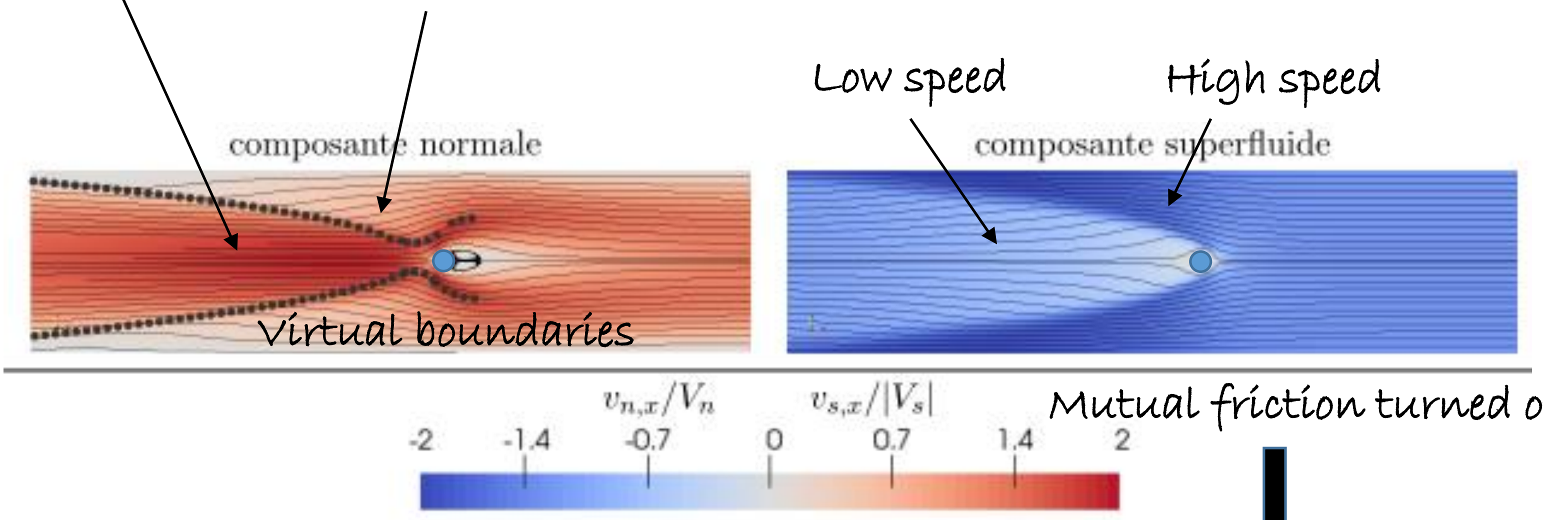


Appearance of high-friction bands : virtual boundaries



T=1.96K

Reynolds number for normal fluid: $Re_n = 10$



High speed

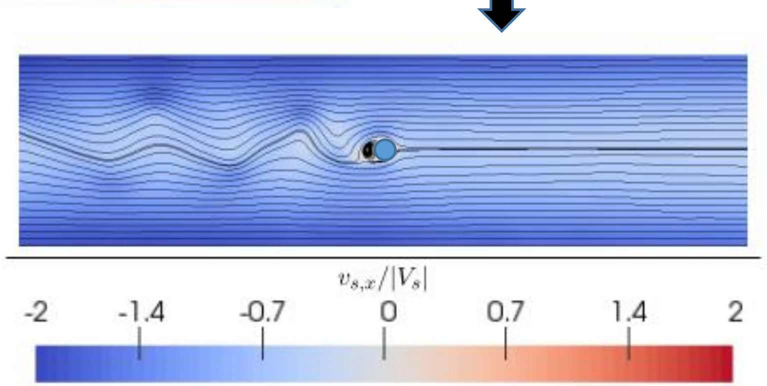
Low speed

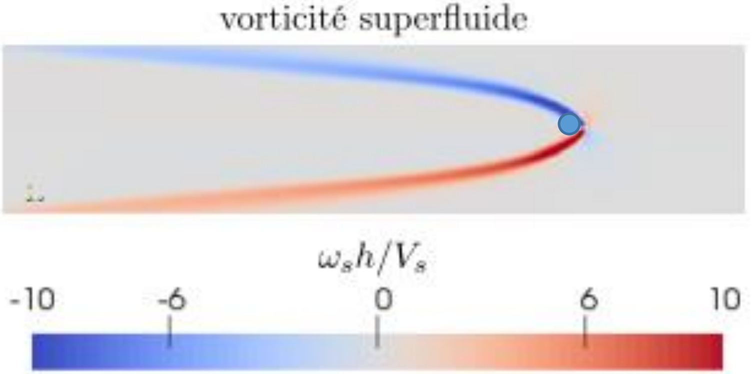
Virtual boundaries

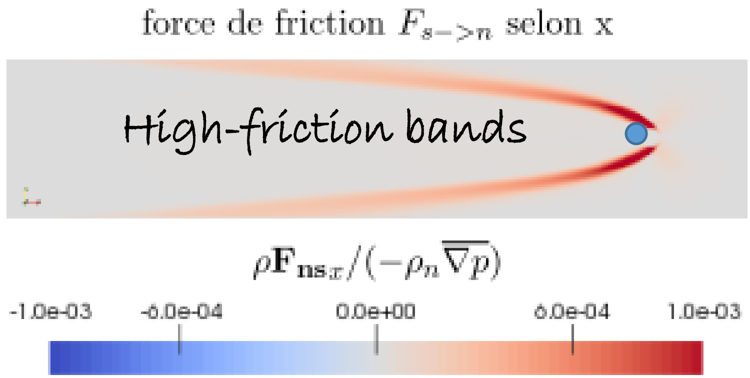
Low speed

High speed

Mutual friction turned off

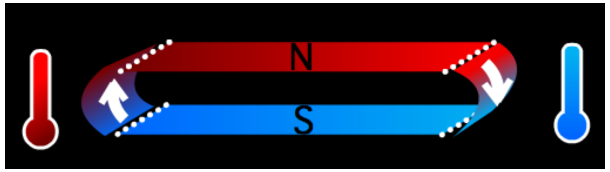






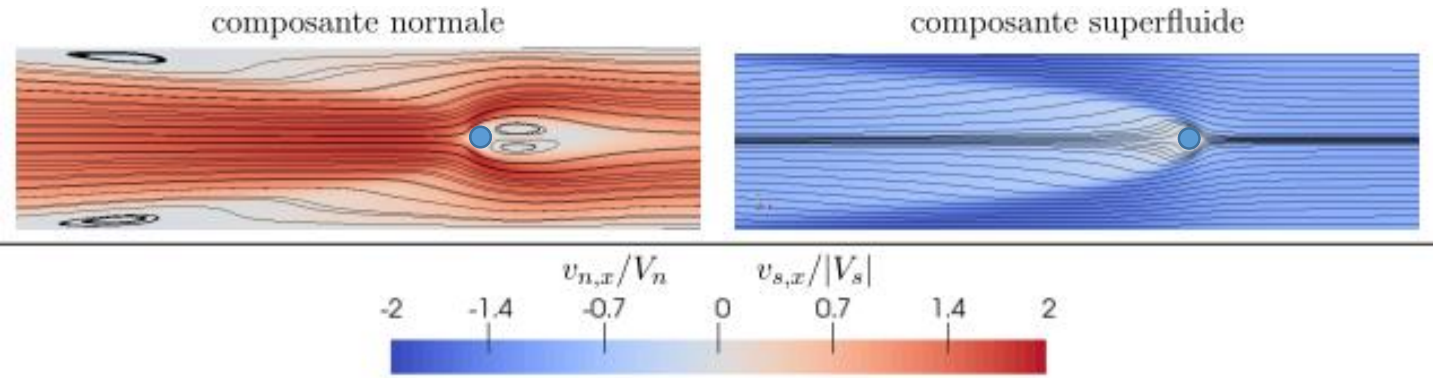
High-friction bands

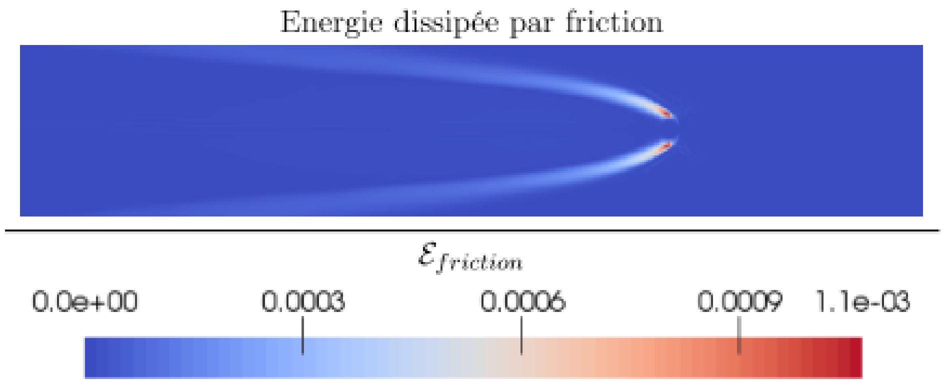
Upstream recirculation zones



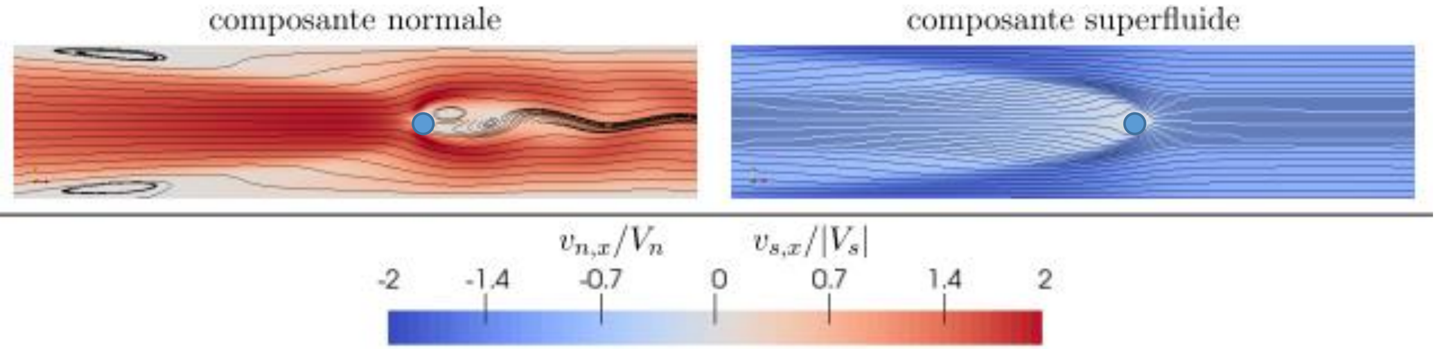
T=1.96K

Reynolds number for normal fluid: $Re_n = 19$

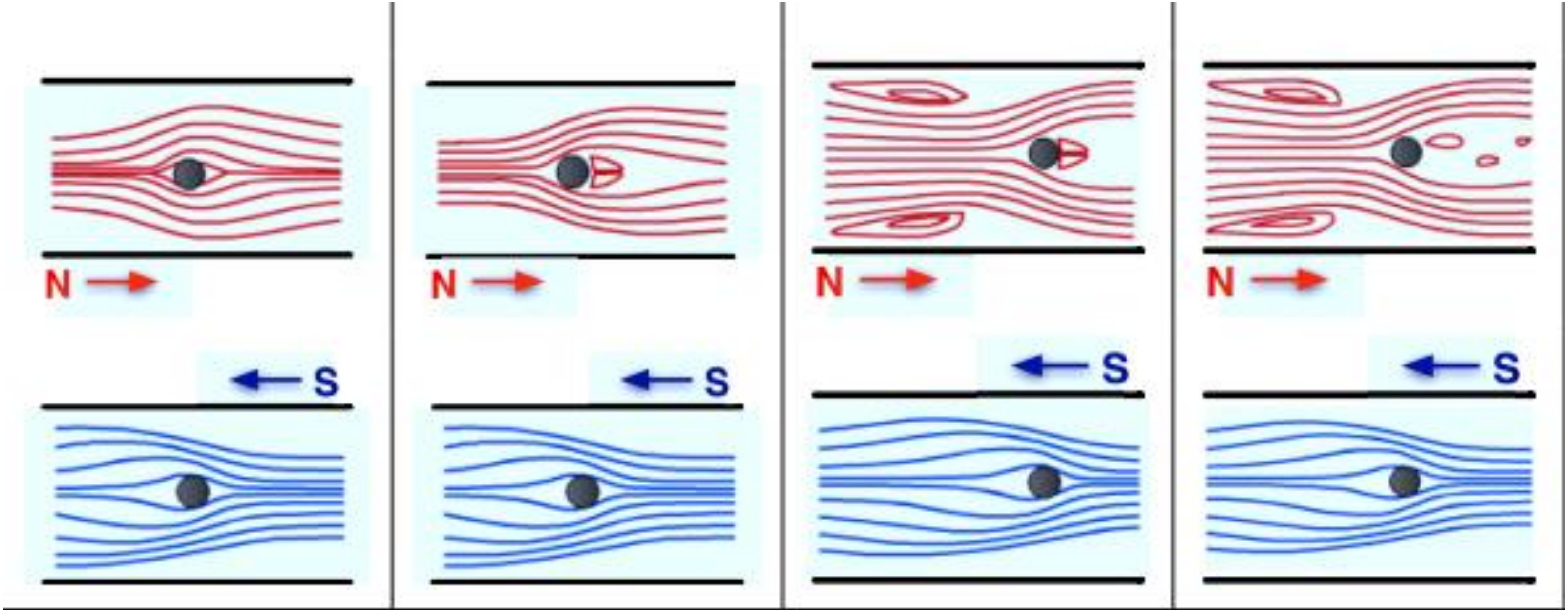




Reynolds number for normal fluid: $Re_n = 20{,}5$

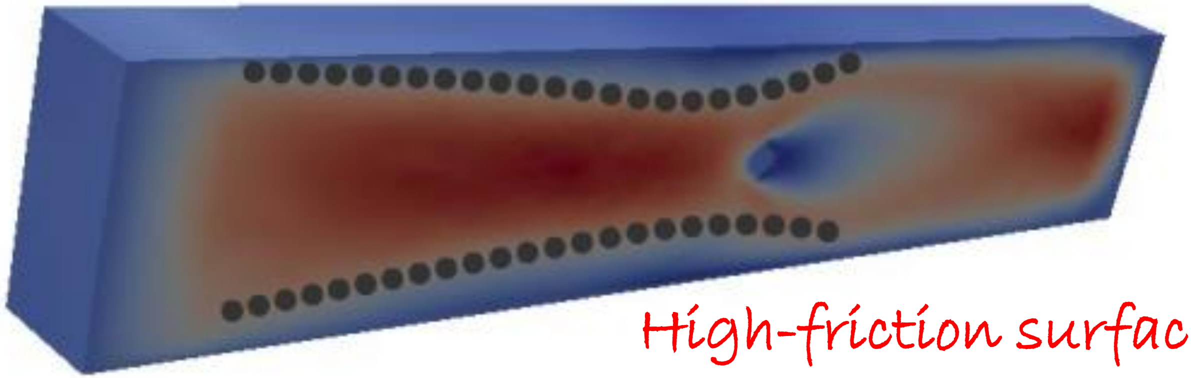


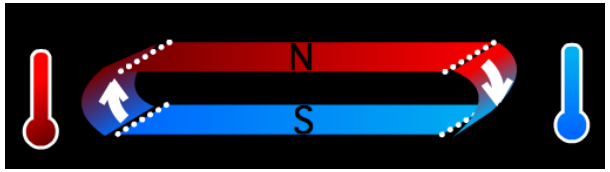
Summary of flow topology



$Re_n < 5,0$ | $5,0 \leq Re_n < 18,5$ | $18,5 \leq Re_n < 20,5$ | $20,5 \leq Re_n$

in three dimensions

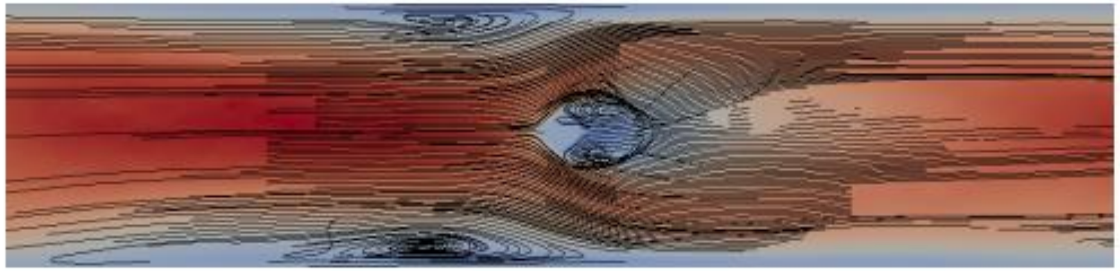


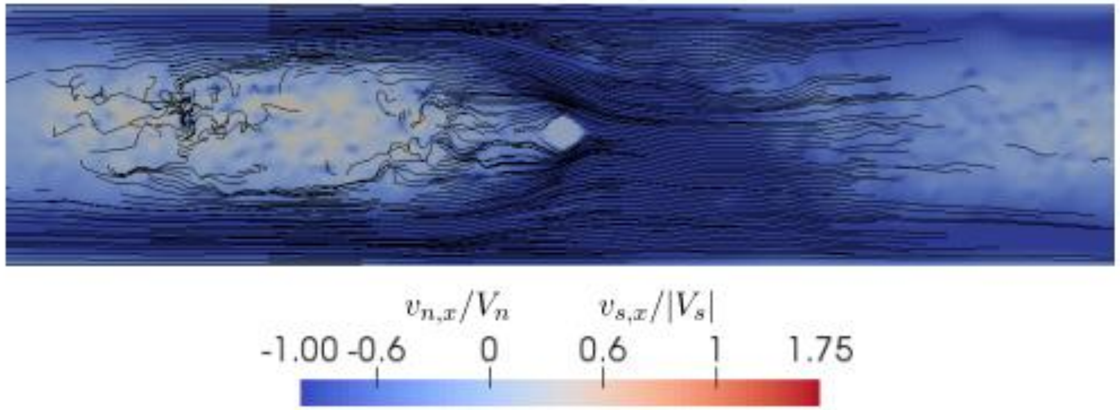


$T=1.96K$

$Re_D=30$

High-friction surface ≈ virtual boundaries


composante normale

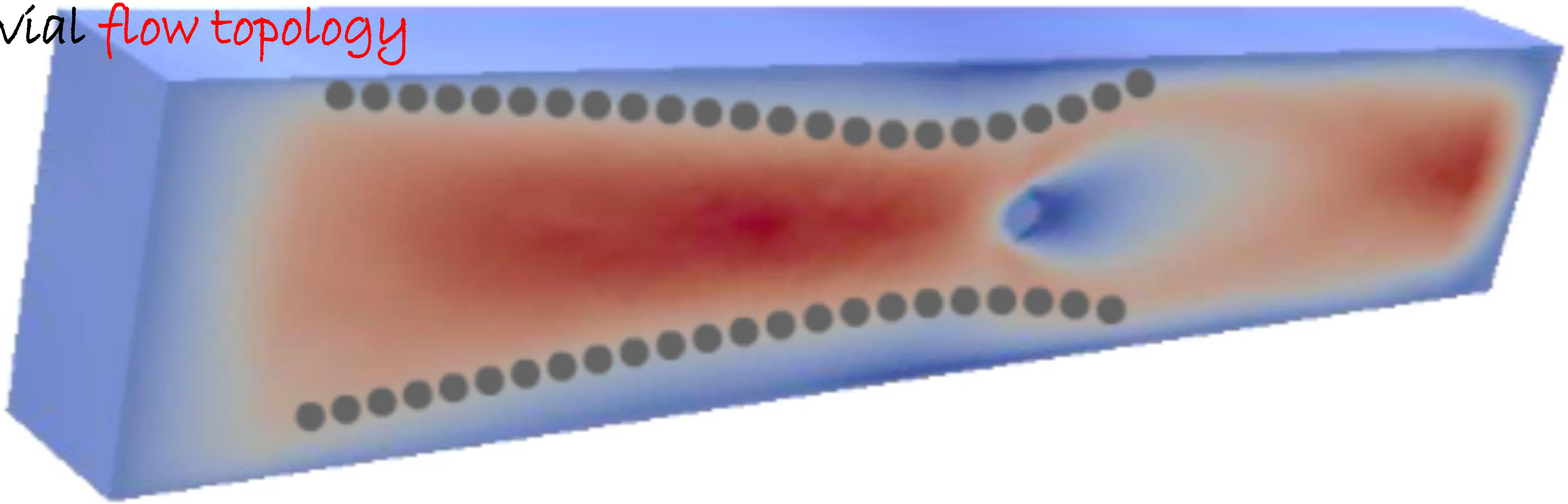

composante superfluide

Conclusions and perspectives

★ Vortical structures are associated with normal fluid rather than a kind of flow separation of the normal fluid and superfluid components as they pass over the cylinder

★ Two-fluid dynamics are strongly influenced by the mutual friction :

- apparition of virtual boundaries which separate the flow of each component
- non trivial flow topology



★ supplementary (to experimental flow viszualisation) insight into He-II counterflows consistent with Joe Vinen's comment ``... need to account for what the normal fluid is doing in a dynamically self-consistent computation of the flow patterns ''

Kinetic Models for CFD in a nutshell

Boltzmann equation (BE)

$$\frac{\partial f}{\partial t}+\vec{\xi}\frac{\partial f}{\partial \vec{x}}=\Omega(f)$$

Kn<<1

CE-expansion

Navier-Stokes equation

$$\frac{\partial(\rho\vec{v})}{\partial t}+\nabla(\rho\vec{v}\vec{v})=-\nabla p+\mu\Delta(\rho\vec{v})$$

continuity equation

$$\frac{\partial\rho}{\partial t}+\nabla(\rho\vec{v})=0$$

BGK-approximation

$$\frac{\partial f}{\partial t}+\vec{\xi}\frac{\partial f}{\partial \vec{x}}=-\frac{1}{\tau}(f-f^{eq})$$

Discrete BE

$$\frac{\partial f_i}{\partial t}+\vec{\xi}_i\frac{\partial f_i}{\partial \vec{x}}=-\frac{1}{\tau}(f_i-f_i^{eq})$$

FD-Discretization

Lattice BE

$$f_i(t+\Delta t,\vec{x}+\vec{\xi}_i\Delta t)-f(t,\vec{x})=-\frac{1}{\tau}(f_i-f_i^{eq})$$

Kn, Ma <<1

Chapman-Enskog expansion