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Simplified Model of Thermo-Fluid Processes in Forced Flow He II

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Outline

- INTRODUCTION \ MOTIVATIONS
- GOVERNING EQUATIONS : A SIMPLIFIED TWO-FLUID MODEL
- EXPERIMENT
- NUMERICAL MODEL
- STEADY-STATE HEAT TRANSFER
- CONCLUSIONS

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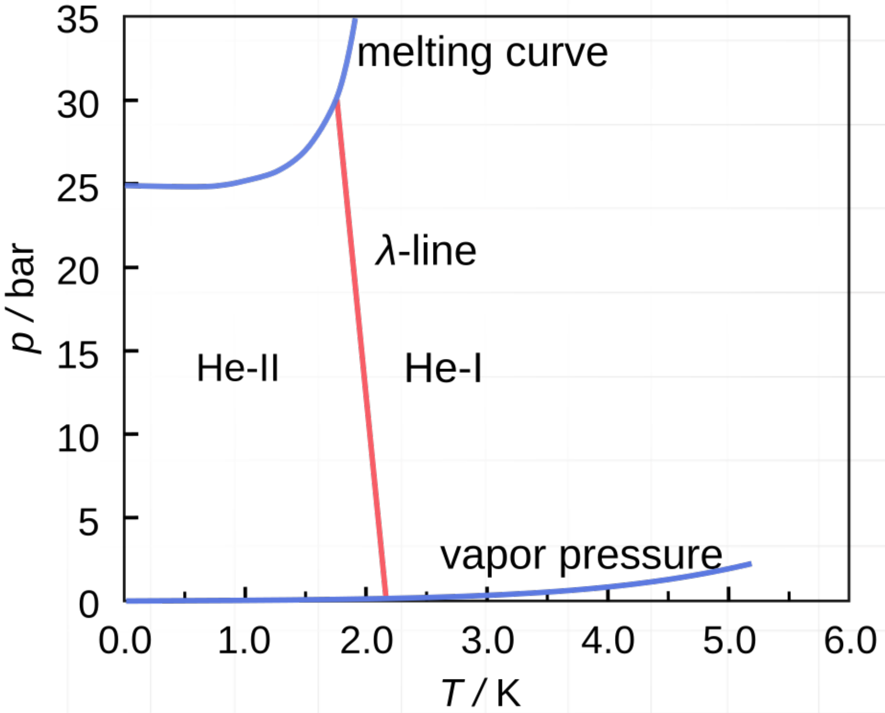
Introduction or motivation

- Different classifications of system with respect to cooling
- Review of the different cooling methods
- Implementation of superfluid helium forced flow in any CFD software.



Introduction or motivation

Where?

1. Cooling Superconducting Magnets
Superfluid helium is used to cool superconducting magnets, such as those found in MRI (Magnetic Resonance Imaging) machines, particle accelerators, and fusion reactors. These magnets operate at very low temperatures (around 4 K or lower) to remain in a superconducting state. The forced flow of superfluid helium ensures efficient heat removal from the system, helping to maintain stable superconductivity over extended periods.

2. Particle Accelerators
In large particle accelerators like CERN's Large Hadron Collider (LHC), superfluid helium is forced through cooling channels to cool superconducting magnets and other critical components. The low-temperature cooling is essential to keep the system at the desired operational temperature, typically in the range of 1.8 K to 2 K, ensuring high performance and energy efficiency in the accelerator.

3. Space Applications
Forced flow of superfluid helium is used in space exploration for cooling sensitive instruments, such as infrared detectors and communication equipment on spacecraft and satellites. In space, superfluid helium is often used to cool equipment down to extremely low temperatures to improve the sensitivity and accuracy of measurements, especially in deep-space observation and astronomy missions.

4. Quantum Computing
Superfluid helium is used in the cryogenic systems of quantum computers to cool quantum bits (qubits) to extremely low temperatures. The forced flow helps maintain stable, ultra-low-temperature environments that are necessary for quantum coherence and reliable qubit operation.

Introduction or motivation

Where?

5. Ultra-Sensitive Detectors
In experimental physics, such as in the search for dark matter or in neutrino detection, ultra-sensitive detectors operate at cryogenic temperatures. Superfluid helium, forced through these systems, helps maintain the low temperatures required to reduce thermal noise and enhance the precision of these detectors.

6. Superfluid Gyroscopes
Superfluid helium is also used in devices like superfluid gyroscopes, which are extremely sensitive rotation sensors. These gyroscopes can be used in space navigation or precision measurement systems. The forced flow of superfluid helium helps maintain the superfluid state, ensuring the device functions with minimal resistance and maximal sensitivity.

7. Nuclear Fusion Research
In fusion reactor experiments, like those involving Tokamak reactors, the forced flow of superfluid helium is used to cool superconducting coils that create the magnetic fields required to contain high-energy plasma. The extreme low-temperature environment provided by superfluid helium ensures that the coils remain superconducting, allowing stable operation of the reactor.

8. Astrophysics and Space Telescopes
Superfluid helium is employed to cool sensors in space telescopes that observe distant cosmic phenomena, particularly in the infrared spectrum. Forced flow cooling ensures that the detectors maintain low temperatures for long periods, which is necessary for capturing faint astronomical signals.

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Governing Equations

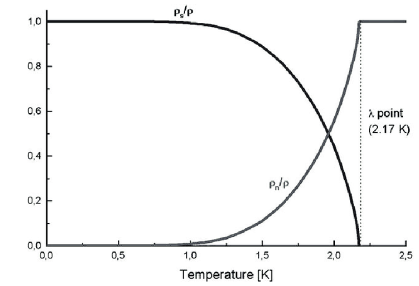
(1/5)

Proposed model is derived from the two-fluid model based on Khalatnikov`s theory

Density of superfluid helium $$\rho = \rho_n + \rho_s \qquad (1)$$

Density flux $$\rho\, u = \rho_n u_n + \rho_s u_s \qquad (2)$$

Continuity equation $$\frac{\partial \rho}{\partial \tau} + \nabla \cdot (\rho_n u_n + \rho_s u_s) = 0 \qquad (3)$$



n – normal component
s – superfluid component

Momentum equation for the total fluid

$$\frac{\partial}{\partial \tau}(\rho_n u_n + \rho_s u_s) = -\nabla \cdot (\rho_n u_n u_n + \rho_s u_s u_s) - \nabla p + \eta\left[\nabla^2 u_n + \tfrac{1}{3}\nabla(\nabla \cdot u_n)\right] + \rho g \qquad (4)$$

Momentum equation for the superfluid component

$$\frac{\partial u_s}{\partial \tau} = -(u_s \cdot \nabla) u_s + s\nabla T - \frac{1}{\rho}\nabla p + \frac{\rho_n}{2\rho}\nabla |u_n - u_s|^2 + A\rho_n |u_n - u_s|^2 (u_n - u_s) + g \qquad (5)$$

Entropy equation

$$\frac{\partial}{\partial \tau}(\rho s) = -\nabla \cdot (\rho s u_n) + \frac{A\rho_n \rho_s |u_n - u_s|^4}{T} \qquad (6)$$

Governing Equations

(2/5)

The Kitamura model

Cryogenics 37 (1997) 1–9
PII: S0011-2275(96)00096-3
0011-2275/97/$17.00

A numerical model on transient, two-dimensional flow and heat transfer in He II

T. Kitamura, K. Shiramizu, N. Fujimoto, Y.F. Rao and K. Fukuda

Department of Nuclear Engineering, Faculty of Engineering, Kyushu University, Fukuoka 812, Japan

Received 12 January 1996; revised 5 July 1996

Assumption : The thermo-mechanical effect, the Gorter-Mellink mutual friction are the dominant terms in the momentum equation

$$s\,\nabla T = -A\,\rho_n|\bar{u}_n - \bar{u}_s|^2(\bar{u}_n - \bar{u}_s)$$

Continuity equation $\quad \dfrac{\partial \rho}{\partial \tau} + \nabla\cdot(\rho\,\bar{u}) = 0 \quad$ (1)

Momentum equation

$$\rho\,\frac{\partial \bar{u}}{\partial t} = -\rho\,(\bar{u}\cdot\nabla)\bar{u} - \nabla P - \nabla\cdot\left\{\frac{\rho_n\,\rho_s}{\rho}\left(\frac{s}{A\,\rho_n\,|\nabla T|^2}\right)^{\frac{2}{3}}\nabla T\,\nabla T\right\}$$
$$+\eta\left[\nabla^2\bar{u} + \frac{1}{3}\nabla(\nabla\bar{u}) - \left(\frac{\rho_s^3\,s}{A\,\rho^3\rho_n|\nabla T|^2}\right)^{\frac{1}{3}}\left\{\nabla^2(\nabla T) + \frac{1}{3}\nabla(\nabla\cdot\nabla)(\nabla T)\right\}\right] + \rho\,g\,\sin\theta \qquad (2)$$

Energy equation

$$\rho\,c_p\,\frac{\partial T}{\partial t} = -\rho\,c_p(\bar{u}\cdot\nabla)T + \nabla\cdot\left\{\left(\frac{1}{f(T,p)|\nabla T|^2}\right)^{\frac{1}{3}}(\nabla T)\right\} \qquad (3)$$

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Cryogenics

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

Numerical study of the thermal behavior of an Nb_3Sn high field magnet in He II

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Governing Equations

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Assumption : The thermo-mechanical effect, the Gorter-Mellink mutual friction and pressure gradient are the dominant terms in the momentum equation

$$s\,\nabla T = \frac{1}{\rho}\,\nabla P - A\,\rho_n |\bar{u}_n - \bar{u}_s|^2 (\bar{u}_n - \bar{u}_s)$$

Velocity fields v_n et v_s in function of v

$$\bar{u}_s = \bar{u} - \frac{\rho_n}{\rho}\,(\bar{u}_n - \bar{u}_s) = \bar{u} + \left(\frac{\rho_n^3\, s}{A\,\rho^3\,\rho_n \left| -\frac{1}{\rho\, s} \nabla P + \nabla T \right|^2} \right)^{\frac{1}{3}} \left(-\frac{1}{\rho\, s} \nabla P + \nabla T \right)$$

$$\bar{u}_n = \bar{u} + \frac{\rho_s}{\rho}\,(\bar{u}_n - \bar{u}_s) = \bar{u} - \left(\frac{\rho_s^3\, s}{A\,\rho^3\,\rho_n \left| -\frac{1}{\rho\, s} \nabla P + \nabla T \right|^2} \right)^{\frac{1}{3}} \left(-\frac{1}{\rho\, s} \nabla P + \nabla T \right).$$

This assumption transforms the two-fluid model into a one-fluid model!

Governing Equations

(4/5)

The one-fluid model is described by

Continuity equation

$$\frac{\partial \rho}{\partial \tau} + \nabla \cdot (\rho\, \bar{u}) = 0 \qquad (1)$$

Momentum equation

$$\rho \frac{\partial \bar{u}}{\partial t} = -\rho\,(\bar{u} \cdot \nabla)\bar{u} - \nabla P - \nabla \cdot \left\{ \frac{\rho_n\, \rho_s}{\rho} \left(\frac{s}{A\, \rho_n \left| -\frac{1}{\rho\, s} \nabla P + \nabla T \right|^2} \right)^{\frac{2}{3}} \left(-\frac{1}{\rho\, s} \nabla P + \nabla T \right) \left(-\frac{1}{\rho\, s} \nabla P + \nabla T \right) \right\}$$

$$+\eta \left[\nabla^2 \bar{u} + \frac{1}{3} \nabla (\nabla \bar{u}) - \left(\frac{\rho_s^3\, s}{A\, \rho^3 \rho_n \left| -\frac{1}{\rho\, s} \nabla P + \nabla T \right|^2} \right)^{\frac{1}{3}} \left\{ \nabla^2 \left(-\frac{1}{\rho\, s} \nabla P + \nabla T \right) + \frac{1}{3} \nabla (\nabla \cdot \nabla) \left(-\frac{1}{\rho\, s} \nabla P + \nabla T \right) \right\} \right] + \rho\, g\, sin\theta \qquad (2)$$

Energy equation

$$\rho\, c_p \frac{\partial T}{\partial t} = -\rho\, c_p (\bar{u} \cdot \nabla) T + (\bar{u} \cdot \nabla) P + \nabla \cdot \left\{ \left(\frac{1}{f(T, p) \left| -\frac{1}{\rho\, s} \nabla P + \nabla T \right|^2} \right)^{\frac{1}{3}} \left(-\frac{1}{\rho\, s} \nabla P + \nabla T \right) \right\}$$

$$+ A\, \rho_n \rho_s \left(\frac{s}{A\, \rho_n} \left(-\frac{1}{\rho\, s} \nabla P + \nabla T \right) \right)^{\frac{4}{3}} + \nabla q_i \qquad (3)$$

Governing Equations

(5/5)

Another model 1D:

NUMERICAL SOLUTION OF FORCED CONVECTION HEAT TRANSFER IN He II

A. Kashani, S. W. Van Sciver & J. C. Strikwerda

Pages 213-228 | Received 06 Oct 1988, Accepted 15 Mar 1989, Published online: 27 Apr 2007

Kashani

$$\rho \bar{u} c_p \frac{dT}{dx} = \frac{d}{dx}\left(\frac{1}{f(T)}\frac{dT}{dx}\right)^{\frac{1}{3}} + q_V$$

$$\dot{q} = \left\{\rho \cdot Cp\frac{\partial T}{\partial t} + \rho \cdot u \cdot Cp\frac{\partial T}{\partial x} - \frac{\partial}{\partial x}\left\{\frac{1}{K(T)}\frac{\partial T}{\partial x}\right\}^{1/3}\right\}$$

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CRYOGENICS

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

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Fuzier

$$\rho c_p \frac{\partial T}{\partial \tau} + \rho \bar{u} c_p \frac{\partial T}{\partial x} - \bar{u}\frac{\Delta P}{L} = \frac{\partial}{\partial x}\left[\frac{1}{f(T)}\left(\frac{1}{\rho s}\frac{\Delta P}{L} + \frac{\partial T}{\partial x}\right)\right]^{\frac{1}{3}} + q_V$$

Good compatibility for low and high flows

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Experiment -validation

(1/2) - National High Magnetic Field Laboratory, Florida State University

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Cryogenics 41 (2001) 453–458

Cryogenics

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Steady-state pressure drop and heat transfer in He II forced flow at high Reynolds number

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Received 1 February 2001; accepted 24 April 2001

Operating range:
Temperatur bath: 1.7 K
Velocity: up to 20 m/s
Heat flux – up 8 W/cm^2

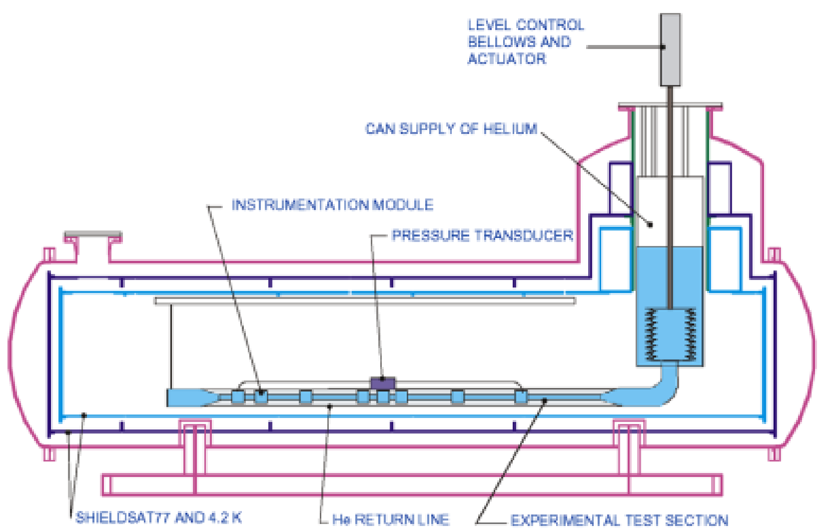

Fig. 1. Schematic of the experiment.

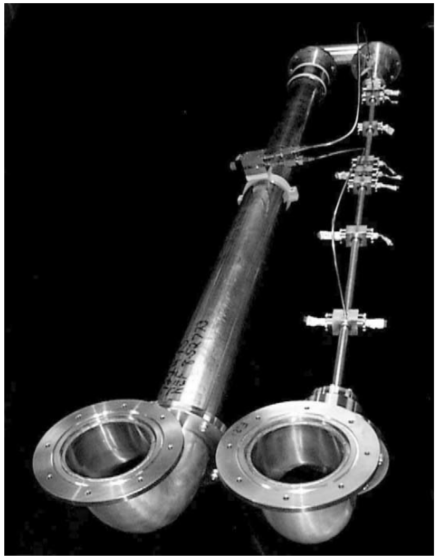

Fig. 2. Experimental loop for He II forced flow.

Experiment

(2/2)

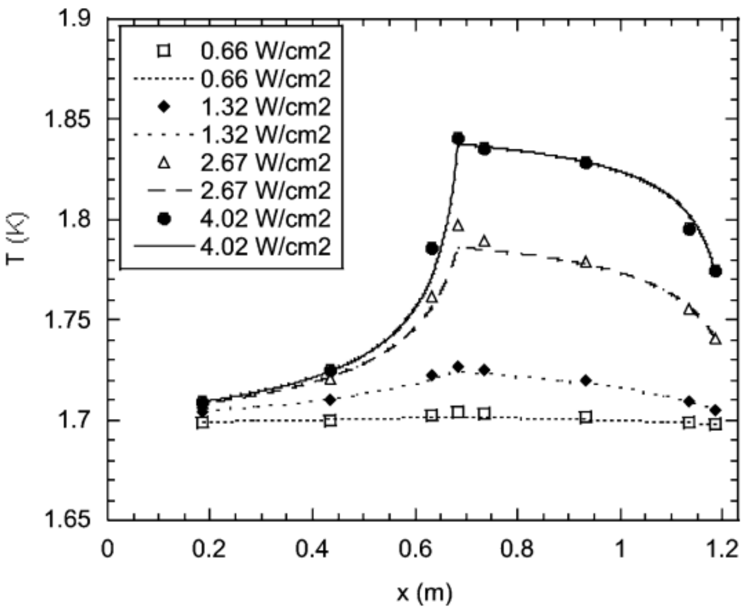

Fig. 6. Heat transfer in the test section for a flow velocity of 0.52 m/s and for several heat per cross-section area ($T_{bath} = 1.7$ K). The markers correspond to experimental results and the lines represent the numerical solution of the He II heat equation (3).

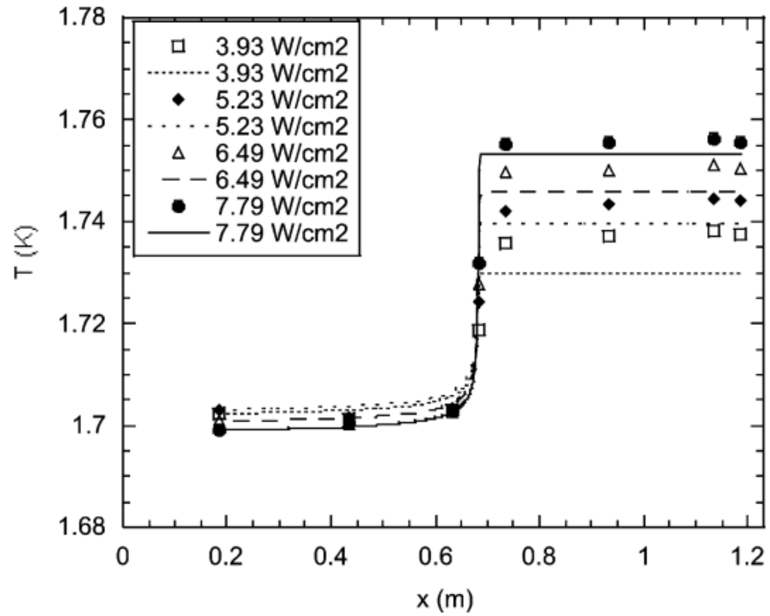

Fig. 7. Heat transfer in the test section for a flow velocity of 4.14 m/s and for several heat per cross section area ($T_{bath} = 1.7$ K). The markers correspond to experimental results and the lines represent the numerical solution of the He II heat equation (3).

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Numerical model

(1/2)

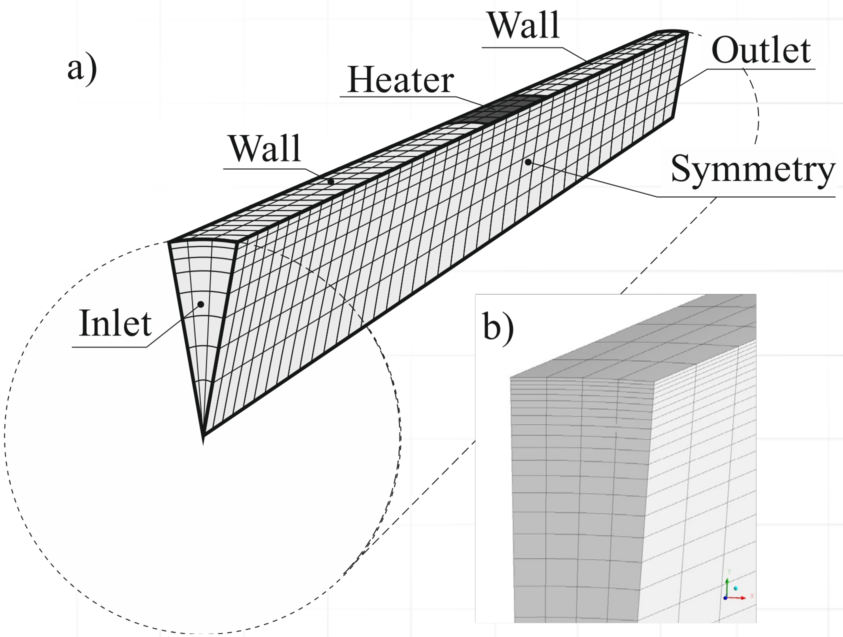
- Equations implemented in **OpenFOAM** software;
- A non – linear system with mixed hyperbolic – parabolic equation system is solved with high resolution scheme which is a bounded second-order upwind biased discretization
- A SST (Shear – Stress - Transport) turbulence model was applied for solving the pressure and velocity fields
- The maximum timescale is 10^{-6} s with a root-mean-square (RMS) residual target smaller than 10^{-7}
- Adiabatic condition applied to the pipe walls except at the heating section
- The boundary conditions for perpendicular ⊥ and tangential || total velocities at the walls

$$u_{\perp} = 0 \text{ and } u_{\parallel} = \left(\frac{\rho_s^3 \, s}{A \, \rho^3 \, \rho_n \left| -\frac{1}{\rho \, s} \nabla P + \nabla T \right|^2} \right)^{\frac{1}{3}} \left(-\frac{1}{\rho \, s} \nabla P + \nabla T \right)_{\parallel}$$

Numerical model

(2/2)

- A symmetric conditions are applied at the two sides of the domain wedge
- Constant temperature and velocity at the inlet
- A zero value of average static pressure was applied at the outlet



a) The computation domain with boundary conditions and b) snapshot of mesh at inlet region near the wall

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Steady - state heat transfer

Comparison with the NHMFL forced flow experiments

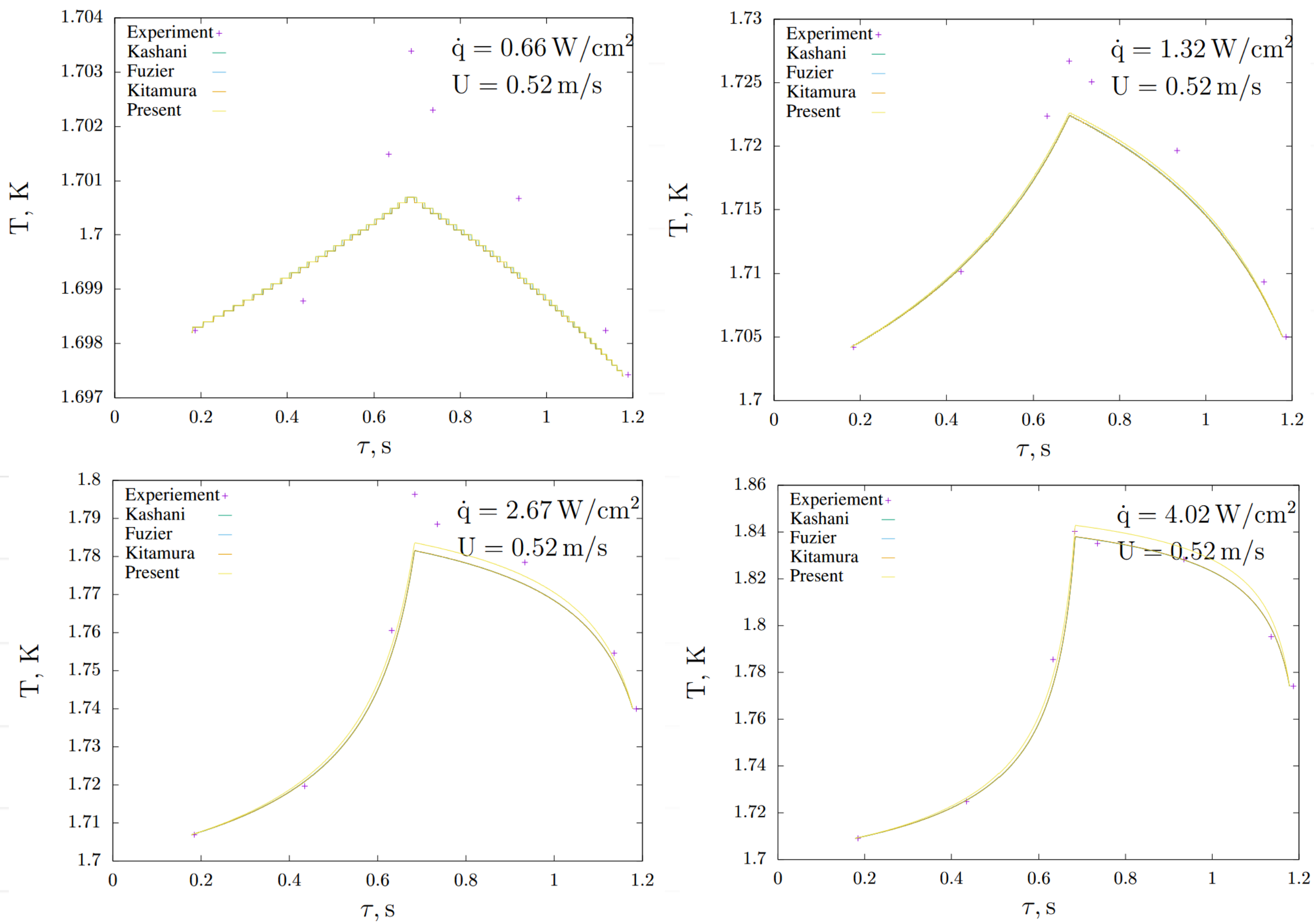
- 1.212 m long straight stainless steel tube of 9.8 mm ID
- Eight temperature sensors and a cold differential pressure transducer along the pipe

Calculation

- Uniform mesh of 2000 nodes along the z-direction
- Heater modeled via volumetric heat source
- Boundary temperatures taken from Fuzier's experiment

Steady - state heat transfer

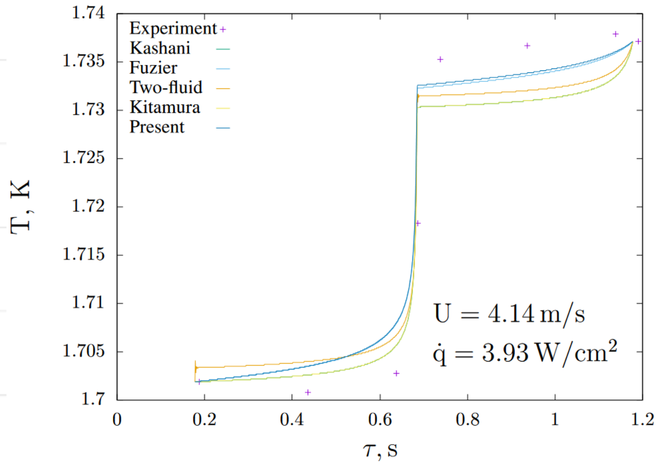
Low velocity 0.52 m/s

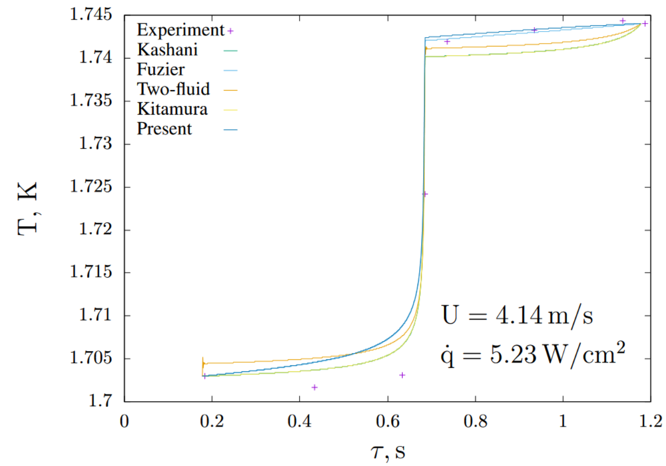


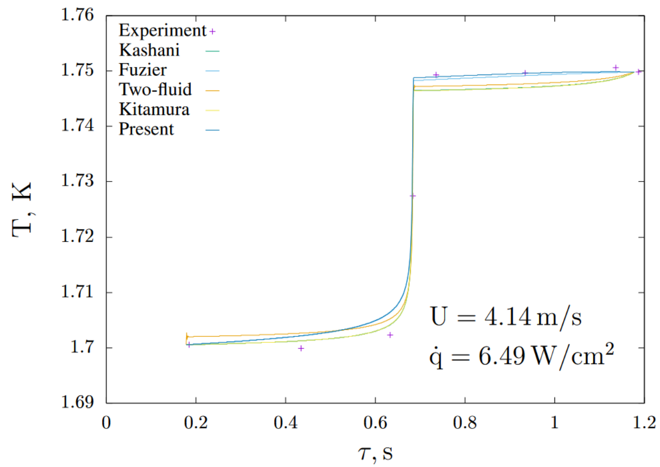
- For low velocity we were not able to use two-fluid code due to numerical errors

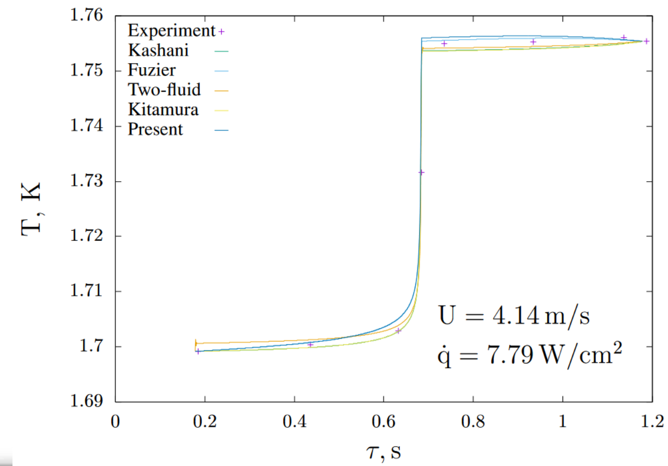
Steady - state heat transfer

High velocity 4.14 m/s









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Conclusions

- The new simplified model of forced flow superfluid helium has been proposed. The model assumes that the dominant terms in the superfluid momentum equation are the thermo-mechanical term, the Gorter-Mellink mutual friction and the pressure gradient;

- To demonstrate the stability and capability of three dimensional (3D) model, the model was validated with experimental data obtained during steady heat transfer processes;

- The model reproduces with a good accuracy experimental data , particularly in 'transition’ regions where other models are 'failing badly'.

Perspective

- To extend the validation procedure for transient processes;
- Optimizing the calculation processes;