Contribution ID: **294** Type: **Regular Oral (15m)**

Numerical study on transient heat transfer in forced flow of superfluid helium

Tuesday 23 July 2024 16:00 (15 minutes)

ABSTRACT:
Superfluid helium (He II) offers unique challenges and opportunities in heat and mass transfer phenomena due to its exceptional thermal conductivity and peculiar flow characteristics. These properties make superfluid helium an indispensable medium in cooling applications, particularly in high-energy physics where maintaining the operational stability of superconducting cavities is critical. A key issue is the prevention of quenching—a sudden loss of superconductivity caused by inadequate heat removal in forced flow He II, which can lead to significant operational disruptions and damage to the equipment.
This study presents a two-dimensional(2D) numerical investigation of the transient heat transfer in forced flow superfluid helium, utilizing Landau's two-fluid model in conjunction with Vinen's vortex density equation. Our program nicely reproduced the temperature variations during the heat transfer process as observed in Fuzier's experiments. In the 2D cases, the result illustrates a unique phenomenon where superfluid helium exhibits a radial velocity near the heater, creating a "nozzle" effect that leads to the contraction and subsequent expansion of the flow. This effect is accompanied by the generation of vortices in the normal fluid component near the heater. Upon cessation of heating, both the "nozzle" effect and the vortices detach from the heater and dissipate downstream with the heat flow. As the inlet velocity increases, the axial motion intensifies, leading to a reduction in vortex size near the heater walls and a decrease in overall thermal contraction, yet the vortices and "nozzle" effect persist downstream post-heating. Furthermore, in line with previous predictions, the mechanism of counterflow remains active even under conditions of forced flow. Following the input of heat, there is a noticeable decrease in velocity at the upstream locations of the heater, whereas the velocity and temperature downstream are significantly enhanced. Specifically, at an inlet velocity of 2 m/s and a heating power of 9.9 W/cm2, the velocity of the normal fluid upstream was reduced by 15%, while it increased by 79% downstream. For the superfluid component, the trend is reversed, aligning with momentum conservation principles. Notably, as the inlet velocity increases, the influence of thermal counterflow diminishes, leading to smaller variations in velocity differences. This study aims at our understanding of the complex dynamics in transient heat transfer of forced flow He II, providing valuable insights for engineering applications, particularly in managing heat dissipation in superconducting accelerators during quench events.
KEYWORDS: Superfluid Helium, Forced flow, Transient heat transfer.

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Session Classification: Tue-Or5

Track Classification: Tracks ICEC 29 Geneva 2024: ICEC 12: Thermal properties and numerical studies