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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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Abstract

An experiment has been built to study heat transfer in forced flow of He II at flow velocities up to 22 m/s. The main part of this experiment is a 10 mm ID, 0.86 m long straight test section instrumented with a heater, thermometers and pressure transducers. The high flow velocities allow clear observation of the effects of the forced convection, counterflow heat transfer and the Joule–Thomson effect. A numerical model based on the He II energy conservation equation and including pressure effects has been developed to compare with the experimental results. The model works well for low flow velocities where the heat flux is primarily driven by the temperature gradient and for high flow velocities where the heat flux is primarily driven by the pressure gradients. In the intermediate velocity region, discrepancies between the model and experiment may result from an inappropriate representation of the heat flux by counterflow when the temperature and pressure gradients have an effect of similar magnitude on the heat flux.

Keywords: Superfluid helium (B); Heat transfer (C); Forced flow (C); Joule–Thomson coefficient (C)

1. Introduction

Due to its excellent heat transfer capabilities, superfluid helium (He II) is often used to cool superconducting magnets to lower temperatures ($T \sim 1.8$ K) to enhance their performance and stability. The main means of heat transfer unique to He II are the second sound, which is a thermal wave, and the heat transfer by counterflow, which is a diffusion-like mechanism with a very high non-linear effective thermal conductivity [1]. Counterflow is the dominant mode of heat transfer in static He II for most engineering applications. As for classical fluids, forced flow can further improve cooling with He II, reducing the quantity of the helium required and the size of the cryogenic system [2,3]. A pressure drop along the flow path however typically corresponds to an isenthalpic expansion (Joule–Thomson effect) resulting in an increase of the temperature of the He II [4,5]. A complete understanding of heat transfer in forced flow of He II therefore requires the consideration of the forced convection, the heat transfer by counterflow as well as the pressure gradient related effects.

For previous transient heat transfer studies in forced flow of He II, Kashani and Van Sciver [6] made measurements for flow velocities up to 0.8 m/s. However, due to the low flow velocity, pressure gradient effects where negligible and the heat transfer consisted simply of a superposition of the counterflow on the ordinary forced convection. Rousset et al. [4] later made some heat transfer measurements for flow velocities up to 1.1 m/s. In that case, the pressure gradient was also small but due to the long length of their test section, they could observe some pressure effects such as the increase of the temperature along the flow path due to the Joule–Thomson effect. More recently, we have performed an experiment expanding the range of flow velocities investigated by an order of magnitude up to 22 m/s. The pressure drop per unit length becomes very significant in this range [7], which allows the clear observation

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Nomenclature

A_{GM}	Gorter–Mellink parameter (ms/kg)	T	temperature (K)
C_f	Fanning friction factor	U	specific internal energy (J/kg)
C_p	specific heat at constant pressure (J/kg K)	v	velocity (m/s)
D	tube diameter (m)		
f	turbulent He II heat conductivity function (m^5 K/W^3)	*Greek symbols*	
h	specific enthalpy (J/kg)	α	thermal expansion coefficient (K^{-1})
L	length (m)	μ	Joule–Thomson coefficient (K/Pa)
$\dot{m}$	mass flow rate (kg/s)	ρ	density (kg/m^3)
P	pressure (Pa)	ε	roughness (m)
q	heat flux per cross-section area (W/m^2)	*Subscripts*	
q_l	heat flux per unit volume (W/m^3)	n	relative to the normal fluid component of He II
s	specific entropy (J/kg K)	s	relative to the superfluid component of He II

of the distinct effect of the forced convection, counterflow and the Joule–Thomson effect as well as their interactions [8]. Qualitative observations of our transient heat transfer measurements suggest that the effectiveness of the counterflow heat transfer may decrease at the highest flow velocities. However, as the counterflow, forced convection and Joule–Thomson effect have an interdependent effect on the shape of the temperature profile, quantitative information about the counterflow heat transport can not be obtained directly from the measurements. We therefore have developed a model incorporating these different modes of heat transfer and compared its solution with our experimental results.

Several models have been developed to characterize heat transfer in forced flow of He II [4,6,9,10]. All these models are based on some variation of the He II heat transfer equation or the two-fluid model with their numerical solutions generally in pretty good agreement with Kashani's or Rousset's data or both. The numerical model we have developed is based on the He II heat transfer equation and includes pressure gradient effects. The solution of this model is compared to our experimental results, which cover a significantly wider range of velocities than in previous studies.

The present paper begins with a brief description of our experimental setup and results to introduce the physical effects observed and the need to develop a numerical model. Further details about the experiment are available in Refs. [8,11]. The physical equations at the origin of our model are presented as well as the method used for the numerical resolution. The paper concludes with a comparison between the experimental and numerical results.

2. Experimental setup and results

The forced flow He II heat transfer experiment is composed of a can/bellows pump assembly which generates the motion of He II through an instrumented experimental loop (Figs. 1 and 2). The can/bellows pump assembly contains a 0.28 m diameter bellows with a 0.3 m stroke actuated by a stepper motor (model ETS80-B04LA41-GF343-A manufactured by Parker Motion and Control). The bellows is located in an 80 l can containing a buffer volume of saturated He II for receiving the return flow and refilling the bellows. This assembly is suspended in the vertical part of the cryostat. The experimental flow loop is supported on a rail system along the top of the inner most thermal shield located in the horizontal part of the cryostat. The main part of the experimental loop is a 0.86 m long, 10 mm ID, straight, smooth stainless steel test section instrumented with heaters, thermometers and pressure transducers (Fig. 2). A larger diameter pipe allows the return of the helium to the can assembly with minimal pressure drop.

The thermometers used in the experiment are bare chip Cernox™ model CX-10-30-BC from LakeShore Cryotronics. They are made of a 0.3 μm thin zirconium oxinitride film deposited on a sapphire substrate. The thermometers are mounted on supports designed to place the sensitive film in direct contact with the He II with minimal disturbance to the flow [8]. With the sensitive film in contact with the He II, the time response of these thermometers is estimated to be around 1.5 μs [12].

The heat pulses are generated by a commercial Nichrome film heater epoxied on the inside wall of the test section. The heater is 2.8 cm long to cover most of the circumference of the tube and 1 cm wide in the direction of the flow (between $x = 30.3$ and 31.3 cm from the inlet). Two differential and one absolute cold pressure transducer, model DP10 and AP10 manufactured by Validyne, measure the pressure drop across 0.6 m of the test section, the divergent section and the absolute pressure at the end of the test section.

Flow velocities up to 22 m/s are generated in the test section. Rectangular heat pulses of duration varying between 1 and 20 ms and power density between 9 and 40 W/cm^2 of channel cross-section are generated by the heater. The temperature evolution is recorded at eight thermometer locations listed in Table 1.

Figs. 3 and 4 show the evolution of the temperature at two locations for different flow velocities for the same heat