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Space Cryogenics Components Based on the Thermomechanical (TM) Effect: I. Vapor-Liquid Phase Separators

S.W.K. Yuan and T.H.K. Frederking,
University of California, Los Angeles,
CA

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SPACE CRYOGENICS COMPONENTS BASED ON THE THERMOMECHANICAL (TM) EFFECT:
I. VAPOR-LIQUID PHASE SEPARATORS

S. W. K. Yuan* and T. H. K. Frederking
University of California
Los Angeles, CA 90024

Abstract

A survey of He II vapor-liquid phase separation is given emphasizing fluid-related transport phenomena. In this Part I flow phenomena are addressed based on the findings of the Ph.D. thesis of the first author**. The historical development in the phase separation area has promoted systems in which the solid state component acts as an insulated body. It is noted though that the "Fairbank plug" *limit* constitutes another type of phase separation mode useful for very low heat rejection rates.

In fluid transport-controlled vapor liquid phase separation (VLPS) the two-fluid model is a most convenient tool for quantification of plug parameters. The "bottleneck mechanism" has been found to be the heat transported through the porous plug in the form of normal fluid convection. Two main regions support stable VLPS: 1. the low speed regime of laminar (linear) flow, and 2. non-linear convection at relatively high speed. Major findings are presented relying on the phenomenological theory for liquid He II and emphasizing the normal fluid component of the two-component system (superfluid and normal fluid) of He II.

The present *extended summary* of "Part I" contains the following subsections: VLPS system categories, two-fluid theory, experimental evidence available, comparison of data with theory, and conclusions.

Extended Summary

Function

The phase separator has the task of keeping liquid inside the tank while rejecting thermal energy in a stable manner (Fig. 1). The heat rejection takes care of the incoming heat leak and instrument loads. A balanced operation with steady temperatures of the cryogenic system implies a suitable selection of the VLPS component. In He II, the thermomechanical forces are available. They are put to use by imposition of a small temperature difference across the phase separation device proper. Figure 1 is a schematic diagram of the system.

VLPS Categories

The classification of VLPS systems has been in part based on control equipment attached to the device. The "passive" VLPS is a system with inherent negative feedback behavior. This makes it possible to operate without excessive controller application implying that all components are designed optimally to make sure that heat input into the He II cryogenic tank is balanced by the heat rejection rate in the form of vapor at the VLPS exit. The "active" VLPS system (called APS in the literature) has the additional task of permitting temporarily the absorption of large amounts of thermal energy. This task is accomplished by a variable position device, such as a needle type or shutter type subsystem which is movable. The needle device has been extensively developed and studied by the Klipping group*. The option exists of dumping a certain amount of liquid downstream by allowing onset of liquid breakthrough and subsequent vaporization. An alternate method is the use of a fountain effect pump which pumps back some of the liquid breaking through during "peak" demand reduction.

Another classification scheme is based on the *transport mechanism:* one VLPS system, the original "Fairbank plug" has highly conducting solid thin walls adjacent to very narrow liquid channels. Therefore, heat is conducted through the solid. Superfluid can flow in very narrow passages between the solid state domains, e.g. tightly wound aluminum foil arranged in a spiral. The very narrow fluid spaces do not permit passage of the viscous normal fluid. The result is a very low heat rejection rate compared to other VLPS systems.

The second category of plug separators is the porous plug with relatively large liquid spaces and adiabatic walls of the solid grains. This plug category has been selected in He II vessel projects for space observations in the far infrared. The porous plug device permits larger heat rejection rates along with mass throughput, for a specific cross section, than the Fairbank plug. The normal fluid carrying heat plays an active role in the heat rejection rate needed. The superfluid is responsible for the thermomechanical force directed into the vessel interior, preventing liquid escape. In view of several mechanisms proposed, the present work has had the purpose of clarifying the mechanisms, in particular the role of heat transport modes. It turned out that first order effects of quite a few experiments all have been predicted, within data scatter, by a rather simple theory. A few elementary notions of the two-fluid model have to be known for the use of this conceptual tool.

Two-Fluid System

The two-fluid postulate leads to a system of equations giving a handle on the complicated transport in the non-Newtonian fluid He II.

The two-fluid theory is a simplification of actual phenomena in general. However it predicts amazingly well effects at *low* energy expenditure in the so-called *linear* regime. There is superfluid with zero viscosity, and normal fluid with a finite viscosity and entropy/heat

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*Permanent Address: Lockheed Palo Alto Research Lab., Palo Alto, CA 94304

** S. W. K. Yuan, Ph.D. thesis, University of California, Los Angeles, 1985; also Manuscript No. T0258).

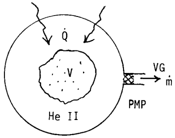

Fig. 1.1

He II vessel with phase separator (schematically). $\dot{Q}$ heat flow rate from parasitic input through insulation and supports, and from instruments; PMP porous media phase separator; V vapor, VG vent gas flowing at mass flow rate $\dot{m}$.

transport capability. Fluids carry heat bodily by convection, and the He II normal fluid is no exception, moving in "internal counterflow" opposite to superfluid. In VLPS practice, the non-linear regime is of great importance, because of microgravity operation in this regime.

Experiments

The porous plug VLPS has been used in line with throughput requirements of He II vessels in the range from 1 to 10 mg/s. The experiments have been conducted with a central vent tube in a surrounding "vessel" of small lab dimensions. Similar arrangements have been used in other labs (described in the thesis cited above). The vessel heat leak is varied using a heater. The flow rate is measured, as are temperatures and pressures upstream and downstream of the porous plug.

The comparison of the data with theory has relied on a uniquely defined throughput measure of the porous medium. Such a measure is the Darcy impedance factor or its reciprocal, the Darcy permeability. Authors have used another "flow impedance factor" easily converted into permeability as soon as dimensions of the plug are known. In the present work the Darcy permeability has been used. It turned out that *integration* over temperature-dependent properties has been essential in order to arrive at satisfactory agreement between theory and experiment. In He II the entropy varies very significantly with temperature. The data are presented as mass flow rate per total plug cross section, i.e. superficial values.

Comparison of Data With Theory

The mass flux density is proportional to the heat flux density (superficial value) of the porous plug VLPS. The unknown non-linear regime has been emphasized using product functions such as thermal energy density times effective velocity. Another factor is the superfluid density ratio. The original wide duct theory has been known as Gorter-Mellink theory. In contrast to the wide duct phenomena, a surprisingly simple pore size dependence is exhibited by the data (within scatter). Porous media have a tendency to reproduce less satisfactorily than other fluid duct systems. Yet manufacturing has made great progress in sintered stainless steel used in many experiments. It turns out that the mass flux density tends toward a simple square dependence on permeability in the range considered. Thus empirical ingredients are used in conjunction with principles established for non-linear counterflow of heat and superfluid.

Conclusions

It has been concluded from the VLPS studies (Yuan, op. cit.) that well-defined convection patterns exist in porous plug phase separators. Similar patterns ought to exist for "He II heat pipes", and preliminary experiments in this area tend to confirm this expectation.