The Cryogenic Parallel Heat Pipe System for Application to Conduction Cooled Superconducting Magnet

伝導冷却超伝導磁石への応用を目指した
極低温パラレルヒートパイプシステムの研究

Ramnarong WANISON

DOCTOR OF PHILOSOPHY

Department of Accelerator Science

School of High Energy Accelerator Science

The Graduate University for Advanced Studies, SOKENDAI

2021

Supervisor:	Prof. NAKAI, Hirotaka Assc. Prof. KIMURA, Nobuhiro
Examiners:	Prof. MAKIDA, Yasuhiro Assc. Prof. OKAMURA, Takahiro Prof. SASAKI, Ken-ichi Asst. Prof. SHIMIZU, Hirotaka Prof. NAKAI, Hirotaka Assc. Prof. KIMURA, Nobuhiro Honorary Prof. MURAKAMI, Masahide Asst. Prof. TAKADA, Suguru
Day of Final Evaluation:	19 August 2021
Day of Submission:	10 June 2021

ABSTRACT

The High Energy Accelerator Research Organization, known as KEK, whose purpose is to operate the largest particle physics laboratory in Japan. Numerous experiments have been conducted at KEK, especially in cryogenic science and engineering that involve the study to support accelerator science research mostly for superconducting magnets. Since a superconducting magnet must be cooled to cryogenic temperatures during operation therefore, a cooling system is necessary. A cryogenic heat pipe has been proposed for the application to conduction-cooled superconducting magnets to improve the efficacy of cooling systems. However, a cryogenic heat pipe has operation limits such as low maximum heat transport capability, Q_{max}. The parallel heat pipe system, which is composed of a combination of individual heat pipes, can enhance the performance of a single heat pipe with respect to Q_{max}, and expand the operating temperature range. This is the experimental study to survey thermal behavior of cryogenic heat pipes under condition of a wide range of heat load and of heat pipe operating states; from the normal heat pipe operation to the local dry-out state. The heat pipes tested in this research were commercially available, but working fluid was replaced by nitrogen (N_2) or argon (Ar) or neon (Ne) to work at cryogenic temperatures. The size of the tubular copper heat pipe is; 6 mm in outer diameter and 200 mm in length. The thermal performance of the heat pipes was examined together with the effects of the working fluid filling ratios, the inclination angle, the condenser temperatures as well as the wick structures such as axial groove (G), sintered metal powder (S), and combination of them (GS). The parallel heat pipe system, which consists of an N_2-heat pipe and an Ar-heat pipe, or of an N_2-heat pipe and an Ne-heat pipe arranged in parallel, was tested in order to investigate the thermal performance for extending the operating temperature ranges. The effective thermal resistance, the axial temperature distribution and the pressure inside the heat pipes were measured for a wide range

of heat load. The thermal behavior even in the local dry-out state for large heat input was also examined for the potential application to a conduction-cooled superconducting magnet. It was experimentally confirmed that the commercially available conventional heat pipes being replaced the working fluid with nitrogen, argon or neon could operate normally at temperatures of 63–87, 83–110 and 27–35 K, respectively.

The followings are the major experimental results obtained in the present study. The prediction of the heat pipe operation at near the critical temperature of the working fluid shows that the maximum heat transport capability, Q_{max}, becomes very small, since the latent heat of vaporization becomes zero at the point. The filling ratio of working fluid should be higher than 50% to activate the cryogenic heat pipe, and the working fluid filling ratio considerably affects Q_{max} of the heat pipe. The gravity force acting on the excess liquid puddle accumulated in the end portion of the condenser section causes increasing of Q_{max} in cases of the filling ratio larger than 100%. The inclination angle of larger than 10° in the case when the evaporator section is below the condenser section can much enhance the value of Q_{max}. The minimum value of the overall thermal resistance, R_{th}, which appeared during the normal heat pipe operation, was 0.20, 0.25 and 0.12 K/W for the N_2-heat pipe, the Ar-heat pipe and the Ne-heat pipe, respectively. It was found that the effective thermal conductance was approximately 150 times superior to that of the heat pipe without working fluid filled where heat transferred by conduction through a copper tube wall, and 75 times superior to that of a simple copper rod having the same diameter and length as the heat pipe. The performance rank by the wick structures on the basis of Q_{max} is as follows in descending order: GS, S and G. It was the results of the experiments that the N_2-heat pipe, the Ar-heat pipe and the Ne-heat pipe with the GS wick structure and 100% filling ratio had the values of Q_{max}, 12, 14 and 7 W, respectively. The parallel heat pipe system can enhance the performance of the single heat pipe with respect to Q_{max}, which was 29 W in the case of the operating temperature of 87 K. It is seen that even in the local dry-out state the heat pipe still has high heat transfer rate compared to solid copper. This seems to indicate it can be utilized for cooling of superconducting magnets from room temperature.

It is experimentally confirmed that the commercially available conventional heat pipe can be utilized as a cryogenic heat pipe for the application to conduction-cooled superconducting magnets. It was demonstrated that the wide range of cryogenic heat pipe operation consisting not only of the normal heat pipe operation but also the local dry-out state is effective for thermal management owing to very small temperature gradient and cooling from room temperature.

THESIS OUTLINE

The outline and the structure of this thesis are introduced in this section. The thesis consists of seven chapters, as follows.

Chapter 1: **INTRODUCTION:**

The background, motivation and objectives of this study. Introduction of the cryogenic heat pipe by using a commercially available conventional heat pipe to superconducting magnet cooling application, and of the experiments that were performed in this study.

Chapter 2: **FUNDAMENTALS OF HEAT PIPES:**

Description of the fundamentals of heat pipes including the historical development of heat pipes, working principle, types of heat pipes, working fluids and operating temperature ranges, wick design and structure, and heat transfer limits.

Chapter 3: **LITERATURE REVIEW:**

Summarizing and finding the knowledge gap from previous studies in order to define the scope of the present research and think more deeply about the experimental results obtained so far as well as the recent cryogenic heat pipes.

Chapter 4: **EXPERIMENTAL APPARATUS:**

Experimental apparatus and measurement technique used in this experiment including the two different kinds of cooling methods, cooling with a liquid nitrogen bath and a cryocooler.

Chapter 5: **EXPERIMENTAL PROCEDURE:**

Experimental procedure including the preparation and method of the experiment, technique, and safety for operating the experiment at cryogenic temperatures.

Chapter 6: **RESULTS AND DISCUSSION:**

Experimental results of the single heat pipes and the parallel heat pipe system on thermal behavior in the normal heat pipe operation and the dry-out state characterized by the overall thermal resistance.

Chapter 7: **CONCLUSION.**

ACKNOWLEDGMENT

First of all, I would like to express my special appreciation and thanks to my supervisor Associate Professor KIMURA Nobuhiro, the Cryogenics Science Center, KEK, for all his invaluable support and guidance. I really appreciate his encouragement, genuine and constant supervision, brilliant ideas, support and motivation throughout the entire study.

My deepest gratitude goes to Professor Emeritus MURAKAMI Masahide at the University of Tsukuba, who is Professor Emeritus at University of Tsukuba, for all the support and encouragement he gave me. Without his guidance and constant feedback, this study would not have been achievable.

I would like to express my sincere gratitude to Professor NAKAI Hirotaka, the Accelerator Laboratory, KEK, for all of his supports during I was studying in SOKENDAI.

I would also like to thank Assistant Professor TAKADA Suguru, the National Institute for Fusion Science (NIFS), for good suggestion and discussion to the experiment on my study.

Sincerely thank the members in the Cryogenics Science Center, KEK, for their very kind assistance in the experiment. Miss A. Ueda for helping us to design the experimental set up and Mr. G. Namai for supporting to construct the experimental set up.

Special thanks to Professor Pradit TERDTOON and his Heat Pipe and Heat System Laboratory, Chiang Mai University, Thailand, for supplying commercially available heat pipes to this study.

Finally, I would like to gratefully acknowledge financial support from the Japanese government scholarship (Ministry of Education, Culture, Sports, Science and Technology, MEXT) for supporting on my whole study.

TABLE OF CONTENTS