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学位（専攻分野）	博士（工学）
学位記番号	総研大甲第1484号
学位授与の日付	平成２４年３月２３日
学位授与の要件	物理科学研究科　核融合科学専攻 学位規則第６条第１項該当
学位論文題目	振動式ヒートパイプによる核融合用超伝導マグネットの高性能化研究
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論文内容の要旨

The superconducting magnets for fusion experimental devices are used in the condition of high magnetic field, high electromagnetic force, and high heat load. The pool boiling liquid helium cooling outside of the conductor or the forced flow of supercritical helium cooling inside of the conductor, such as the cable-in-conduit conductor, are used so far for the cooling method of the superconducting magnet for the present fusion devices. The pool cooling magnet has the disadvantages of low mechanical rigidities and low withstanding voltages of coil windings. The forced flow cooling magnet with cable-in-conduit conductors has the disadvantages of the restriction of the coil design because of the path of the electric current must be the same as that of the cooling channel for refrigerant. The path of the electrical current and that of the cooling channel for refrigerant can be independently designed by adopting an indirect cooling method that inserts the independent cooling panel in the coil windings and cools the conductor from outside. In this study, this indirect-cooling method is adopted as a promising candidate for fusion magnets.

Improvement of superconducting magnets for high magnetic field and high heat load is an important subject to achieve the early realization of nuclear fusion power generation. Application of high-temperature superconductors (HTS) to magnets has widely been studied, ever since the discovery of the high temperature superconductivity in late 1980s. HTS magnets may achieve higher magnetic fields with less operation cost and higher stability against a coil quench compared to low-temperature superconducting magnets. In HTS magnets, the stability of winding conductors is assured by the rise of operating temperatures. However, it is difficult to remove the local heat generated in an HTS magnet because the thermal diffusivity of each component material used in the magnet, such as copper, aluminum alloy, epoxy resin, GFRP, etc., decreases as the operating temperature increases. When a part of the windings turns into the normal-conducting state, therefore, large temperature gradients are easily produced in magnets, which could cause degradation of superconducting properties and mechanical damages by thermal stresses. In other words, the protection of magnets becomes more difficult than the case for low temperature superconducting magnets.

We propose a new method of including cryogenic oscillating heat pipes (OHPs), which is also called pulsating heat pipes (PHPs), in the HTS magnet windings as a heat transfer device. The OHP is a highly effective two-phase heat transfer device which can transport several orders of magnitude greater heat flux than the heat conduction of solid metals and be formed in a thin plate structure. In these respects, we consider that the OHPs imbedded in the coil windings can enhance the heat removal characteristics in HTS magnets.

The OHP is a wickless and typically exists as a serpentine-arranged tube where the tube forms a closed or open loop. The OHPs in the form as they are being investigated today have been first proposed and patented in 1990 by H. Akachi. The OHP is partially filled with a working fluid and the inner diameter of the tube is made sufficiently small in order to induce surface tension allowing formation of liquid slugs and vapor bubbles. Successful OHP operation occurs by an oscillatory pressure field and via the constant phase change of the internal working fluid. A pressure change induces a pseudo-chaotic displacement and circulation of the internal working fluid. The performance of an OHP is known to depend on thermo-physical properties of working fluid, filling ratio (the total internal liquid volume divided by the total internal channel volume), channel geometry (i.e. hydraulic diameter and length), number of turns, operating orientation and length of heating and cooling areas.

A modest number of studies about OHPs have been performed at room temperature and some types of OHP for electronics products have been already used as a high performance heat transfer device. The result of the fundamental experiment that uses the cryogenic loop heat pipes for the cooling between superconducting magnet and cryocoolers was reported in few literatures. However, there is a limitation in the orientation of the installation of the looped heat pipe and its shape is not applicable to the usage imbedded in magnets as a cooling panel. In this study, firstly proof-of-principle experiments of cryogenic OHP has been conducted using nitrogen, neon, and hydrogen as working fluids of OHP.

Prototype cryogenic OHPs to be used by being imbedded in superconducting magnets have been designed and manufactured. A stainless-steel pipe of 1.59 mm(1/16 inch) in outer diameter and 0.79 mm in inner diameter is bent 10 times at both ends with the straight sections of 160 mm in length. Two Cu blocks of 8 mm in thickness and 30 mm in length having grooves according to the pipe positions and are soldered with the pipes. A experimental apparatus for cryogenic OHP testing has been prepared, which consists of a cryostat, a GM cryocooler, a vacuum pump, gas cylinders (for nitrogen, neon and hydrogen), etc. The testing OHPs are placed in a vacuum chamber in the cryostat enclosed by the 60–80 K radiation shields and the working fluid is vacuum-encapsulated into the OHP and the OHPs are isolated by closing a valve on an inlet pipe. One of the two Cu blocks of OHP which works as a condenser is connected to the cold head of the cryocooler and the other Cu block which works as an evaporator attached with a foil heater. In the experiment procedure, the temperature of the condenser is maintained at a prescribed point which is below the condensation temperature, and the temperature of the evaporator is raised by the heater. The heat transport characteristics of the OHP have been measured by the temperature difference between the heating part (evaporator) and the cooling part (condenser) of the OHP. The effective thermal conductivity of portions of the fluid path in the pipes is calculated by each experimental data.

In the proof-of-principle experiments of cryogenic OHPs, the measured effective thermal conductivities have been measured to be 500–3500 $Wm^{-1}K^{-1}$ for H_2, 1000–8000 $Wm^{-1}K^{-1}$ for Ne and 5000–18,000 $Wm^{-1}K^{-1}$ for N_2 at the operating temperature ranges of 17–25 K, 26–32 K, and 67–80 K, respectively. These effective thermal conductivities are all larger than those of high-purity metals which are used as components of the conduction at low temperature engineering. It is, consequently, suggested that cryogenic OHPs can be applied to cooling of superconducting magnets. As a reference, the thermal conductivity of Cu with RRR (Residual Resistivity Ratios) = 100 at the magnetic field of 1 T and 20 K is about 2000 $Wm^{-1}K^{-1}$.

Having been encouraged by this successful experimental results, the performance characteristics of OHPs have been intensively examined, furthermore. The additional experimental parameters are the liquid filling ratio, pipe diameter, inclination angle and length of the heat transfer of the OHP.

Here in this abstract, the two experiments on the effect of pipe diameter and inclination angle are introduced. The effect due to the inner diameter of the OHP has been examined by changing the outer diameter from 1.59 mm to 3.18 mm and the inner diameter from 0.79 mm to 1.59 mm. The effective thermal conductivities of this OHP have reached to 11,000 $Wm^{-1}K^{-1}$ for H_2 and 19,000 $Wm^{-1}K^{-1}$ for Ne. The measured effective thermal conductivities of this OHP have been two times larger than those of the proof-of-principle experiments OHP for both H_2 and Ne.

In order to effectively cool HTS magnets, it is required that cryogenic OHPs can operate in a variety of installation orientations. In this respect, the operating characteristics of the OHPs have been examined by changing the inclination angle a. The installation orientation is set at the following four angles: horizontal ($a = 0$), vertical with the evaporator located at the bottom ($a = +90$ degrees), diagonal with the evaporator at the bottom ($a = +45$ degrees) , vertical with the evaporator at the top ($a = -90$ degrees)and diagonal with the evaporator at the top ($a = -45$ degrees) . For the orientations with the evaporator located at the bottom ($a = +90$ and +45 degrees) and for the horizontal orientation ($a = 0$), the OHP has operated stably with an effective thermal conductivity observed at 2,000–11,500 $Wm^{-1}K^{-1}$ for H_2 and 5,100–19,500 $Wm^{-1}K^{-1}$ for Ne. For the orientations with the evaporator located at the top ($a = -45$ and -90 degrees), however, the OHP has not worked stably. There have been many reports that OHPs can work also with these orientations at room temperature. Further optimization is necessary in order to operate cryogenic OHPs in various configurations, especially the turn number and the inner diameter of pipes. In order to mitigate the problem associated with the installation orientation, we propose a modified-type of OHP, with both ends cooled (condenser) and the center heated (evaporator), and stable operations have been confirmed experimentally. However, the measured effective thermal conductivity was found to be been smaller than that observed in the conventional type OHP. We consider that the effective thermal conductivity can be further improved by incorporating an optimized configuration for the OHP structure.

It is generally convenient to analyze the thermo-hydrodynamic properties for heat transfer using dimensionless quantities. In this work, it has been also attempted to get a comprehensive understanding of cryogenic OHPs by the semi-empirical correlations, which are based on values of thermo-hydrodynamic dimensionless numbers of the internal fluid. Using the model, of which the heat flux is expressed by the Karman number Ka, the Prandtl number Pr , the Jacob number Ja and inclination angle, a correlation has been formulated for the heat flux in OHPs, which is stated as follows: $\dot{q} = 2.61(\exp(a))^{0.05} Ka^{0.05} \Pr^{0.77} Ja^{-0.97}$. A total of 59 experimental data sets is used to make a fitting by means of multi-regression analysis. It is considered that this modeling with non-dimensional quantities is useful for the design of cryogenic OHPs.

The cryogenic OHPs used by being imbedded in superconducting magnets as a heat transfer device has been demonstrated for the first time in the world, and high heat transport properties of the cryogenic OHPs have been experimentally confirmed. A modified-type OHP, with both ends cooled and the center heated, has been proposed to reduce the negative effect of installation orientation and it has been tested successfully. We consider that it is possible to dramatically improve the performance of HTS magnets by using cryogenic OHPs.

博士論文の審査結果の要旨

将来の磁場閉じ込め核融合炉には、安定かつ安全で高効率な超伝導マグネットの実現が求められている。最近の高温超伝導材料の技術進展により、核融合装置用マグネットへの高温超伝導の応用が期待されている。しかし、高温超伝導の長所である運転温度の上昇に伴い、冷凍負荷は軽減するが、高温超伝導マグネットに適する伝導冷却方式においては、構成材料の熱拡散率の低下によってマグネット内部の温度を速やかに下げ難くなることが問題となっている。特に超伝導マグネットの一部が常伝導転移した場合に過度の温度勾配が生じると超伝導特性の劣化や機械的な破損の原因となるため、高い熱伝導率と熱拡散率を有する新たな冷却構造の開発が求められている。そこで、夏目恭平氏は、常温で高い熱輸送特性が実証されている自励振動式ヒートパイプ（OHP , Oscillating Heat Pipe）に着目し、超伝導マグネットに組込可能な高性能な熱輸送素子として、OHPの極低温域における動作特性の研究を行った。室温動作のOHPは既に実用化されているもののその動作特性は一般化されておらず、まして80 K以下の極低温域での研究は液体窒素温度での原理実証実験に限定されていた。そこで、作動流体として水素、ネオン、窒素の3種類を採用し、温度、液体充填率、設置方向依存性、配管径、配管長などをパラメータとしてOHPの動作範囲と実効的な伝熱特性を詳しく調べ、超伝導マグネットへの応用が十分可能となる性能を持つことを明らかにした。

博士論文は、序論（1章）、OHP を組み込んだ冷却システム（2章）、低温動作OHPと特性試験装置（3章）、OHP低温動作試験の結果と考察（4章）、半経験式モデルを用いたOHP低温動作試験の結果の解析（5章）、および総括（6章）で構成されている。1章において、将来の核融合装置用大型超伝導マグネットには高温超伝導体が採用され、20 K以上で運転することが期待されているが、その温度域ではマグネット構成材料の熱拡散率が低下することから熱応答特性に優れたOHPを伝熱媒体とする新しい伝導冷却マグネットの概念を提案している。2章において、有限要素法を用いた熱計算によってその冷却概念の有効性を示すとともにOHPの要求仕様を明らかにしている。3，4章に低温動作OHPの実験結果を纏めている。極低温と室温では作動流体の密度などの物性値が大きく異なるため、低温を維持する断熱真空容器や小型冷凍機、OHP内の作業流体充填率等を制御するためのバッファータンクや導入配管等を用いて独自に工夫することにより、OHPの極低温域での動作を世界で初めて系統的に実証した。OHPの伝熱特性試験結果から、作業流体に水素、ネオン、窒素を用いた場合の動作温度範囲はそれぞれ17-30 K、27-39 K、67-91 Kとかなり広いこと、および、加熱・冷却部の配管の横断熱抵抗を含めた実効的な熱伝導率が10,000 W/m/Kを超えることを明らかにした。この値は、残留抵抗比100の純銅の20 Kでの熱伝導率の5倍程度に相当する。また、液体充填率、配管長、高温端温度の広い範囲で実用的な動作特性を有することを明らかにした。さらに、OHPの設置方向依存性について、自励振動が発生し難い加熱端が高い姿勢の場合にも、加熱端が冷却端より低い姿勢の別のOHPと連結することにより全体が自励振動を開始することを実証するとともに、設置方向に依存しない両端冷却・中央加熱の新しいタイプのOHPを考案してその安定動作を実証した。5章において、実験で得られたOHP特性をレイノルズ数、プラントル数、ヤコブ数などの無次元数で整理することによって、OHP 構造や作動流体の物性値から熱輸送量を求める経験式を導出している。

以上のように、本研究は将来の核融合装置用超伝導マグネットに高温超伝導体が採用される場合の効果的な伝導冷却の手段として OHP を用いる概念を提案し、その低温動作 OHP の特性を詳しく調べたものであり、超伝導工学のみでなく核融合工学として非常に価値の高い内容となっている。特に、水素やネオンを作動流体とする自励振動式ヒートパイプの動作を実証した成果は世界初であり、また、極低温域において様々な形態の OHP の動作特性を明らかにし、超伝導マグネット冷却への応用の道を開いたことは博士論文として十分な価値を有すると共に核融合研究に資するものであると判断した。