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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: $\dot{q} = 2.61(\exp(a))^{0.05} Ka^{0.05} \mathrm{Pr}^{0.77} Ja^{-0.97}$. 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

核融合炉を実現するために、高温プラズマへの燃料粒子供給手法を確立することは必須の課題である。必要な性能として、①高い粒子供給効率、②少量から多量まで任意の粒子供給量制御性、③速い時間応答特性、を同時に達成することが求められる。これまで燃料ガスをプラズマに吹き付けるガスパフと、冷却固化した水素ペレットを入射する手法が研究されてきたが、①～③の同時達成は困難だった。村上昭義君は新たに超音速ガスパフに着目し、大型ヘリカル装置（LHD）の大型かつ高温のプラズマを対象とした実験を行い、核融合炉相当の条件下でも①～③の同時達成が可能なことを明らかにした。

超音速ガスパフは近年各国の装置で導入されつつあるが、単純な円錐型ノズルを用いているものが多く、ガス圧力も数気圧程度と低い。ノズルからプラズマまでの距離も数十 cm と、核融合炉で想定される数 m の距離とは 10 倍もの隔たりがあった。村上君はこれらに先んじて、より収束性の高い超音速ガス流を発生できるよう、プラズマ実験用として世界にも例を見ない精密内部構造を有する金属製大型ラバールノズル（最小内径 0.1 mm、最大全長 400 mm）を複数設計・製作し、最大 80 気圧の高圧ガスを用いて実験を行った。LHD ではノズル-プラズマ間距離を 4 m 以上に離せること、及びプラズマの温度・密度が高いことを利用し、他装置では実現困難な核融合炉相当条件での実験を世界で初めて行った。

村上君が開発した超音速ガスパフ装置によって、プラズマ周辺部密度が中心密度に比べて 10 倍程度も高いという、他の手法では実現不可能だった極端にホローな密度分布の形成も容易になった。このことは、超音速ガスパフの粒子供給効率が従来型ガスパフに比べ 2 倍程度高く、条件によっては固体水素ペレット入射に匹敵する高粒子供給効率も得られるという結果に結びついている。超音速ガスパフが、核融合炉で必須のプラズマ対向機器熱負荷低減を実現するために重要な優れた周辺プラズマ冷却特性を有すること、連続パルス入射によって密度変調を励起することで ELM と呼ばれる周辺局在モード制御への応用が可能なことなどについても、世界に先駆けて明らかにした。

基礎実験では超音速ガスパフの特長であるガス流の収束性を可視化によって定量評価している。可視化にはクラスター化したガス流にレーザーを照射し、その散乱光を観測するなどの手法を用いた。ガス流の凝縮過程に関し、温度・圧力依存性などの詳細なデータベースを提示した。1960 - 1980 年代に行われた実験を再現しつつ、クラスター流内部の密度分布が中空のピーク構造を有することを現代のカメラ性能によって高い空間分解能で明らかにした。メタン等の複数原子からなるガスと水素等の単原子分子ガスではクラスターの成長過程が異なるという興味深い結果も得ている。これらの実験により、ラバールノズルを用いることで20度以上あったガス流の拡散半角を5度程度にまで収束できることを確認している。

LHD におけるプラズマ実験では、超音速ガスパフによる粒子供給効率がターゲットプラズマの密度に依存することを示した上で、これが粒子輸送機構に依るものであることを密度分布データの解析によって議論している。その結果、超音速ガスパフでは多量の粒子が短時間にプラズマ周辺部に供給されることで大きな内向きの密度勾配ができ、これに駆動される拡散によってコア領域への粒子供給がなされること、このため低密度で高い粒子供給効率が得られることを明らかにした。超音速ガスパフの粒子供給効率は低密度で 15 -

25 %と、従来型ガスパフに比べ約2倍の値を得ている。周辺部を冷却して、供給粒子の電離位置を入れ子状の磁気面が存在するプラズマ閉じ込め領域のより内側へと移した場合には、粒子供給効率が 40 %程度に向上することも見出した。

更に、超音速ガスパフにはその特長を活かした周辺プラズマ冷却や不安定性制御等の有用な用途があることも提案し、それらの実証実験を行っている。特に、超音速ガスパフを行った場合、従来型ガスパフと比べて、同じプラズマ周辺部密度でも周辺部温度を半分程度にまで下げられるという優れた周辺プラズマ冷却特性の同定は、高収束ガス流の利点を明確にするものであり、将来の核融合炉で必須のプラズマ対向機器熱負荷低減を実現するためにも重要な発見である。また、連続パルス入射による ELM 制御は、この不安定性による間歇的熱負荷の軽減という喫緊の課題の解決に向けた発展が期待されるものである。

以上のように、村上君は新たに設計製作した超音速ガスパフの特性を同定し、大型高温プラズマへ応用することによって高効率の粒子供給を実証するとともに、周辺プラズマの制御に関する重要な実験検証を行った。核融合炉における制御ツールとしての超音速ガスパフの可能性を示したことは核融合研究の進展に大きく貢献するものである。よって本論文の内容は学位（工学）の授与に十分値すると判断した。

審査委員会（平成 24 年 1 月 17 日開催）における村上昭義君の説明に対し，審査委員から超音速ガスパフに用いられている原理や機構、燃料供給の対象となったプラズマの特性、磁場構造と粒子密度分布との関係、粒子輸送、従来型のガスパフや世界の他の研究との差異に関する知見等、研究の基礎から専門に至る知識について質問が出された。村上君は研究の背景と意義、装置の設計製作からテストスタンドで行った開発研究による超音速ガスパフ装置としての特性評価、そして大型ヘリカル装置でのプラズマ実験による検証という流れに沿い、これらの質問について実験での経験を交えながら実験結果や計算結果を示すことにより的確に答え，基礎から専門に至る十分な知識を備えていることを示した。今後の課題についての質問についても、論文にまとめた成果をもとにして、プラズマ応答の局所性の可視化による同定など、明瞭な課題意識を持っていることが確認された。1 月 25 日に行われた公開発表会においても村上君は明確な発表を行い，出席者からの超音速ガスパフの収束性など得られた性能に関する質問やプラズマ周辺部における粒子輸送や摂動印加の影響などに関する物理的な質問に対しても的確に答えた.本論文は英語で書かれており、村上昭義君が第一著者となっている査読付き英文論文が学術雑誌から既に 3 編出版され，同じく第一著者として投稿中の査読付き英文論文が 1 編ある．国際会議での発表も 6 件あり、審査委員会は村上君の英語の学力についても十分と判断した。

以上の結果により、本審査委員会は全員一致で試験を合格とした。