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論　　文　　名	「Time-dependent calorimetric analysis for estimation and control of heat load to plasma facing components in future fusion reactors （将来の核融合炉におけるプラズマ対向機器への熱負荷の評価と制御のための時間依存熱量解析）」
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論文要旨

Nuclear fusion energy, which is expected to be a new sustainable source of energy, has gained public attention recently. In contrast to the nuclear fission reaction in which the heavy elements are split turning mass into energy, the energy of a nuclear fusion reaction is from the combination of light elements. Generally, the fusion reactions produce more energy, less risk of nuclear waste, and even no CO2 emission. Successful development of fusion energy, however, requires further studies including plasma operation, materials, fuel breeding, heat exhaust, and safety. Such studies have been conducted on many fusion devices in the world.

Divertor is an important component in the fusion reactor. Its main function is to remove the impurity particle during the operation. The divertor is the component which receives the most severe heat load concentration in the fusion reactor. To ensure a safe operation in the fusion reactors, ti is necessary to control the divertor heat flux. Accordingly, monitoring divertor heat flux becomes an urgent task to verify the ability of control processes. In this thesis, studies of sensor design and estimation methods to precisely monitor divertor heat fluxes are proposed.

In Chapter 1, general information about nuclear fusion energy and magnetically confinement plasmas are presented. Besides, the goals and outline of this thesis are included in this chapter.

In Chapter ,2 the calorimetric methods for divertor heat flux estimation are introduced. In general, the divertor heat flux can be inversely evaluated from monitored temperature data with the heat conduction model. Such a model assumes a control volume (CV) containing the temperature measurement point and must satisfy the heat conservation law. In other words, heat flux crossing the boundary, heat generation in the CV, and internal energy evolution must balance. Temperature response function has been developed to describe CV temperature response toward the step-like heat flux applied at the irradiated surface. By fitting such a response function to the monitored temperature data, the time-dependent heat flux can be obtained.

Chapter 3 describes the improvement of a temperature response function in 1-dimensional (1D). The 1D temperature response function is applicable for the small sensor target where the heat flux is assumed to be homogeneous at its irradiated surface. In the previous work, the temperature response functions in 1-dimension (1D) for different back-side boundary conditions have been proposed and successfully described the delay of the thermocouple (TC) signal owing to the diffusion time in the target material. However, as an empirical phenomenon, another time delay in the order of several hundred ms has been observed repeatedly in our sensor data. Due to this unknown delay, observing the changes in heat flux for fast events during plasma discharge is impossible. In this chapter, the primary delay mathematical model, which is used to describe TC signals subjected to time delay is proposed. Using the primary delay model, the unknown time delay involved in TC systems can be measured experimentally. According to the findings, the main causes of delayed signals in TC systems are the intrinsic delay of TC wires with finite heat capacity and contact heat resistance between TC and the target surface. In addition, a method to artificially reconstruct the delayed signal from the measured value of time delay is suggested.

Chapter 4 involves the expansion of the temperature response function into 2-dimensional (2D). In the fusion devices, the heat flux profile is in cm order. If the sensor target is bigger than such an order, the temperature distribution will be inhomogeneous and the heat flux estimation using the ID temperature response function will be insufficient. In this chapter, 2D temperature response functions are proposed including parallel and perpendicular directions to the tile surface. The surface temperature data from the LHD divertor tile is analyzed with the 2D temperature response function. The results obtain temperature and heat flux spatial profiles, as well as their time evolution. Using the 2D response function, temperature profiles can be successfully reconstructed from sparse temperature data with low spatial resolutions. The findings suggest that 10 thermometer channels would be sufficient to reproduce the temperature profiles from the target size in the order of 10 cm. This number can even be optimized if magnetic field data is known in advance so that the thermometers can be concentrated only in the area of consideration.

In Chapter 5, the construction of a novel sensor to monitor the heat flux in long-pulse scenario is proposed. Currently, in most of the existing fusion devices, the plasma discharge duration is in the order of hundred milliseconds. However, the pulse duration in the future DEMOs is expected to be much longer and requires active cooling to sustain plasmas and ensure a safe operation. In such a scenario, the effects of heat loss will dominate the observed heat fluxes. The new sensor consists of a glass target with a relatively low conductivity. TCs are embedded in the top and bottom surfaces so that the effect of heat loss can be distinguished. Findings show that the heat loss time constant of the target is in the order of hundred seconds. Using this sensor, the heat flux estimation is performed with irradiation time ranging from minutes to more than an hour. For the fast events, the heat flux estimation methods proposed in the previous chapters can be applied. On the other hand, when the irradiation time becomes long, the heat flux can be estimated with a simplified heat balance model which takes into account the effect of heat loss. This provides some hints to construct the heat flux sensor and develop the heat flux estimation method for future commercial fusion reactors.

Chapter 6 is the summary of the previous chapters and the conclusion of this thesis. Cooperation of the temperature response functions with the pulse decomposition method can be a useful tool for the estimation of divertor heat fluxes. In this thesis, the temperature response functions have been modified to describe the time delay effect and expanded to deduce multi-dimensional heat fluxes. Moreover, a novel sensor has been developed and successfully estimate the long-pulse heat flux with consideration of heat loss effect. The reconstruction of divertor heat flux can be improved by carefully determining the sensor target boundary condition or consideration of heat transfer in different direction. This will be left for future research.

審査結果の要旨

本論文は、近年ゼロカーボン政策の切り札として期待されている核融合炉建設に際して克服すべき炉工学的問題の解決につながる研究をすすめたものである。強力な磁場で閉じ込められた、水素の同位体から生成される超高温プラズマを安定に保持するため、核融合反応で生まれるヘリウムやプラズマ対抗材料から困窮する不純物イオンを中性化して排出する必要がある。このための機器、あるいは概念をダイバータと呼ぶ。そのため、ダイバータの主要部であるターゲット板には太陽表面に匹敵する熱流束が手中する。この熱流束の正確な値を決定し、プラズマ対抗材料の温度変化を予測する方法を確立するのが本研究の目的で、特に注目すべき成果は以下のとおりである。

(1)プラズマ照射された固体表面への熱流束は、固体内部の熱伝導の逆問題を解き、固体内の温度モニタの測定を再現するような、照射面側の境界条件として決定される。既存研究で、温度モニタ点がプラズマ照射面から任意の距離にあっても対応できるような温度応答関数を導出したが、京都大学や筑波大学で設計、製作した熱流束センサーの応答が、予想よりはるかにゆっくりしていることが示されていた。これは温度変化と熱電対信号の間の時間遅れに起因するものであり、一次遅れの数学モデルをつかって、補正できることと、実際のセンサーごとに特徴的な遅れ時間をあらかじめ実測できることが示された。本研究のこの成果は、筑波大学での加熱用ビームを使った実験や、京都大学での最新の熱流束センサーでの測定で、その有効性が示されている。

(2)ダイバータは特別な磁場構造を構成してシート状のプラズマをターゲット板に導かれる。その際、シートの厚みはターゲット板の大きさより小さいため、プラズマ照射面に沿った、温度や熱流束の分布が重要になる。他方、実用核融合炉では計測ポートの設置が制限されるため、IR カメライメージによる温度の分布計測はできなくなる。本研究では、温度応答関数をフーリエ級数の利用により多次元化し、展開係数を有限数のセンサーのデータから決定する方法を提案した。核融合研究所の実験装置のダイバータタイルの表面温度測定データに、この方法を適用し、必要な測定チャンネル数などについての検討を進めた。

(3)実用的な核融合炉では、放電時間が 1 時間を超えると予想されている。そのためプラズマ対抗機器は、熱流束センサーを含めて、何らかの冷却系で除熱されることになる。しかしながら、既存の実験装置での研究では、この冷却効果を正しく取り入れていない

にも拘わらず、放電時間が短いためこの問題は見過ごされていた。本研究では、長時間放電である応用プラズマの分野での熱バランスモデルと、これまで開発した高速応答の熱流束計測を組み合わせる可能性を初めて検討した。

以上の諸成果は、次世代の核融合炉での熱流束センサーの設計についての重要な知見を与える。本研究はこのように特定のプラズマ装置のセンサーや解析法の改良のみならず、将来にわたっての応用の上からも有益な情報を提供したものであり、核融合工学の学術的・産業的な発展に貢献するところ大である。また、申請者が自立して研究活動を行うのに必要な能力と学識を有することを証したものである。

学位論文審査委員会は、本論文の審査および最終試験の結果から、博士（工学）の学位を授与することを適当と認める。