Proceedings of CONF-FMCE 2025 Symposium: Semantic Communication for Media Compression and Transmission
DOI: 10.54254/2755-2721/2025.GL28001

The Application of Heat Flux Sensors in Multiple Fields and Their Comparison with Other Common Sensors

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Abstract. As a key device for measuring heat transfer rates, heat flux sensors are irreplaceable in industrial, architectural, medical, and other fields. Against growing demands for refined thermal management across industries, traditional sensors such as temperature and pressure sensors fail to directly quantify heat transfer processes, creating a technical gap that heat flux sensors address. In this investigation, I center on heat flux sensors, methodically examining their application modalities via a synthesis of literature, case studies, and a comparative analysis of performance parameters.. It emphasizes specific scenarios in industrial equipment thermal management, building energy efficiency monitoring, and medical thermal metabolism assessment. It compares them with standard sensors regarding measurement principles, performance characteristics, and applicable scenarios. The research reveals that heat flux sensors excel in direct heat transfer measurement, contributing to industrial quality improvement, building energy optimization, and precise medical treatment. However, they still face measurement accuracy, stability, and cost control challenges. This study references technical selection and heat flux sensor technology development in related fields.

Keywords: Heat Flux Sensor, Industrial Application, Architectural Application, Medical Application, Sensor Comparison

1. Introduction

In pursuing energy efficiency and sustainable development, various industries and research fields increasingly emphasise precise heat transfer monitoring, making heat flux sensors crucial. Deng, Yujun, et al. have demonstrated that a flexible, body-worn device employing a heat flux sensor can non-invasively quantify blood flow variations in major vessels, enabling continuous monitoring for early detection of vascular access (VA) dysfunction [1]. This indicates the trend towards miniaturized and highly sensitive heat flux sensors. Furthermore, Le Li et al. engineered a pliable heat flux sensor exhibiting exceptional sensitivity [2], compensating for existing sensors' shortcomings under extreme temperature conditions. This is of great significance in the fields of superconductors and cryobiology.

Despite these efforts, there are still significant research gaps. Most studies are confined to a single application field and lack comprehensive cross-disciplinary research. In addition, there is a

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lack of in-depth comparison between heat flow and ordinary sensors, leaving engineers lacking clear guidance in technical selection.

This research endeavors to address these lacunae by investigating the diverse applications of heat flux sensors, contrasting them with alternative sensing technologies, and pinpointing potential avenues for development and associated challenges. Employing a methodology encompassing literature review, case studies, and comparative analysis of performance parameters, this study seeks to furnish a holistic understanding and offer insightful guidance for subsequent technological advancements and industrial implementations.

2. Application forms of heat flow sensors

2.1. Industrial field

In the industrial field, heat flux sensors are significant for optimizing production processes and enhancing energy efficiency. For instance, in the aerospace industry, the precise measurement of the heat flow of aero-engine turbine blades is of vital importance, as it ensures that the turbine blades can operate under extreme conditions of high temperature and high pressure. Shao, C, et al. implemented heat flux transducers on the airfoil surface to monitor the real-time heat flux [3]. By doing so, the cooling strategy can be adjusted to ensure the engine's reliability and extend the blades' service life. In the clothing system, heat flux sensors can provide information about the heat exchange between the body and the environment, thereby offering direct input to enhance the thermal comfort of the clothing. Gidik et al. innovated a textile-based heat flux sensor, achieved through the integration of thermoelectric (TE) wires within a textile matrix [4]. TE wire is composed of two metals, constant and copper, which form a thermocouple at the junction. These nodes form on both sides of the fabric. Based on the Seebeck effect, the voltage will be measured when the temperatures on both sides of the fabric are different or there is a heat flux.

Moreover, in manufacturing processes like metal casting, heat flux sensors can monitor the heat dissipation rate of moulds. This enables manufacturers to control the solidification process more precisely, reducing defects in cast products. Heat flux sensors are essential for modern industrial operations, contributing to cost-effective production and equipment durability.

2.2. Construction field

In architecture, heat flux density sensors enhance energy efficiency and ensure a comfortable indoor environment. In a similar vein, Gloriant, F., et al. engineered an experimental apparatus for a novel tri-layer glass gas delivery window [5]. Using heat flux sensors makes the estimation of heat flux more reliable. Through comparing experiments and numerical simulations, the validity of the numerical model assumptions relative to the actual conditions set in the experiments can be obtained, reducing heat loss or increase, which is crucial for the operation of energy-efficient buildings.

Overall, heat flux sensors in the construction field are essential tools. They help evaluate the effectiveness of insulation materials, monitor energy usage in buildings, and guide the design and retrofit of buildings to meet higher energy-efficiency standards, thus contributing to sustainable construction and reduced energy consumption in the long run.

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2.3. Medical field

Heat flux sensors have become valuable tools for precise physiological monitoring and treatment optimization in the medical field. One notable application is vascular health assessment. As the abstract mentions, a flexible thermal flux sensor integrated into wearable devices monitors blood flow at vascular access sites, such as dialysis catheters [1]. This sensor can detect subtle thermal changes caused by blood flow, thereby assessing the patency of the catheter in real time. Clinical trials have shown that it can identify the early signs of thrombosis and reduce complications in dialysis patients.

A significant application involves the evaluation of core body temperature. In their study, Hein A.M. Daanen et al. investigated the precision of a heat flux sensor in determining core body temperature. Subjects were equipped with three commercially available heat flux devices (3 M, Medisim, and Core) to monitor temperatures, and the readings were then compared to temperatures obtained via rectal and esophageal probes [6]. The Medisim system rises faster than the Tre during exercise. The core system tends to show systematic overestimation throughout the exercise period. The 3M system shows a significant error at the end of the exercise, which may be due to sweat entering the sensor. Therefore, the heat flux sensor values should be interpreted cautiously as core body temperature estimates. More research is needed to clarify the physiological significance of the generated temperature values in the future.

3. The differences between heat flow sensors and common sensors

A heat flux sensor is an instrument used to measure the heat transfer rate per unit area. It is a sensor that generates an electrical signal (output voltage), which will be proportional to the measurement of this thermal conductivity [7]. The heat flux density is calculated by measuring the temperature gradient of a material with a known thermal conductivity within the sensor, which directly reflects the intensity and direction of heat transfer. Its core formula is:

$$q = -k\,\Delta T / L \tag{1}$$

Here, q represents the heat flux density, k is the thermal conductivity of the sensor material, ΔT is the temperature difference on both sides of the material, and L is the thickness of the solid (plate) through which the heat flux penetrates. This is called differential temperature heat flux measurement technology.

This sensor can measure all three forms of he at transfer on or from the surface of an object - conduction, convection and radiative heat transfer. The essential differences between it and standard sensors, such as temperature and pressure sensors, lie in three aspects: measurement principle, core parameters and application scenarios. These differences determine their complementarity and irreplaceability in the field of thermal management. Regarding the measurement principle, the heat flow sensor is based on Fourier's heat transfer law. However, temperature transducers like thermocouples and platinum resistance thermometers infer temperature by gauging the correlation between a material's electrical characteristics and its thermal state.. Still, they cannot directly quantify the heat transfer rate. Pressure sensors are based on mechanical principles and measure pressure values through the deformation of elastic elements, having no direct connection with heat transfer.

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4. Opportunities and challenges

4.1. Development opportunities

Driven by technological progress, regulatory pressure and emerging applications, heat flux sensors are at the forefront of significant growth in multiple industries. The following are the key opportunities.

Promoting clean energy has pushed heat flux sensors to the forefront of renewable energy technology. Baygildina et al. introduced and investigated the gradient heat flux sensor (GHFS) [8], subsequently employing it for thermal monitoring of wind power electronic systems, with specific attention to local heat flux measurements in insulated gate bipolar transistor (IGBT) modules. GHFS is based on the transverse Seebeck effect and features a thin structure (0.2mm), high sensitivity (15.9mV/W), and direct measurement capability. It can be placed between the IGBT substrate and the heat sink without interfering with the regular operation of the equipment. Experimental verification shows that under steady-state currents of 15A, 30A, and 60A, the deviation between the heat flux measured by GHFS and the simulated IGBT power loss is at most only 3.7%, indicating that it can be used as an effective tool for online condition monitoring (CM) of IGBT heat load, helping to enhance the reliability and lifespan of wind power generation equipment.

The emphasis on intelligent data detection in the era of Industry 4.0 provides a massive opportunity for heat flux sensors. Addressing the need for heat flux measurement in extreme aerospace conditions, Xu, G., et al. introduced an innovative thin-film heat flux sensor architecture [9] to enhance measurement accuracy and achieve bidirectional heat flux measurement. Through numerical simulation methods, the influences of geometric parameters, physical properties and working conditions on the test errors of sensors were studied, and their steady-state and transient performances were analyzed. The data indicates that the sensor's test error is primarily influenced by the thermal resistance ratio within the measurement system. Accuracy improves with larger sensor dimensions or increased local total thermal resistance. The novel sensor design exhibits superior steady-state and transient performance, characterized by a low time constant, rapid response, and a strong linear correlation between temperature difference measurement and surface heat flux, offering a valuable benchmark for heat flux measurement in aerospace applications.

In the medical field, heat flux sensors are revolutionizing the monitoring and treatment of patients. Immonen et al. verified a novel method of measuring arterial pulse on the skin surface using a heat flux sensor (HFS). By comparing the simultaneously collected electrocardiogram (ECG) and photoplethysmography (PPG) signals, it was found that the heat flux (HF) waveform measured by HFS above the radial artery was similar to that of PPG. And there is a precise time alignment between ECG and PPG. Additional investigations reveal that heat flux (HF) assessment is capable of monitoring arterial pulsations across varying skin-environmental temperature gradients, thus presenting an innovative thermal measurement approach for cardiovascular surveillance in wearable technology.

Buildings account for a large proportion of global energy consumption, and heat flow sensors are key to improving their energy efficiency. Sensors can measure the heat transfer of building envelopes, which helps optimize insulation materials and window designs, thereby reducing energy consumption for heating and cooling. Within smart building infrastructures, heat flux sensors are amenable to integration with the building management system, thereby enabling real-time monitoring of heat distribution patterns. This allows for more precise control of heating, ventilation and air conditioning (HVAC) systems, further enhancing energy conservation. As governments

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worldwide introduce stricter building energy efficiency regulations, adopting heat flux density sensors in the construction and building management industries will increase significantly.

4.2. Challenges

Although the application of heat flux sensors is increasing, they still face some challenges, which limit their broad adoption and optimal performance in various industries.

Under conditions of high temperature and high pressure, such as in the turbine of an aero engine, sensors face significant obstacles. Shao, C., et al. noted that the severe operational environment of aero-engine turbine blades, characterized by temperatures surpassing 1100°C and elevated pressure levels, predisposes the sensor coating to delamination and subsequent degradation of its insulation properties [10]. This not only affects the accuracy of heat flux density measurement, but also shortens the sensor's service life. Although Shao, C., et al. proposed a composite process for the in-situ preparation of high-temperature heat flux sensors [10]. However, traditional heat flux sensors still struggle to adapt to such harsh conditions, and obtaining accurate aerodynamic thermal test results is difficult.

Developing low-cost and miniaturized heat flux density sensors remains a challenge. Using advanced materials and complex manufacturing processes in sensor manufacturing often leads to high costs. For instance, the production of some high-performance sensors requires precise manufacturing techniques and expensive materials, which limit their large-scale application. Furthermore, maintaining sensor performance while simultaneously reducing its dimensions presents a significant challenge. With the increasing demand for sensors in miniaturized devices such as wearable medical devices or microelectronic devices, achieving miniaturization without sacrificing sensitivity, accuracy and stability has become a crucial but unmet need in the development field of heat flux sensors.

5. Conclusion

Through multi-field application analysis and performance comparison of heat flux sensors, this study draws comprehensive conclusions regarding their practical value and developmental prospects. Heat flux sensors exhibit versatile applicability across various domains: in industrial settings, they optimize processes and bolster energy efficiency by monitoring heat transfer in equipment such as reactors and engines; within the construction sector, they facilitate precise energy consumption monitoring of building envelopes, enabling data-informed energy-saving renovations; and in healthcare, they enhance the safety of thermal therapies and the efficiency of metabolic monitoring, thereby assisting in precise treatment and physiological assessment.

Regarding performance differences, heat flux sensors differ fundamentally from temperature and pressure sensors: based on Fourier’s law, they directly measure heat flux density, whereas others focus on temperature or pressure. They excel in dynamic response to heat changes but lag behind mature sensors in accuracy, stability, and cost-effectiveness, requiring targeted technical improvements.

The research significance lies in systematically clarifying heat flux sensors' application value and technical characteristics, providing references for technical selection in related fields, and guiding industry-academia-research collaboration for innovation. However, limitations exist: the study relies mainly on literature and case syntheses, lacking on-site experimental data, and performance comparisons do not cover all sensor types, such as flow sensors.

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To bridge these gaps, future investigations ought to incorporate experimental validations to bolster empirical data and broaden comparisons across a wider array of sensor modalities. In addition, paying attention to materials with extreme environmental adaptability and low-cost manufacturing technologies is crucial for overcoming challenges such as extreme ecological adaptability and cost control, thereby further expanding the application scenarios of heat flux sensors.

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