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A review of coaxial thermocouples on transient heat flux measurement

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Abstract

In this review, we have endeavored to summarize and describe the research conducted to date on coaxial thermocouples for transient heat flux testing as well as the manufacturing processes. The review paper not only summarized important advances in coaxial thermocouple research along the time, but also suggested future directions and trends in coaxial thermocouple development. Main sections of presentation include major calibration techniques for coaxial thermocouples, experimental evaluation of coaxial thermocouple performance, and the influence of lateral heat transfer benefits on thermal measurements. In addition, the design of new type coaxial thermocouples, heat flux inversion methods and applications of coaxial thermocouples in other fields were also introduced. Finally, the direction of coaxial thermocouple development was discussed based on the needs of hypersonic thermal testing.

Keywords: Coaxial thermocouples, Surface heat flux, Calibration technique

1 Introduction

When a vehicle is flying at hypersonic speed, the airframe and various aerodynamic components of the vehicle are subject to shock interference [1, 2]. The complex shock structure will generate huge aerodynamic heat on the surface of the vehicle [3, 4], which affects the aerodynamic performance of the vehicle. Therefore, accurate measurement of aerodynamic heating is crucial. The shock tunnel is an important ground experimental facility for reproducing the flight environment, and its basic compositions include the driving section, the driven section and the test section [5, 6]. High pressure is generated at the driving section of the experiment, and the driving gas stream is ejected from the driven section at high temperature and high speed from the nozzle to the test section.

Heat transfer devices that measure the instantaneous thermal response can be divided into two types by operating principles: surface thermometers and calorimeters [7–9]. The surface thermometer uses a surface thermometer to measure the surface temperature of 1D body, and then obtains the surface heat flux according to the Laplace transform [10]. The calorimeter uses a calorimetric element to absorb the heat transferred to it, measures the average rate of change of the calorimetric element temperature, and then calculates the surface heat flux [11, 12]. Common surface temperature measurement devices include coaxial thermocouples and film resistance thermometers. In high-enthalpy shock wave tunnels, strong airflow can significantly reduce the survival rate of film resistance thermometers, often resulting in severe damage. Calorimeters typically have a sampling frequency of only 100 Hz, rendering them unsuitable for heat flow measurements in wind tunnels with millisecond-scale operational times. Coaxial thermocouples are widely applied to aerodynamic thermal measurements in shock wind tunnels because of their fast response and resistance to airflow washout [13, 14]. In 1953, the structure of coaxial thermocouples was first given by Bendersky [15]. The structure schematic of the coaxial thermocouple is shown in Fig. 1. For E-type coaxial thermocouples, the inner constantan core is the negative electrode and the chromel annulus is the positive electrode, respectively. The insulation layer of coaxial thermocouples is polished for creating a small junction with a depth of approximately 10 ms. After decades of research, the performance and reliability have been greatly improved.

In this paper, we described the calibration methods of coaxial thermocouples, the influence of numerous experiments on performance validation, and the lateral heat conduction in coaxial thermocouples. New coaxial thermocouple developments, heat flux inversion methods, and other applications of coaxial thermocouples were also discussed. Finally, a summary of the development direction of coaxial thermocouples was given to provide a reference for researchers.

2 Thermal effusivity and sensitivity calibration method

The sudden immersion is a static method for coaxial thermocouples calibration. When two surfaces of different temperatures are suddenly contacted and intersected, the contact surfaces of the two objects will reach the same temperature, and the coaxial thermocouple surface temperature change can be calculated. The sensor is first placed over a hot cell, where the liquid in the hot cell is kept at a constant temperature. Then the sensor is immersed in the liquid, the temperature of probe surface rises and the voltage is recorded. The structure schematic of sudden immersion device is shown in Fig. 2.

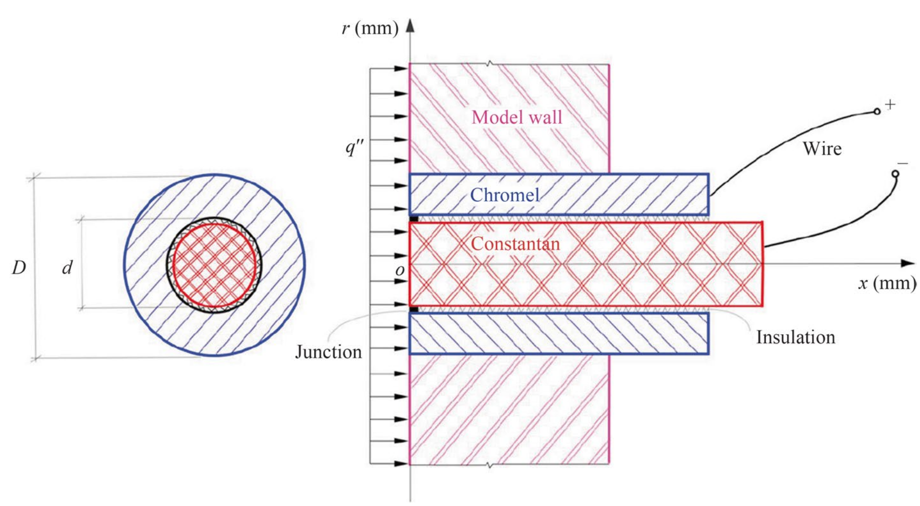

Fig. 1 Structure schematic of coaxial thermocouple

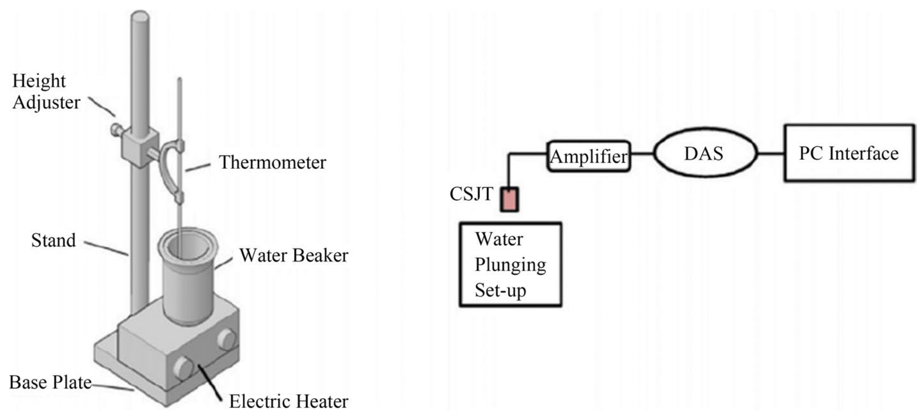

Fig. 2 Structure schematic of sudden immersion device [16]

Agarwal et al. utilized the sudden immersion method to calibrate type E and J thermocouple probes and found that the calibrated thermal effusivity of the type E coaxial thermocouple is in good conformity with the literature. Meanwhile, they pointed out that frequent immersion of the sensor in hot water can cause large calibration errors in the calibration of the thermal effusivity coefficient and that the use of paraffin oil as a thermostatic liquid can be tried [16]. Manjhi and Kumar calculated the thermal resistance and sensitivity by the oil bath [17]. But they assumed that thermal effusivity was a constant as the arithmetic average of two metallic materials. Actually, thermal effusivity of each coaxial thermocouple should be recalibrated. Rout et al. used a glycerine bath for the static calibration of type E coaxial surface probe. The calibration of the coaxial thermocouple was carried out by using the glycerine bath. The probe was statically calibrated and displayed a linear relationship between potential difference and temperature. And the sensitivity of 59 μV/°C was calculated [18].

Conducting coaxial thermocouple fine surface morphology and chemical composition measurements are important for thermal matching of coaxial thermocouple parts. Scanning electron microscopy can measure the insulating layer thickness on probe surface and the dimensions of the junction. Energy dispersive X-rays qualitatively identify the material composition of coaxial thermocouple surface [19, 20]. Mohammed et al. demonstrated that the entire surface of a coaxial thermocouple contained two thermoelectric material compositions, aluminum alloy and nickel-chromium alloy, and observed a junction width of 25 μm after sanding of 15 μm thick of insulating layer [13]. In this work, the method for calculating thermal effusivity from the composition of various metals is an area that requires further exploration. Manjhi and Kumar observed the coaxial thermocouple junction using the field emission scanning electron microscopy (FESEM) technique. The insulation layer between two thermocouple materials was varied from 2 μm to 10 μm for types K, E and J probes. The polishing of the thermocouple surface makes a material in the insulation layer to make good contact with the thermocouple element. And the presence of two thermoelectric metals on probe surface was confirmed using energy dispersive X-rays [21, 22]. The E-type thermocouple sensing surface pictures are shown in Fig. 3. And the chemical composition of thermocouple material from Spectrum processing are shown in Fig. 4. This work is significant at the microscopic scale and is highly valuable

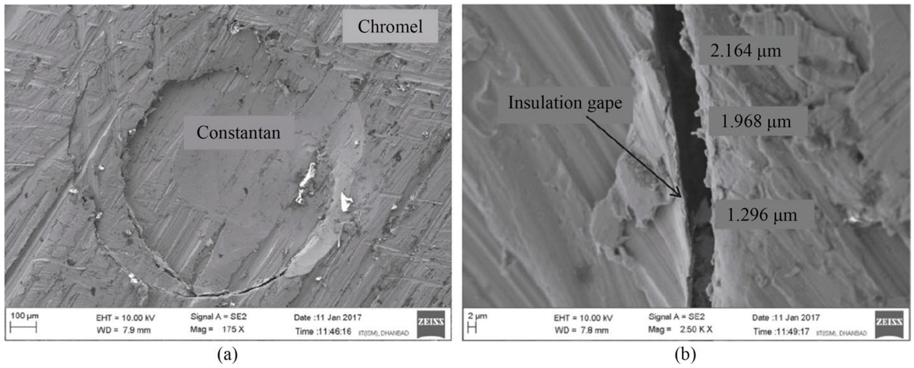

Fig. 3 E-type thermocouple sensing surface using the FESEM technique [21]

for the calibration of coaxial thermocouples. Manjhi and Kumar calibrated the thermal effusivity using the sudden immersion method, and results showed that the average errors of type K, E and J coaxial surface junction thermocouples (CSJTs) were 3.08%, 1.70%, and 2.28%, respectively [23, 24]. With advancements in microscopic observation techniques, this area of research is set to become a focal point for calibrating thermal effusivity.

The shock wind tunnel is commonly used for the dynamic calibration process of coaxial thermocouples. The thermal effusivity of coaxial thermpcouples depends on Mach number, junction polishing technique, position of the junction, and enthalpy, while the selection of a suitable scratch blade ensures the consistency of the calibration [25]. Li et al. pointed out in the shock tube calibration experiments for the E-type CSJT that the average value of thermal product factor was 7970 $Jm^2Ks^{0.5}$, which was

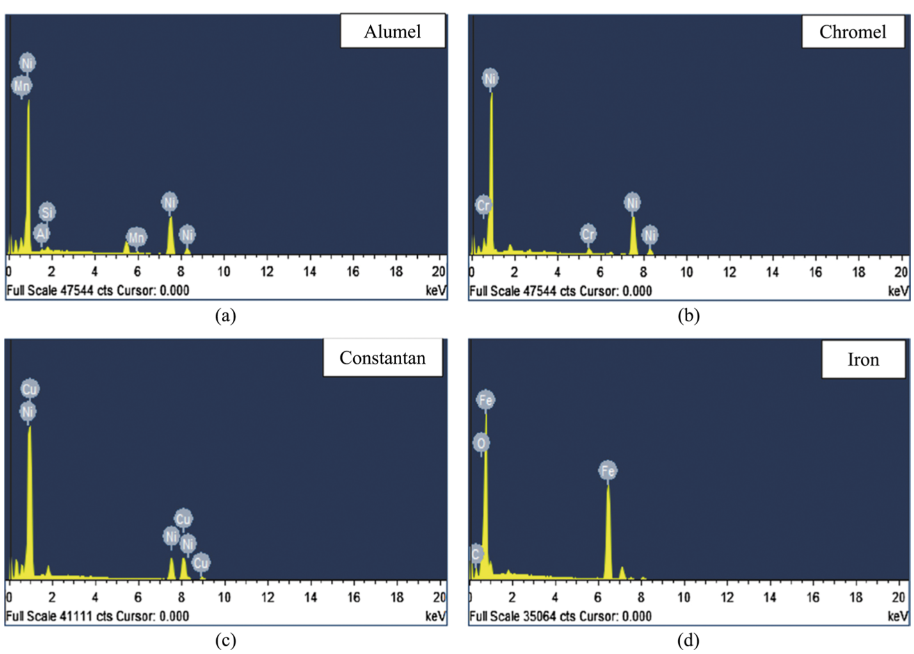

Fig. 4 Chemical composition of thermocouple material from Spectrum processing [21]

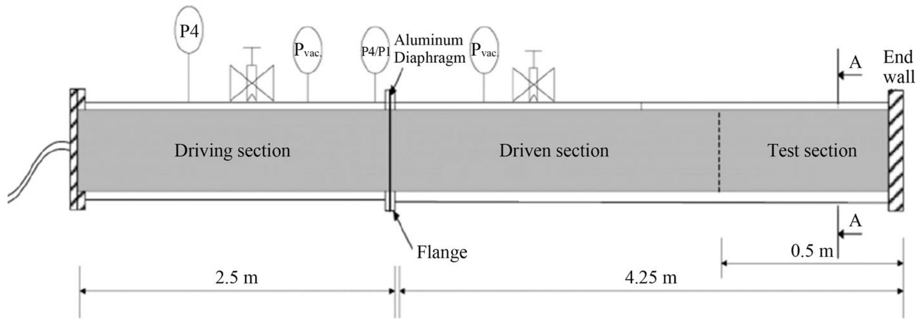

Fig. 5 Structure schematic of shock tunnel [25]

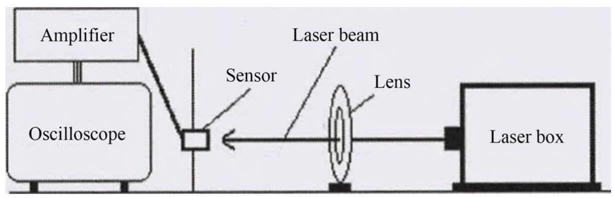

Fig. 6 Schematic representation of calibration for coaxial thermocouple using a laser [29]

about 8% less than the average value of two electrodes and the maximum error of surface heat flux was 10% [26]. The structure schematic of the shock tunnel is shown in Fig. 5. Nanda et al. found a hysteresis time of 9 μs and a response time in 0.3 ms to 0.4 ms for the E-type CSJT by shock tube experiments [27]. Rout, Agarwal and Sahoo's shock tube calibration experiments yielded an effect time of 265 μs for the E-type coaxial thermocouple, and the error from peak heat flux predicted from the temperature response is ±2% [28]. Although shock tube calibration methods are more aligned with practical applications, calibration results are influenced by incoming flow conditions. Accurately determining the relationship between the thermal product coefficient and Mach number, Reynolds number, total temperature, and total pressure is crucial.

The laser calibration method involves applying a constant heat flux of known wattage to the surface of CSJT, and the components are a laser source, a lens, an amplifier, and a signal acquisition device. The energy source emits a laser beam onto the surface of the sensor to heat it. Kumar and Sahoo showed that the predicted surface heat flux of the type K coaxial thermocouple in the range of 60 KW/m^2 to 90 KW/m^2 was about 4% lower than the true value for a step load of laser [29]. The schematic representation of calibration for coaxial thermocouple using a laser is shown in Fig. 6.

The water droplet method is also a common means of calibrating the thermal effusivity on surface. A dropper is located at an elevated position, a copper plate is used as a constant heat source to keep the temperature uniform, and a coaxial thermocouple is fixed to the copper plate with its surface facing the dropper. An adiabatic plate separates the dropper from the copper plate, ensuring that the droplet temperature is not affected by the copper plate. At the beginning of the calibration, the room temperature droplet falls freely to the CSJT surface at a higher temperature and the change in temperature is detected by the coaxial thermocouple. Agarwal et al. utilized

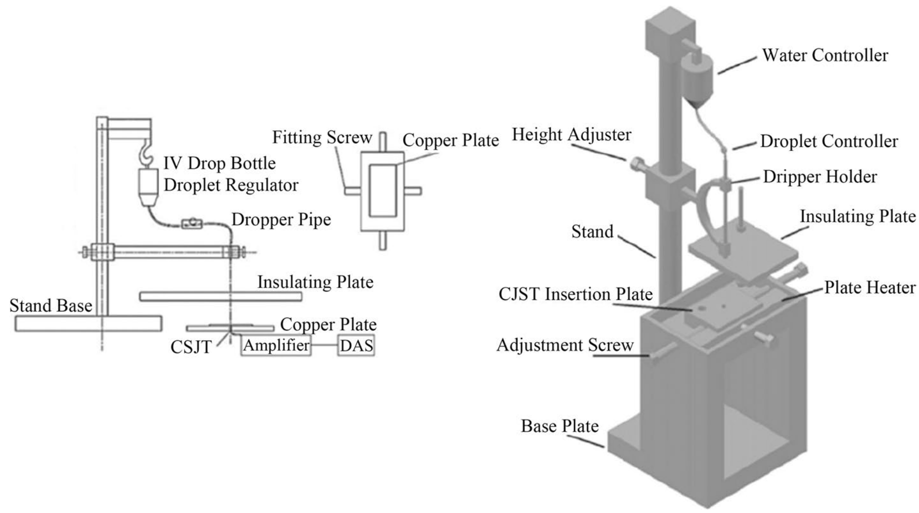

Fig. 7 Structure schematic of water drop device [16]

the water droplet method to calibrate the thermal multiplication factor of the type E and J CSJTs. The error in calibration of the type E coaxial thermocouple was 2%, and calibration of the type J coaxial thermocouple had a thermal multiplication factor that only differed from the theoretical average by 0.18% [16]. Nanda et al. noted in their water droplet method calibration experiments that the response time for a Type E coaxial thermocouple to reach peak heat flux was approximately 0.375 ms [27]. Rout et al. observed the transient response characteristics of coaxial thermocouples using a coaxial thermocouple with a sensitivity of 59 μV/°C at 55 °C by means of a water droplet test with 20 ms duration [30]. The structure schematic of water drop device is shown in Fig. 7.

Five methods for calibrating the thermal product coefficient and sensitivity were summarized in Table 1. The water droplet method exhibits a smaller calibration error, while the shock wind tunnel method shows larger errors due to challenging parameter control. Both the water droplet method and the oil bath method are cost-effective. Additionally, there is significant potential for improvement in the scanning electron microscopy method.

3 Experimental evaluation for heat flux measurement

In this section, we discuss the experimental evaluation of coaxial thermocouples. Chen and Frankel proposed a parameter estimation method based on the least squares method and a quantitative heat flux source for estimating the effective heat outflow rate of coaxial thermocouples [31]. Salvador et al. pointed out that for higher enthalpies, the sensor's thermal junction must be formed with higher grit sandpaper, which reduces its sensitivity, and thus there is a trade-off between junction strength and sensitivity. In order to avoid problems such as junction loss during calibration, calibration should start at an enthalpy of 2500.54 kJ/kg and end at an enthalpy of 790.91 kJ/kg [32]. Menezes and Bhat mounted a coaxial thermocouple of 3.25 mm diameter on a 25 mm diameter

Table 1 Summary of the calibration method

Calibration method	Authors/year	Type of CSJT	Calibration parameters and deviations
Oil bath	S. Agarwal et al. (2016)	E-type J-type	Thermal effusivity (2.8%) Thermal effusivity (29%)
	S. K. Manjhi and R. Kumar (2019)	E-type J-type K-type	Sensitivity (0.03%)
	A. K. Rout et al. (2021)	E-type	Thermal effusivity (3%)
Scanning electron microscopy	A. K. Rout et al. (2020)	E-type	Sensitivity (1%)
	H. Mohammed et al. (2008)	K-type	Thermal effusivity (15%)
	S. K. Manjhi and R. Kumar (2018, 2019, 2020)	E-type J-type K-type	Surface temperature (0.25%) Surface temperature (0.17%) Surface temperature (0.2%)
Shock wave tunnel	H. Mohammed et al. (2011)	K-type	Thermal effusivity of a particular CTP depends on the Mach number and enthalpy conditions
	J. Li et al. (2017)	E-type	Thermal effusivity (8%)
	A. K. Rout et al. (2021)	E-type	Thermal effusivity (3%)
Laser	R. Kumar and N. Sahoo (2013)	K-type	Surface heat flux (4%)
Water droplet	S. Agarwal et al. (2016)	E-type J-type	Thermal effusivity (2.1%) Thermal effusivity (0.18%)
	A. K. Rout et al. (2019)	E-type	Thermal effusivity (2.0%)

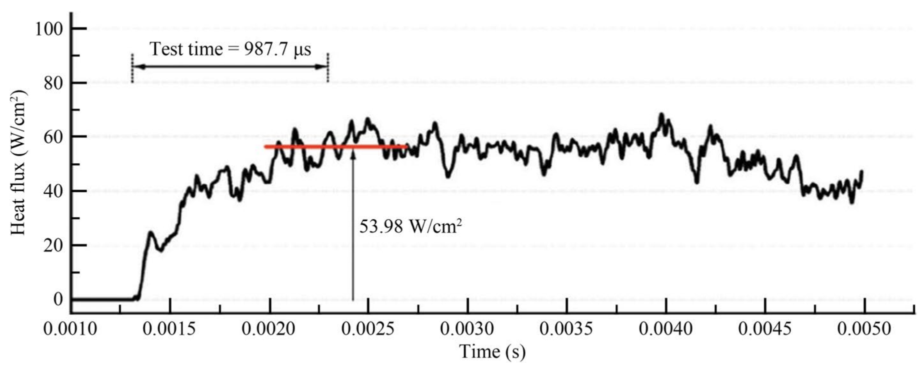

Fig. 8 Heat flux signal corresponding to the temperature signal [33]

hemisphere with an overall measurement accuracy of about 10%, and the heat flux signal corresponding to the temperature signal is shown in Fig. 8 [33]. Hariprakasham et al. validated inexpensive, reliable and robust coaxial thermocouples with shock tubes [34]. Flaherty compared experiments with CSJT that are very robust, which can withstand the harsh experimental environment. Thin-film resistivity meters offer better measurement levels but must be singly calibrated, which are less robust and typically used for lower enthalpy flows [35, 36]. Flaherty's experiments also demonstrate that coaxial thermocouples have greater resistance to erosion than thin-film resistance temperature sensors. The same conclusion was reached in the study of Shams et al. that the type E CSJTs are fit in high enthalpy measurements [37]. In addition, the signal-to-noise ratio of the coaxial thermocouple fails to meet experimental requirements.

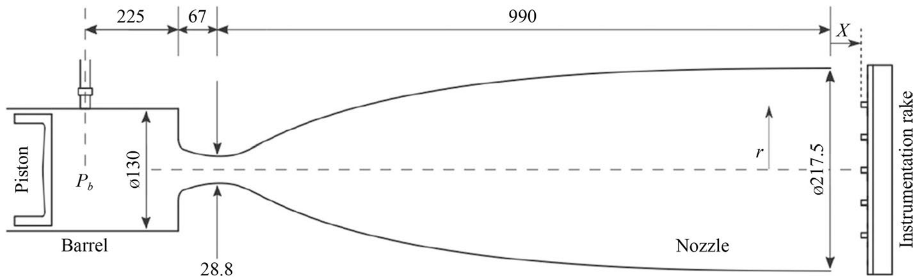

Fig. 9 Schematic of the Mach 6 nozzle and the instrumentation rake position [41]

Desikan et al. applied a type K CSJT with a response time of 3 μs to obtain the heat flux on a hemispherical cylinder, and the experimental results differed from the Fay-Riddell theoretical value by only 5.5% [38]. Sahoo and Kumar evaluated thin film gauges (TFGs) made of pure platinum, TFGs made of platinum mixed with carbon nanotubes and Inconel-Aluminum-Nickel CSJT. The platinum TFG was more efficient than the coaxial surface junction thermocouples because its temperature coefficient of resistance (TCR) was 25 times that of the CSJT and its sensitivity was 1.5 times that of the CSJT [39]. Agarwal et al. noted that Type E and J CSJTs were more suitable for measuring thermal signals in shock wind tunnels [40]. Surface junction thermocouples are generally considered to be relatively low signal-to-noise devices and are less suitable for measurements in low-enthalpy, high-supersonic flows. Birch, Buttsworth and Zander's study pointed out that CSJT had the ability to obtain 10 kWm^{-2} of heat flux prediction, as well as the ability to measure wind-tunnel standing temperatures varying over a 200 ms duration [41]. The schematic of the Mach 6 nozzle and the instrumentation rake position is shown in Fig. 9. Birch, Buttswrth and Zander's experiment conducted at Mach 6 effectively demonstrates the suitability of coaxial thermocouples for measurements in high-enthalpy environments. Conducting validation experiments at other high Mach numbers would further enhance the persuasiveness of this research.

In Manjhi and Kumar's experiments with a homemade shock tube flow, the average error in the heat flux measurements of the three coaxial thermocouples was not higher than 4% [42]. In Manjhi and Kumar's study, 25 kWm^{-2} was loaded to the type K CSJT and temperature histories were obtained. Finite element analysis was used to verify test results. The surface heat fluxes were evaluated from temperature histories obtained by test and simulation, and compared with the initial heat flux. The heat flux prediction accuracy of test and simulation was within 3.4% [43]. Thermocouples that form a surface junction by whacking impacts are called impact coaxial thermocouples, and Park noted that impact coaxial thermocouples exhibit good heat resistance, but rather low impact resistance. In addition, impact coaxial thermocouples show stable performance in terms of repeatability [44].

Agarwal et al. demonstrated the scheme of cheap and fast response E-type CSJT for combustion measurements in internal combustion engines [45]. There are two aspects of the experimental design in their work that require improvement. Firstly, the engine head could accommodate four sensors to enhance the credibility of the experimental results, yet only one was utilized in the experiment. Layout of the CSJT fitted on the engine head

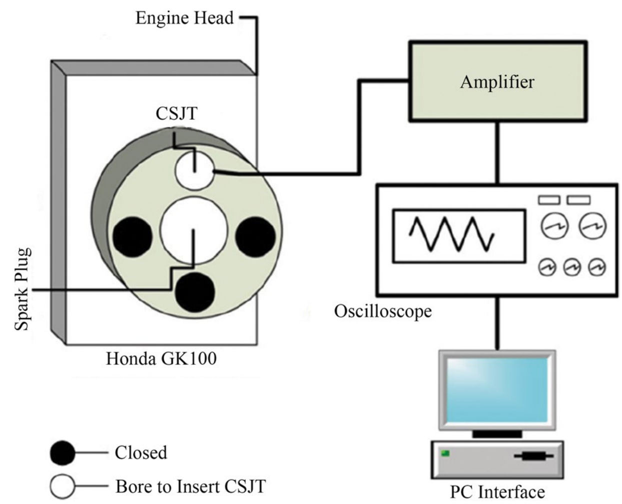

Fig. 10 Layout of the CSJT fitted on the engine head along with its accessories [45]

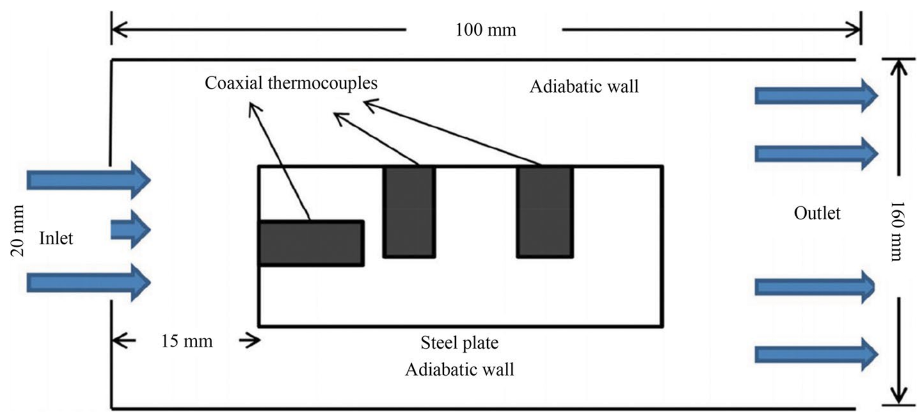

Fig. 11 Schematic diagram of the numerical simulation [47]

is shown in Fig. 10. Secondly, the article explicitly states that transverse heat transfer is not permitted within the coaxial thermocouple. However, periodic heating inevitably induces temperature gradients, making transverse heat transfer unavoidable. Rout et al. calculated the time required for the engine to complete a full cycle at two different rotational speeds based on the temperature variations recorded by a type K coaxial thermocouple, and compared it with the theoretical cycle time calculated from an analysis of the rotational speeds recorded by the engine sensor. The results indicated that the cycle times of both are in close agreement. As a result, the fabricated CSJT was capable of capturing transients quickly and could be applied as a thermal measurement device for obtaining transient signals. This application can also be applied to obtain other transient physical quantities in unsteady test processes [46].

Manjhi and Kumar used three types of CSJTs to measure the heat flux on the surface of a steel plate with 0°, 15°, 30°, and 45° angles of attack, respectively. And schematic diagram of the numerical simulation is shown in Fig. 11. The prediction error between the numerical and experimental values of the surface heat flux was less than 2.5%, and the overall uncertainty of the surface heat flux was calculated to be 0.78%. The results of their study showed

Table 2 Summary of experimental evaluation of coaxial thermocouples

Experiment time	Authors/year	Type of CSJT	Surface heat flux	Average measurement error
1.8 ms	S. L. N. Desikan et al. (2015)	K-type	229.6 KW/m^2	5.5%
2 ms	S. K. Manjhi and R. Kumar (2022)	E-type J-type K-type	16 KW/m^2	2.5%
3 ms	S. Park and G. Park (2022)	K-type	2.03 MW/m^2	6%
4 ms	S. Agarwal et al. (2017)	E-type J-type K-type	360 KW/m^2	47.2% 58.3% 147.2%
4 ms	S. Park and G. Park (2020)	K-type	1.37 MW/m^2	6%–15%
5 ms	V. Menezes and S. Bhat (2010)	E-type	520.16 KW/m^2	10%
80 ms	S. K. Manjhi and R. Kumar (2020)	E-type J-type K-type	6793.8 KW/m^2	2.8% 7.1% 13.7%
100 ms	W. Flaherty and J. Austin (2010)	E-type	6.1 MW/m^2	1.7%
200 ms	N. Sahoo and R. Kumar (2015)	K-type	86 KW/m^2	4%
200 ms	S. Park and G. Park (2020)	E-type	10 KW/m^2	2.4%

that coaxial thermocouples can accurately measure the surface heat flux on an inclined surface [47]. However, the numerical simulation section by Manjhi and Kumar did not clearly describe the modeling and mesh generation of the coaxial thermocouples, which was crucial for computational fluid-structure interactions. Park experimentally examined the effect of roughness and model size of coaxial thermocouples on thermal measurements and demonstrated that the heat flux prediction was proportional to the average roughness [48].

We summarized the experimental evaluation of coaxial thermocouples based on heating time, heat flux, and measurement error, as shown in Table 2.

4 Lateral heat transfer

Lateral heat transfer within a coaxial thermocouple has a significant impact on the measurement of heat flux. Assanis and Badillo analyzed coaxial thermocouples applied to a combustion chamber by the finite element method and illustrated that the heat flux measurement errors were caused by different materials between the thermocouples and the cast iron pistons. For surface heat flux measurements on aluminum components, the peak heat flux can be measured with an error of up to 80% [49, 50]. Sanderson and Sturtevant used a slightly tapered center conductor with a tapered fit between the two probe elements, creating a thin but strong joint that reduces the junction's effective thickness. The taper of the conchoidal material reduces its thermal diffusivity, and this error tends to offset the inevitably lower thermal diffusivity of the Inconel alloy [51]. Buttsworth et al. noted that the one-dimensional heat conduction model for the sensor response would lead to significant errors in the predicted value of the heat flux, and that the rapid decay of the impulse response was related to lateral heat transfer between the substrate and the housing [52]. Coblish et al. investigated the substrate material for matching Type E coaxial thermocouples in wind tunnel experiments. 15-5 stainless steel could provide a more suitable lateral heat transfer balance for coaxial assembly mounting substrates than 17-4 stainless steel, and should be selected as the experimental model material for Tunnel 9 [53]. Hendricks et al. developed a two-dimensional finite-difference numerical model with a time-step Crank-Nicholson integral routine to investigate surface temperature measurements, focusing on transverse effects and incorporating the different materials applied in CSJT. The two-dimensional numerical model showed a slightly higher peak in average heat flux distribution compared to the one-dimensional analytical model [54].

In Marineau and Hornung's study, they noted that one of the reasons for the overestimation of heat fluxes when calculating heat fluxes using the one-dimensional inversion method in solids using the average values of two electrodes is that junctions are non-homogeneous materials consisting of three materials. The epoxy insulation led to overheating of the junction, an effect that is stronger for a short period of time and diminishes with time because the transverse temperature gradient establishes a transverse heat flux. And in the vicinity of the junction, the heat transfer deviated significantly from the one-dimensional model. The center electrode increasing was also important because the raised junction accepts additional heat from the transverse direction [55]. Zeng et al. proposed a two-dimensional axisymmetric heat conduction model and a numerical calculation method to obtain the temperature distribution of coaxial thermocouples with surface cladding under constant surface heat flux or constant temperature boundary conditions. The method provided a technical way to improve the accuracy of heat flux measurement and finally obtained a family of curves describing the conversion between constant heat flux and temperature, which was favorable for engineering applications [56].

Wang et al. investigated the transverse heat transfer between coaxial thermocouples and model materials, and found that coaxial thermocouple surface heat flux measurements were low at 100 ms with deviations of about 20.5% and 13% for aluminum and carbon steel as wall materials, respectively [57]. This work was important for studying the response characteristics of coaxial thermocouples under prolonged heating. Further development of surface heat flux correction formula for coaxial thermocouples during prolonged heating could be considered. Zhang et al. investigated the effect of lateral heat transfer on coaxial thermocouples. The results indicated that the influence of transverse heat transfer and physical parameter changes due to temperature increase must be considered under long duration heating. The heat flux deviation was less than 10% when the Fourier number is less than 0.52. The error of predicted heat flux was not reduced as the length of CSJT increases [58]. Qi et al. investigated the phenomenon of nodal overheating and briefly analyzed the influence of wall materials [59]. Li et al. established a two-dimensional model of coaxial thermocouples. Three temperature correction methods were proposed for serious measurement errors, and the correction effect was verified for coaxial thermocouples of types E, J and K with various film thicknesses [60]. The error decomposition of the temperature correction algorithm for coaxial thermocouples with different film thicknesses (CTFTs) is shown in Fig. 12. Qi et al. pointed out that the coaxial thermocouple junction surface has a temperature maximum and it is displaced with heating time. The lateral heat flux distributions on the junction were shown in Fig. 13. Optimizing the sensor size based on this phenomenon, the coaxial thermocouple heat flux error of type E was reduced to 0.5% [61, 62].

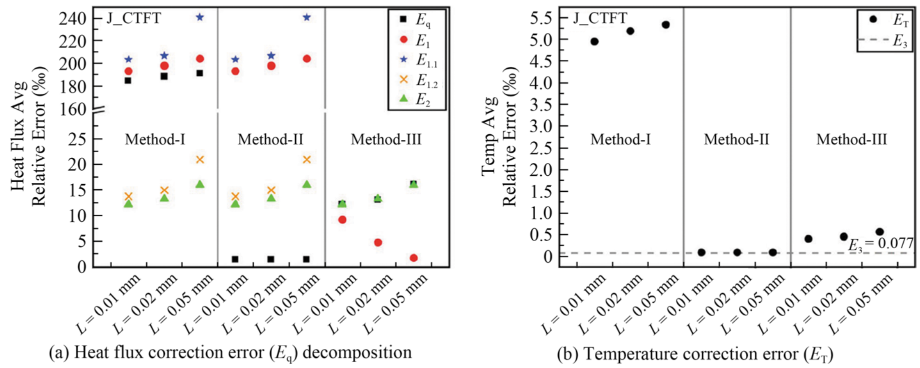

Fig. 12 Error decomposition of the temperature correction algorithm for CTFTs [60]

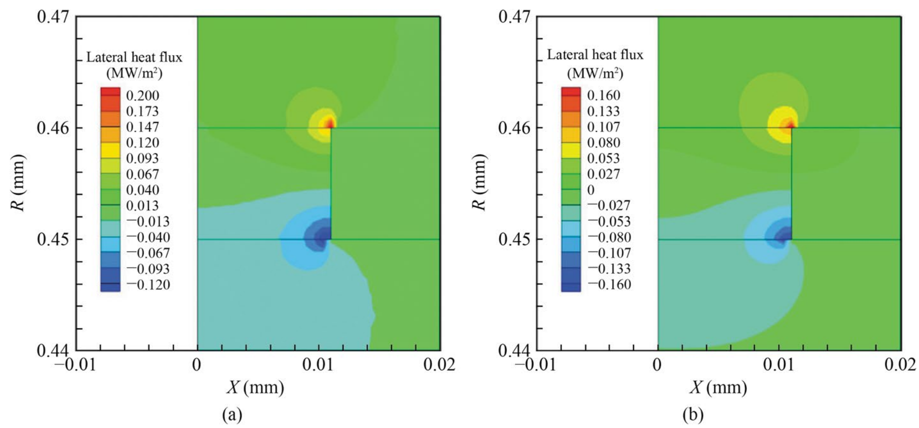

Fig. 13 Lateral heat flux distributions on the junction area at **a** 10 ms and **b** 50 ms [61, 62]

5 Design of coaxial thermocouples

An effective design comprehensively addresses multiple factors, including the dimensions of the electrodes and the configuration of the junction. Proper design of coaxial thermocouple construction will reduce measurement errors. Smith et al. combined a fast-response CSJT with a backside thermocouple through a simple design. This configuration provides a temperature history of CSJT and known strain gage geometry and material properties on the backside [63]. Marr et al. developed a CSJT to measure the surface temperature of aluminum components in an internal combustion engine (ICE). The main features of the design were the use of an aluminum substrate as one of the thermocouple metals and the use of a copper layer as the thermal contact material on the surface. It was found that the optimum thickness of the copper layer was between 100 μm and 125 μm [64]. Murayama et al. fabricated a novel sensing device with a sandwich coaxial thermocouple that can directly cool or heat an object, reducing the escape of heat from the object through the sensor itself and reducing the error in temperature assessment [65]. James et al. designed a novel and extremely durable E-type coaxial thermocouple, which incorporates an oxide layer between a tapered ring and a matching

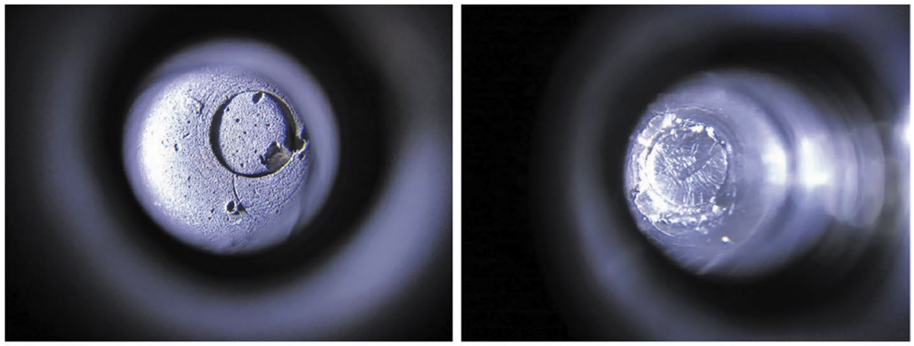

Fig. 14 Magnified photos of used and unused thermocouples glued into the stagnation point heat flux probe [66]

tapered pin [66]. After completing 28 experiments, the first thermocouple was removed from the facility. Subsequently, the second thermocouple was installed on the stagnation point heat flux probe before undergoing testing within the facility, as illustrated in Fig. 14. This sequential approach highlights the effectiveness and durability of their design in practical applications.

Manjhi and Kumar developed a novel experimental technique to calibrate the transient heat fluxes of coaxial thermocouples of type K, type E, and type J, respectively, with the help of concentrated sunlight, and the main advantage of this calibration technique is that it is reliable and cost-effective, with an error of only 3% in the measurement of the heat flux [67]. Birch et al. developed a fast response heat transfer meter to measure the radial distribution and fluctuations of heat flux in a supersonic arc-jet plasma wind tunnel [68].

6 Methods of analysis

Frankel and Keyhani proposed an innovative calibration methodology for estimating surface heat fluxes based on transient surface temperature data acquired from thin film resistance thermometers and coaxial thermocouples. This approach entails deriving the net surface heat flux by solving a first-kind Volterra integral equation. To enhance numerical stability, the first-kind Volterra integral equation is reformulated into a stable second-kind Volterra integral equation through the application of the local-future information method [69]. This advancement in calibration techniques has significantly enhanced the accuracy of heat flux measurements in transient thermal environments.

In the domain of instrumentation development, Irimpan et al. uncovered a significant finding regarding the type E coaxial thermocouples employed in pulsed facilities. Their research demonstrated that these thermocouples do not require cold-end compensation, thereby simplifying their application in experimental setups [70]. This finding has practical implications for thermal measurement systems operating in high-speed testing environments.

Additionally, notable progress has been achieved in sensor technology with the introduction of a robust, fast-response calorimeter heat transfer meter, commonly referred to as the diamond heat transfer meter. This innovative instrument, specifically designed for transient hypersonic ground test facilities, incorporates a synthetic diamond disk, 150–325 μm thick, as a calorimeter element. The device features a platinum thin-film resistance temperature detector mounted on the backside of the diamond disk, enabling precise measurement of temperature rise during transient thermal events [71].

In the realm of computational heat transfer analysis, Rout et al. have made substantial contributions by employing advanced soft computing techniques. They utilized the Adaptive Neuro-Fuzzy Inference System (ANFIS) to recover step surface heat loads with remarkable accuracy. Their methodology involved training the ANFIS network with step heat loads of 2 W and 3.5 W, followed by the recovery of intermediate heat flux signals of step magnitude using the trained network. This sophisticated training process incorporates temporal data, temperature measurements, and corresponding heat flux values, creating a comprehensive signal analysis framework. The results demonstrated excellent consistency with both the imposed thermal loads and predictions generated using conventional techniques. In the study, ANFIS has exhibited improved predictive capabilities by integrating Gaussian input affiliation functions for time and trigonometric functions for temperature. This hybrid approach has yielded heat flux signal predictions that align remarkably well with the applied heat fluxes across all training scenarios [72].

Building on these developments, Priya and Peetala's research has provided valuable insights into thermal measurement techniques utilizing various thermocouple types. In their study, transient temperature data were collected from coaxial surface junction thermocouple models of type K, type E, and type J under controlled thermal simulations. These datasets were meticulously discretized and processed to recover convective heat fluxes. The analytical method employed in this research yielded heat flux histories that closely matched the predefined input heat loads of 1000 W/m^2 and 5000 W/m^2, thereby demonstrating the reliability and accuracy of the approach [73]. Collectively, this body of work signifies substantial advancements in thermal measurement and heat flux estimation techniques, offering improved methodologies for both experimental and computational analyses in heat transfer studies.

7 Other applications for coaxial thermocouples

Agarwal and Sahoo conducted a comprehensive numerical simulation study to investigate exhaust gas flow in internal combustion engines, utilizing a type E coaxial thermocouple with a diameter of 3.25 mm for temperature measurement within the exhaust pipe. Through systematic analysis of various thermocouple placements, it was determined that the optimal measurement position could be any axial location within the range of 0–20 mm from the exhaust port [74]. This finding offers valuable guidance for sensor placement in engine exhaust systems, ensuring accurate temperature measurements while minimizing flow disturbance.

In the realm of solar energy research, Sagar and Kumar made significant contributions by employing a type K coaxial thermocouple to evaluate the thermal performance of parabolic trough collectors. Their experimental investigations focused on three key parameters: useful heat gain, heat loss, and thermal efficiency during sunny days. The results revealed a distinct diurnal pattern in solar radiation intensity, with peak values occurring at noon that significantly exceeded measurements taken at 9:30 and 15:30 [75]. These findings underscore the importance of temporal considerations in the design and optimization of solar energy systems.

Advancing the understanding of thermocouple applications in extreme environments, Lefevre et al. explored the use of type E thermocouples in ionized shock layers subjected to magnetic fields. Their research illustrated that these thermocouples maintain reliable performance in such challenging conditions, with the notable advantage that modeling and sensing surface insulation properties become less critical factors in measurement accuracy [76]. This discovery broadens the potential applications of type E thermocouples to include high-temperature, ionized environments where traditional measurement techniques may falter.

Collectively, these studies demonstrate the versatility and reliability of coaxial thermocouples across diverse applications, from internal combustion engine diagnostics to solar energy system evaluations and measurements in extreme environments. The type E and type K coaxial thermocouples have proven to be robust measurement tools, capable of delivering accurate temperature data under various challenging conditions.

8 Future perspective in coaxial thermocouples

Coaxial thermocouples still have an irreplaceable role in the field of hypersonic heat flux measurements. As the Mach number increases, there is a growing demand for coaxial thermocouple surfaces to resist scrubbing. Firstly, the structure of coaxial thermocouples needs to be improved to minimize heat flux measurement errors caused by nodal overheating phenomena, which requires refinements of the sensor manufacturing process. Secondly, the accuracy of heat flux inversion under multi-dimensional heat transfer situations is also an urgent need in some hypersonic vehicle surfaces with significant aerodynamic heating. Thirdly, coaxial thermocouples still exhibit a measurement error of approximately 10% in wind tunnel experiments. Future heat flux sensors must be miniaturized for measuring surface heat flux at the tips of aircraft. In addition, the cold end of coaxial thermocouples cannot be guaranteed to have a constant temperature during the long heating process, and the heat flux measurement value needs to be corrected. Finally, for the thermal measurement process, the effect of the change of the flow field on the measurement of coaxial thermocouples also needs to be investigated by experiments and simulations.

9 Conclusions

With their fast response and high resistance to washout, coaxial thermocouples are important devices for measuring surface heat flux in ground-based wind tunnel experiments. This paper describes the important research progress and future development direction of coaxial thermocouples. The following conclusions can be drawn from the description:

1. Energy dispersive X-rays are an important means of detecting the surface composition of coaxial thermocouple junctions, which have both thermoelectric metals and insulating layer material compositions.
2. The E-type coaxial surface junction thermocouples have been experimentally demonstrated to be the best choice for high enthalpy flows due to their ruggedness and abil-

ity to survive in challenging ultra-high speed environments. The type E, J and K-type coaxial thermocouples can achieve a minimum heat flux measurement error of 2.5%.

3. Lateral heat transfer consists of nodal superheating within the coaxial thermocouple and heat exchange in the wall material. Lateral heat transfer can introduce significant heat flux measurement errors into coaxial thermocouples. When using aluminum and carbon steel as wall materials, the heat flux measurement errors are approximately 20.5% and 13% at 100 ms, respectively.
4. Sunlight can be used to calibrate coaxial thermocouples with a calibration error of 3%, which is very cost effective.
5. Adaptive Neuro-Fuzzy Inference System (ANFIS) can be used to invert the surface heat flux.
6. E-type thermocouples can be used for measurements in ionized shock layers where magnetic fields are present.
7. The accuracy of heat flux inversion under multi-dimensional heat transfer modeling needs to be improved. The coupled heat transfer process of flow field and coaxial thermocouples needs more research.

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Authors' contributions
LQ designed the framework of this paper, and was a major contributor in writing the manuscript. HCC participated in the design of this paper, and was a major contributor in revising the manuscript. ZTY and ZCY polished the language of this manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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