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WORLD FIRST EXPERIMENTAL VISUALIZATION OF DIESEL SPRAY–WALL HEAT LOSS: INSIGHTS FROM HIGH-SPEED INFRARED THERMOGRAPHY AT MEIJI UNIVERSITY

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ABSTRACT

This report describes the world's first successful experimental visualisation of wall heat loss generated by an impinging Diesel spray flame, demonstrated during a technical training session at Meiji University. Conventional heat-flux sensors provide only point measurements and cannot reveal the spatial and temporal behaviour of heat transfer during spray-flame impingement. The researchers overcame this limitation by combining a chromium-coated quartz window, a constant-volume combustion chamber, and a high-speed infrared camera capable of 10 kHz imaging. This setup enabled direct observation of the wall's thermal response under engine-relevant conditions. The infrared radiation recorded from the coated surface was calibrated to temperature and subsequently converted to heat-flux distribution through transient heat-conduction analysis of the window material. The results show clear differences between flame luminosity and infrared radiation behaviour, confirming that the measured signal originates from the heated wall rather than from combustion light. Distinct radial streak patterns were observed, revealing the significant influence of turbulent structures on wall heat transfer. The reconstructed heat-flux values, including a peak of approximately 18 MW/m², agreed well with previous point-sensor measurements. This study demonstrates a practical and reliable approach for visualising spray-wall thermal interaction and provides new insight into the role of turbulence in Diesel engine cooling losses.

KEYWORD

Infrared high-speed thermography, wall heat transfer, diesel spray flame, wall heat flux.

INTRODUCTION

Despite inevitable concern on the carbon footprint from internal combustion engine ICE, Diesel engine is proved to be the most efficient, reliable and practical solution especially when it comes to medium-heavy duty mobility.

The limitation on the zero emissions Battery Electric Vehicle in eliminating carbon emissions from the tailpipe from all vehicle sectors seems to become clearer in recent years. BEV is still generally 10~20% more expensive than comparable passenger vehicles models. For commercial vehicles, BEV batteries are too large, need longer charging time, limited charging station and the battery capacity will deteriorate after several years of usage, e.g. it degrades faster for frequent fast charging. Fuel Cell Vehicle FCV is technology that practically eliminates those BEV limitations, however it is far more expensive, almost double that of the conventional Diesel engine.

Researchers across Europe, North America and Japan have long pointed out the impact of the total ICE removal scenario is not feasible in the foreseeable future. In recent years, the automotive power trains R&D is moving towards decarbonizing the Diesel fuel itself rather than a drastic shift toward the new BEV and FCEV technology. For example, Mazda Motor Corporation Japan is putting effort in developing Diesel engine technology to best suit biodiesel from self-harvest algae. European research groups are focusing more on the synthetic fuel production technology and its integration with the conventional Diesel engines technology including the engine itself, injection, post treatments and other circumference systems.

Figure 1: TELOPS FAST M3K enables up to 1.5 – 5.4 µm IR spectral range capture at up to 10 kHz frame rate (left) and wall heat loss mechanism observation settings (right).

Similar to biodiesel, the synthetic or E-fuel process is regarded as a carbon-neutral alternative, as the carbon dioxide is taken from the atmosphere for the fuel production, e.g. the CO_2 emitted during combustion is balanced out by the CO_2 captured during production. Those biodiesel and synthetic fuels can be used in existing Diesel engines and refuelling infrastructure, making them suitable for heavy duty transports where electrification is difficult.

Thus it is important to shift the effort in improving the thermal efficiency of the Diesel engine. Depending on the Diesel engine size, modern light duty passenger vehicle, medium duty urban delivery truck and heavy duty truck/bus thermal efficiency is reported at around 45% to 60%: bigger engine permits higher compression ratio and thus higher thermal efficiency. Two main thermal losses for Diesel engines could be attributed to the exhaust gasses mass and enthalpy losses through the tailpipe. Recent technology to recover that heat from the hot gasses through a Thermoelectric Generator TEG device which converts heat to electrical energy via the Seebeck effect is gaining momentum. However, the biggest thermal inefficacy is owing to the wall heat loss which is more difficult to tackle since it occurs inside the cylinders during the combustion: simple insulation coating will result in significant increase of NOx emissions (Horibe, 2018).

Although Diesel combustion has been studied extensively, the detailed mechanism of wall heat loss during spray-flame impingement has remained unclear. Traditional fast-response heat-flux sensors provide only point measurements, making it difficult to understand the full spatial and temporal nature of the heat transfer. For decades, researchers lacked an experimental method capable of visualizing what truly happens when a high-temperature Diesel spray flame interacts with a much colder wall surface—precisely where most cooling loss is believed to occur (Dejima, 2019).

Only in the last decade has high-speed infrared (IR) imaging technology matured to the point where it becomes feasible to attempt such measurements. The TELOPS FAST M3K, for example, can capture broadband infrared radiation at up to 10 kHz (Figure 1), providing the temporal resolution required to observe rapid, unsteady wall-heat-transfer phenomena (Aizawa, 2021).

This sets the stage for one of the most remarkable recent breakthroughs in Diesel combustion research. During training at Meiji University, we had the opportunity to learn how their researchers developed the world's first experimental method capable of visually observing wall heat loss caused by an impinging Diesel spray flame. This report summarises our understanding of their approach, highlights the engineering challenges involved, and reflects on the significance of their achievement.

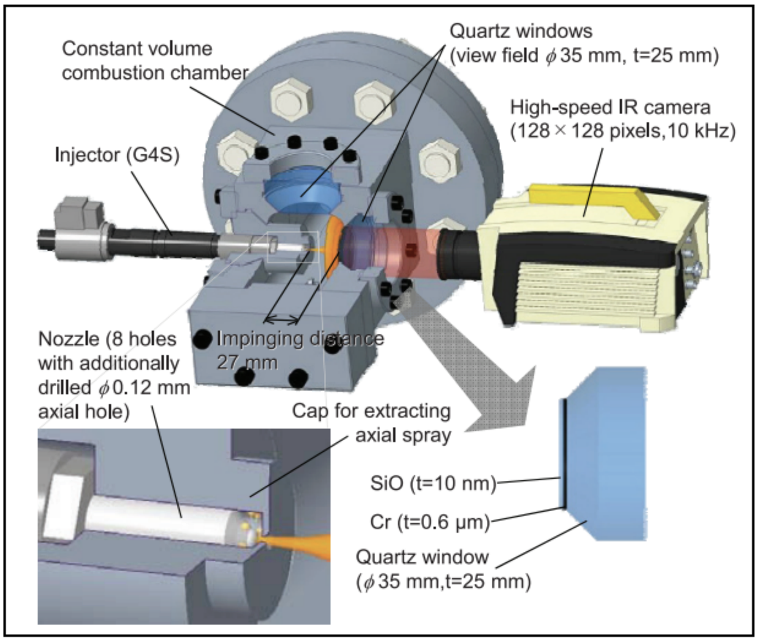

Figure 2: Experimental setup for high-speed imaging of infrared thermal radiation from diesel-flame-impinged wall surface in optically-accessible constant-volume combustion vessel.

MATERIAL AND METHODOLOGY

The experimental methodology developed at Meiji University is based on replicating the spray–wall interaction under controlled, engine-relevant conditions while enabling direct thermal observation of the impacted surface is shown in Figure 2. To achieve this, a 35 mm quartz window was installed in an optically accessible constant-volume combustion chamber CVCC at the opposite direction of the Diesel injector. The window inner surface was coated with a thin chromium layer to block bright radiation from combustion and further protected by a SiO overcoat, forming a durable radiating surface that responds to the flame's thermal loading. Quartz was selected as the window's material as its thermal properties allow a sufficiently large surface temperature swing for infrared detection.

A modified Denso G4S injector generated a single, centrally directed Diesel spray that impinged perpendicularly on the coated window at a 27 mm distance, representative of piston-bowl configurations in modern Diesel engines. The chamber was conditioned to high-pressure, high-temperature environments matching typical engine operation. Injection pressures from 120 to 200 MPa were tested. As the spray ignited and the flame front interacted with the chromium layer, a TELOPS FAST M3K infrared camera operating at 10 kHz recorded the infrared emission from the back side of the window. Background radiation from the preheated quartz was subtracted to isolate the temperature rise attributable solely to the impinging flame.

To quantify the thermal response, the infrared intensity was calibrated against known temperatures by heating the coated window in a separate furnace and acquiring reference images with the same optical setup. This calibration allowed the high-speed infrared recordings to be converted into two-dimensional temperature distributions. To obtain quantitative heat-flux information, the temperature fields derived from the infrared calibration were applied as boundary conditions to a three-dimensional transient heat-conduction model of the quartz window. This simulation enabled estimation of the surface heat flux required to produce the observed temperature response, given the known thermal properties of the window material. This approach enables visualization on how the wall surface heats up and how local heat-transfer intensity varies during the flame–wall interaction.

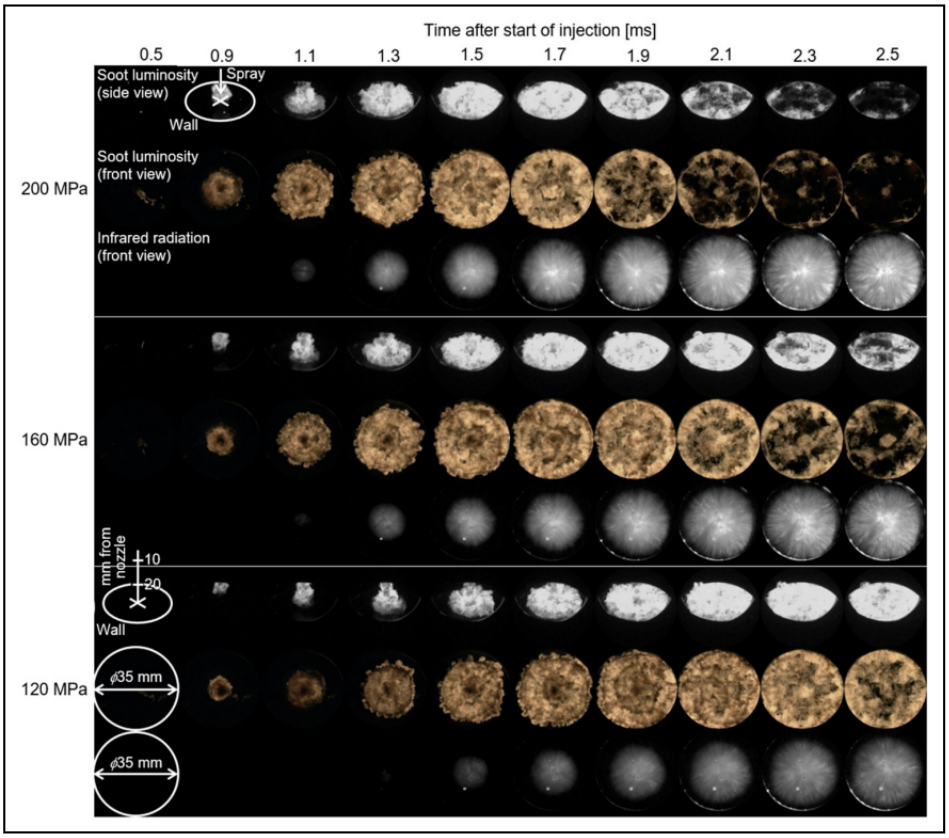

Figure 3: Example high-speed images of side-view (top) and front-view (middle) diesel flame soot luminosity and infrared radiation from chromium layer (bottom) impinged by diesel flame at P_{inj}=200 MPa, 160 MPa, 120 MPa. Ambient conditions: ρ_a = 23.8 kg/m^3 , P_a = 4.8 MPa, T_a = 1050 K and 17% O_2. Injection conditions: φ0.12 mm orifice, m_f = 5 mg.

RESULT AND DISCUSSION

The comparison between the high-speed flame luminosity images and the infrared radiation images (Figure 3) demonstrates that the two signals originate from different physical processes. The soot-luminosity views show the evolution of the reacting spray plume, including ignition, growth, and later decay, with the flame front spreading radially across the wall surface at approximately 30 m/s. In contrast, the infrared images captured from the chromium-coated window represent the thermal response of the wall surface. Their appearance is slightly delayed relative to the flame arrival, and their outward propagation is slower at roughly 10 to 15 m/s. This difference confirms that the infrared signal is not residual flame luminosity passing through the coating. It is genuine thermal radiation emitted from the chromium layer as it is heated by the impinging flame. The slower spread is consistent with the finite rate of heat transfer from the flame to the wall surface, particularly in the outer region where the flame motion decreases and the boundary layer becomes thicker.

A characteristic feature of the infrared radiation field is the presence of coherent radial stripe patterns emerging from the stagnation point, as shown in Figure 3 and Figure 4. These streaks vary from straight to curved shapes and often display a gentle waving motion over millisecond timescales. Their width remains almost constant as they extend outward, and their behaviour closely resembles the turbulent streak structures previously observed in engine heat-transfer studies. The alternating bright and dark bands indicate spatial variations in near-wall turbulent transport. Regions with stronger upward motion deliver hotter gas to the surface, while neighbouring regions experience lower convective activity. The existence and motion of these stripes provide direct experimental evidence that turbulent structures in the impinging diesel flame strongly influence the local and instantaneous heat-transfer distribution on the wall.

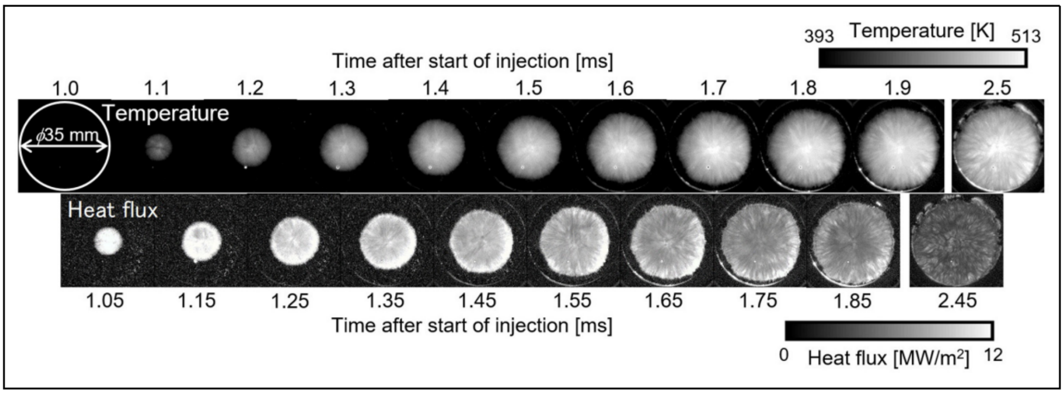

Figure 4: Example of temperature (top row) and heat flux (bottom row) image sequences converted from high-speed infrared radiation images of chromium-coated quartz window impinged by diesel spray flame at injection pressure of 200 MPa.

The calibrated infrared data were converted to temperature fields, and these fields were used as boundary conditions within a transient three-dimensional heat conduction model of the quartz window. This allowed estimation of the corresponding surface heat flux distribution (Figure 4). The wall temperature increased by as much as 150 K above its initial level, and the peak estimated heat flux reached approximately 18 MW/m^2, which is comparable to values reported in previous sensor-based measurements. High heat flux first appeared at the primary flame impingement point and then intensified at the expanding outer edge of the heated region. This behaviour corresponds to the first contact between the hot flame and relatively cool surface areas. The reconstructed heat-flux maps also preserved the radial stripe patterns, with peak-to-peak variations of about 20 K in temperature and 2.3 MW/m^2 in heat flux. These results confirm that wall heat transfer during diesel spray-flame impingement is highly unsteady and strongly affected by turbulent flow structures. The method used in this study provides unique spatial and temporal insight that has not been achievable with conventional point measurement techniques.

CONCLUSION

Through this work, the researchers at Meiji University demonstrated that it is finally possible to experimentally record the wall heat flux produced by an impinging Diesel spray flame, something that had remained unachievable for decades despite many attempts. After numerous trials refining the coated window, optical setup and calibration procedure, they successfully captured clear temperature and heat-flux distributions using a high-speed infrared camera. The resulting images revealed strong turbulent influence on wall heat transfer, visible in the form of dynamic radial streaks and wavy patterns that move across the surface. These structures highlight how unsteady turbulence controls both the magnitude and the spatial variation of heat flux during spray impingement. Most importantly, the heat-flux values obtained from the infrared-based method showed good agreement with earlier point-sensor measurements, confirming that this new imaging technique is not only innovative but also quantitatively reliable for studying wall heat loss in Diesel engines.

ACKNOWLEDGEMENT

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REFERENCE

Aizawa, T., Kinoshita, T., Akiyama, S., Shinohara, K., & Miyagawa, Y. (2022). Infrared high-speed thermography of combustion chamber wall impinged by diesel spray flame. International Journal of Engine Research, 23(7), 1116–1130.

Horibe N, Bao Z, Taguchi T, Egoshi K, Kawanabe H and Ishiyama T. (2018). Improvement of thermal efficiency in a diesel engine with high-pressure split main injection. SAE technical paper 2018-01-1791.

Dejima K, Nakabeppu O, Nakamura Y, Tsuchiya T, Nagasaka K. (2019). Three-point MEMS heat flux sensor for turbulent heat transfer measurement in internal combustion engines. Int J Engine Res; 20(7): 696–705.