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Laseroptische Temperaturmessung in Flüssigkeiten mittels gefilterter Brillouin-Streuung

Laser-optical temperature measurement in liquids by Filtered Brillouin Scattering

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Laseroptische Temperaturmessung, Brillouinstreuung, Jodzelle, Absorptionsfilter
Laser-optical temperature measurement, Brillouin scattering, iodine cell, absorption filter

Zusammenfassung

In diesem Beitrag wird ein neuartiges, laserbasiertes Messverfahren zur Erfassung der Temperatur von Flüssigkeiten vorgestellt. Das Verfahren basiert auf der temperaturabhängigen Brillouin-Streuung von Laserlicht kombiniert mit einem optischen Filter in Form molekularen Joddampfes. Das Verfahren kann beispielsweise zur örtlich und zeitlich aufgelösten Erfassung des Temperaturprofils einer Rohrströmung eingesetzt werden. Der nichtinvasive Charakter laseroptischer Messverfahren verhindert dabei die Beeinflussung des Strömungsprofils durch Sensoreinbauten. Der vorliegende Beitrag führt kurz die physikalischen Grundlagen aus, beschreibt den Einsatz eines Molekularfilters und stellt die verschiedenen Teilkomponenten des Messsystems vor. Anschließend wird mit ausgewählten Messergebnissen für stationäre und dynamische Temperaturzustände die grundsätzliche Funktionsfähigkeit des Messprinzips nachgewiesen.

Summary

This article introduces a novel, laser-optical method for measuring the temperature of liquids. The method utilizes the phenomenon of temperature-dependent Brillouin scattering of laser light in liquids in combination with an optical filter based on molecular iodine. This method allows for spatially and temporally resolved measurements of a temperature profile, e.g. that of a pipe flow. The non-invasive character of laser-optical measurements thereby avoids the perturbation of the flow field as no intruding sensors are necessary. The article starts with a very brief introduction to the phenomenon of Brillouin scattering, the application of a molecular optical filter and a description of the measurement system's different components. It concludes

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with several experimental results that can be seen as a proof of concept for the temperature acquisition in liquids by filtered Brillouin scattering.

Motivation

Conventional, intruding temperature measurement in a fluid flow by RTDs or thermocouples causes perturbation of the flow field. Additionally, the response time and therefore the temporal resolution are dependent on both the sensor size and the heat transfer coefficient between sensor and fluid. These restrictions could be overcome by applying a non-invasive, laser-optical temperature measuring system which could provide an improved temporal resolution independent of the thermal coupling between sensor and fluid. When coupled with a measurement of the velocity profile by LDV, a combined system is possible that is able to measure the heat flow in a fluid by point-wise determination of both temperature and velocity.

Principle of laser scattering for flow measurements

When laser light is passed through a fluid, scattering occurs. In comparison to the narrow-bandwidth incident light, the scattered light acquires a change of spectrum, in which several components are distinguishable (Miles et al. 2001). The magnitude of the different scattering phenomena is strongly influenced by the properties of the fluid (e.g. its density). The relevant effects for the proposed method are Mie scattering (caused by macroscopic particles like gas bubbles or dust) and Rayleigh scattering by particles which are much smaller than the incident wavelength. Brillouin scattering is caused by thermally induced acoustic waves traveling through the fluid with the speed of sound specific to the medium, causing density fluctuations. Scattering occurs in forward or backward direction (Anti-Stokes and Stokes), creating two distinguished Lorentzian curves (Figure 1). The effect can be regarded as equivalent to the Doppler effect.

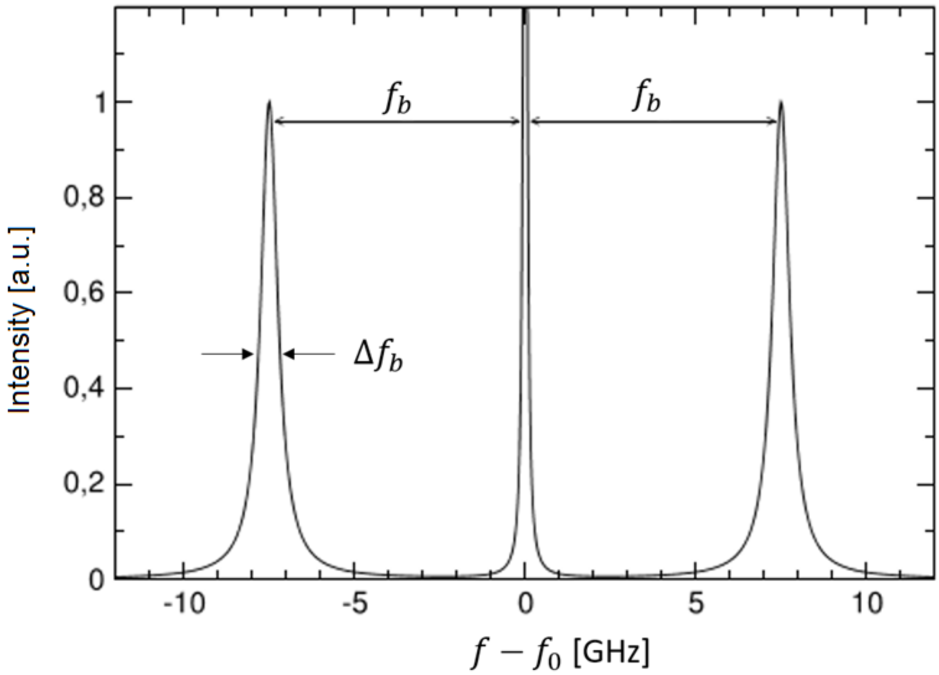

Figure 1: Calculated Brillouin spectrum of water with a frequency shift of ±7,5 GHz, f_0 is the frequency of the incident laser light (similar to Schorstein 2009)

$$f_B = \pm 2 \frac{v_S n}{\lambda} \sin \frac{\theta}{2} \ with\ v_S = v_S(T, S)\ and\ n = n(T, S, \lambda)$$ Equation 1

$$\Delta f_B = \frac{\Gamma}{2} \left(\frac{4\pi n}{\lambda} \sin \frac{\theta}{2} \right)^2 \ with\ \Gamma = \Gamma(T, S)\ and\ n = n(T, S, \lambda)$$ Equation 2

The two characteristic properties of the Brillouin spectrum, frequency shift f_B and linewidth Δf_B can be calculated through equations 1 and 2, where v_S is the speed of sound, n the refractive index of the fluid, λ the incident wavelength, θ the angle between incident light and the detector's optical axis and Γ is the damping constant of the density fluctuations (Fry et al. 2002). The damping constant strongly depends on the physical properties of the fluid (e.g. salinity).

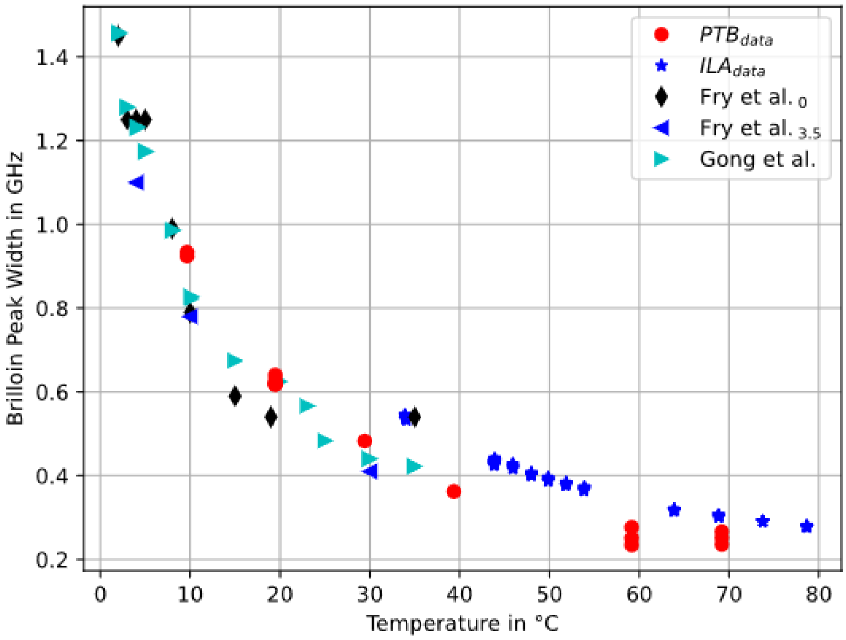

Figure 2: Brillouin peak width of water as a function of temperature, data either found in literature (Fry et al. 2002 for two different salinities, Gong et al. 2006) or obtained experimentally (labeled ILAdata and PTBdata)

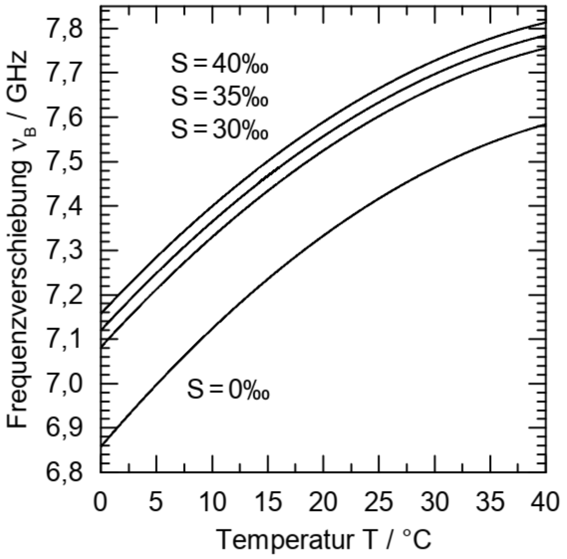

Figure 3: Brillouin shift of water as a function of temperature and salinity (Rudolf 2013)

The speed of sound in a liquid is temperature-dependent – water for example shows an increasing speed towards higher temperatures. Thus, the Brillouin spectrum is influenced by the fluid temperature as well, which can be derived from Equation 1 (for water, rising temperature yields higher frequency shift). The refractory index is also a function of temperature, salinity and the incident laser wavelength, but the influence of the variables on n is very small and therefore negligible. Examples for the influence of changes in temperature and salinity on the spectral properties are illustrated in the Figures Figure 2 and Figure 3. This leads to the conclusion that the phenomenon of Brillouin scattering can be utilized for temperature measuring purposes.

The method of filtered Brillouin Scattering (FBS)

The acquisition of the scattering spectrum requires a high spectral resolution, achievable by using interferometric devices which in turn demand elaborate thermal and mechanical stabilization. However, the extraction of the temperature information is possible without knowing the exact shape of the spectrum. This can be achieved by transforming the spectral measurement to a measurement of integrated intensity through the utilization of an optical filter, in this case molecular iodine vapour (Forkey 1996). The iodine is contained in an evacuated and heated glass cylinder and acts as a notch filter with a very stable absorption spectrum and a great number of narrow absorption lines (Figure 4). The difference between maximum and minimum wavelength on the x-axis hereby equals about 40 pm.

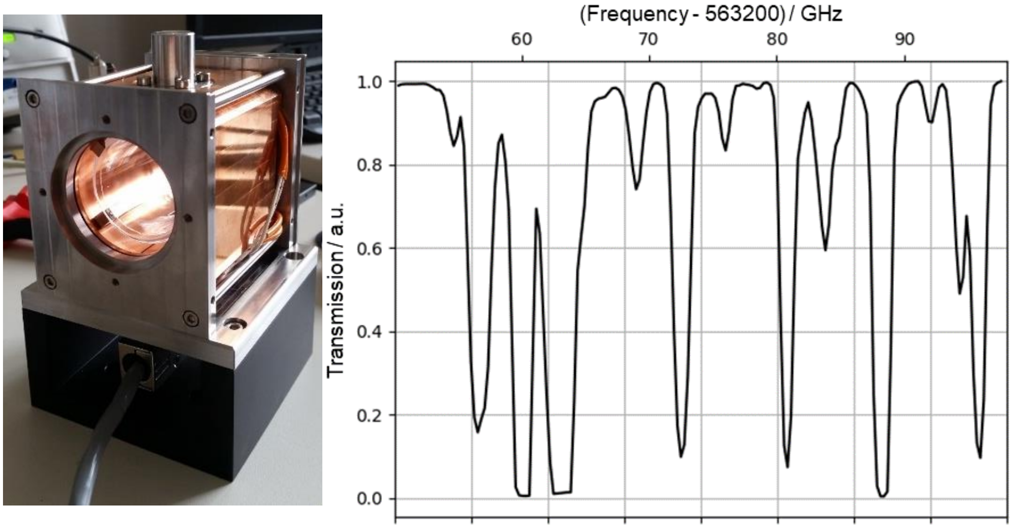

Figure 4: Iodine cell without covers and protective windows and measured transmission spectrum of an iodine cell in the frequency range relevant for Brillouin scattering of water

If the Brillouin spectrum is matched with a combination of iodine absorption lines in a way that a shift in frequency moves the Brillouin peaks along the rising or falling slope of the transmission, the intensity change in the light passing the filter is dependent on the frequency shift (Figure 5). Mathematically, this is a convolution of the Brillouin spectrum and the iodine absorption function. Scanning the laser frequency will yield a different integrated intensity value for each frequency and the resulting curve of intensity over frequency shows a characteristic fingerprint for each liquid and temperature.

A further advantage of the filtered measurement lies in the possibility to block out unwanted components such as reflections of the laser and Mie scattering. Both phenomena have a similar wavelength as the original incident wavelength of the laser. Therefore, tuning the laser wavelength in a way that it coincides with an absorption line of iodine enables the absorption of unwanted components (marked with “Laser” in Figure 5).

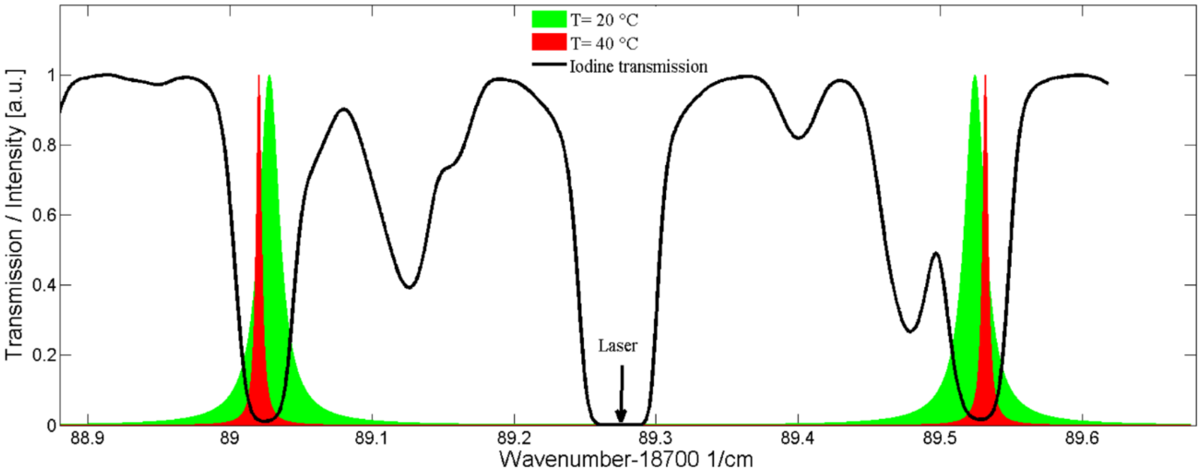

Figure 5: Brillouin spectrum of water with two different temperatures in comparison to part of the iodine transmission spectrum (Stockhausen et al. 2014)

Experimental Setup

To test the novel method for temperature measurement, several experimental assemblies have been developed. The principal device to obtain the temperature is a combination of a novel FBS system with an established LDV system to measure the volumetric flow. Both devices were joined in a common assembly (Figure 6). Once the two systems are aligned internally in order to precisely overlay the measurement volume of both LDV and FBS, a single traversing system can be used to move the combined measurement volume to the region of interest in the liquid. The system design and basic studies were a joint work of ILA R&D GmbH and DLR with BHT providing the fundamental FBS model for the software evaluation to determine temperatures from the acquired light intensities.

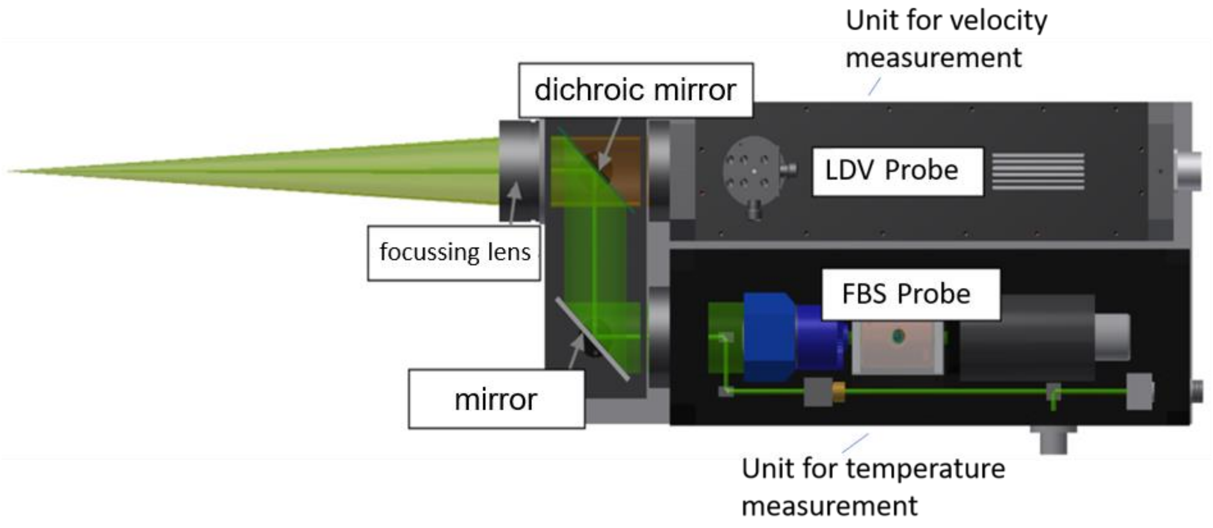

Figure 6: Combined FBS-LDV probe, devised and built by ILA R&D GmbH

In order to validate the measurement system, a flow test facility was required that could provide defined conditions in regard to its volumetric flow profile, a well-defined temperature profile along with precise and fast temperature sensors. The PTB developed a purpose-built flow facility (Figure 7). A high precision hexapod with six degrees of freedom was installed as a positioning system for the combined LDV-FBS-probe. More details regarding the flow test facility can be found in (Kühn 2021).

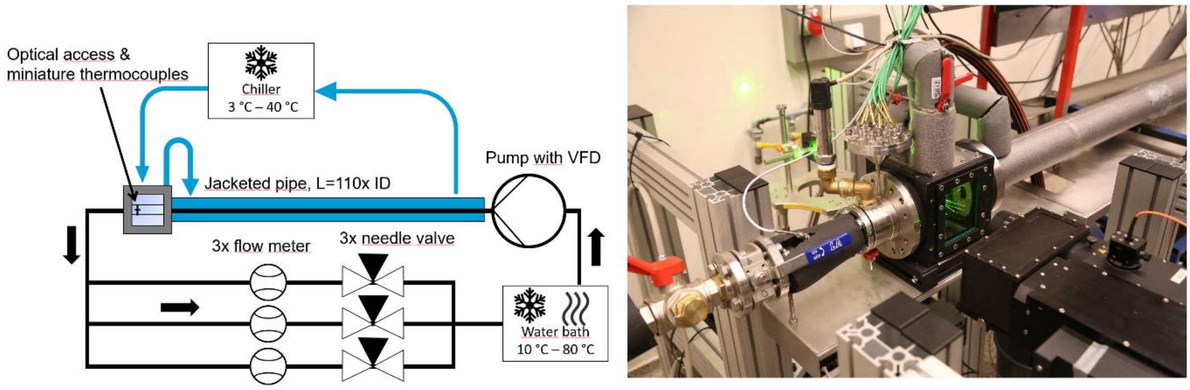

Figure 7: Flow diagram and photograph of the flow test facility, devised and built by Physikalisch-Technische Bundesanstalt Berlin

As already discussed earlier and illustrated in Figure 2 and Figure 3, several factors influence the Brillouin spectrum of a liquid. Especially different additives or deposits in real-world applications such as power plant piping systems or domestic heating networks can notably change the spectrum. To be able to determine the spectrum of the relevant liquid with the required precision and over a wide temperature range, a variation of calibration tools was devised by OPTOLUTION GmbH. Each can hold a small amount of liquid, provide optical access for the FBS measurement system and guarantees a stabilized and homogeneous temperature of the fluid (Figure 8). The obtained calibration spectra will then be the basis of the temperature measurements conducted in the process of facility itself.

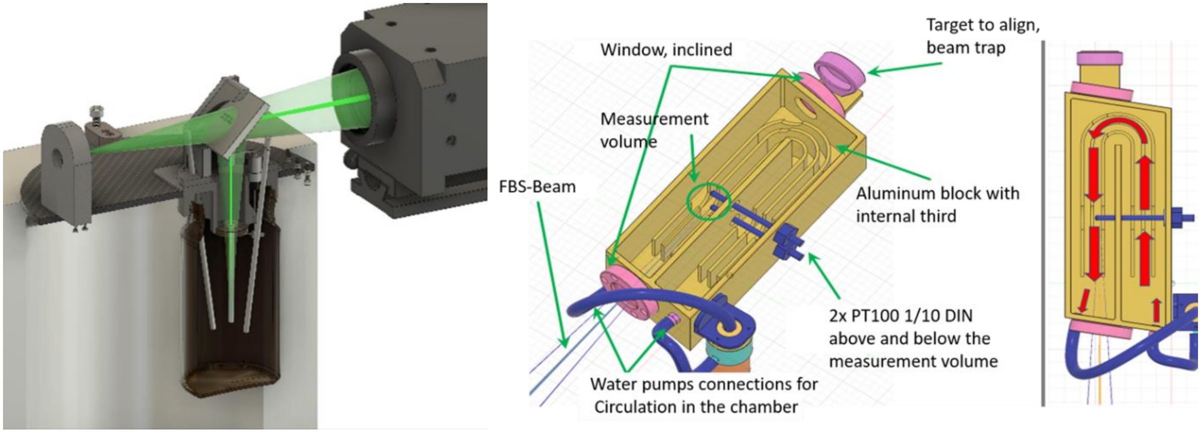

Figure 8: Two iterations of the spectral calibration device, devised and built by OPTOLUTION GmbH

Measuring stationary temperatures

Figure 9 compiles the results of temperature measurements in a pipe flow with a homogenous temperature profile. Shown is a comparison of the temperatures determined by different FBS measurement and evaluation algorithms and the reference temperature that has been

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acquired with a calibrated Pt100 system. Additional details regarding the various FBS approaches can be found in (Röhle et al. 2021). Good agreement is evident for both the scanning and two-wavelength strategy with the reference temperature, providing an achievable uncertainty of the temperature determination in the order of 1 K. Towards higher temperatures the uncertainty somewhat increases which indicates that the underlying FBS model and algorithms should be further refined with emphasis to this temperature region.

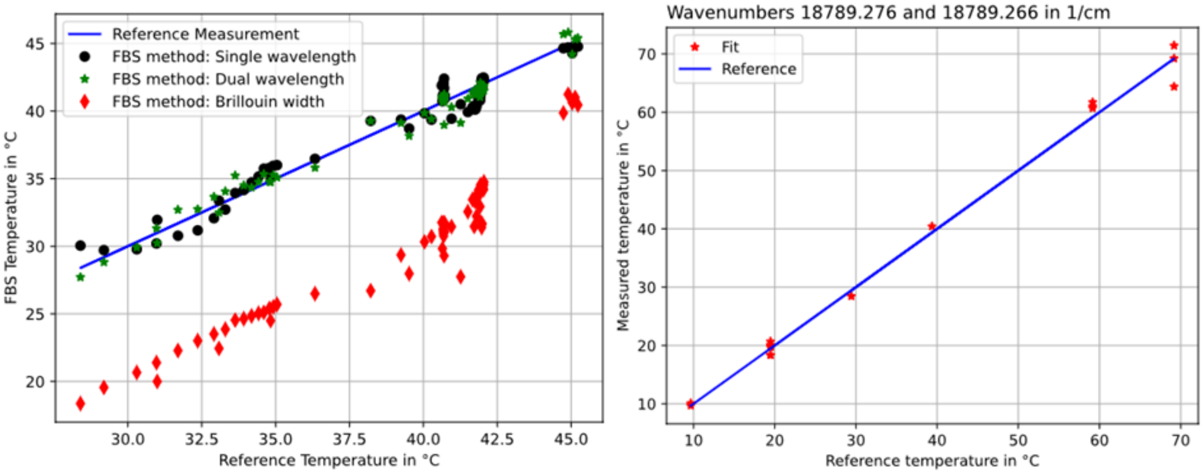

Figure 9: Results for stationary temperature measurements with different FBS strategies (left) and for an extended temperature range with the FBS dual wavelength strategy (right)

Performance of the FBS system for measuring temperature transients

To test the responsiveness of the FBS system, a transient temperature experiment was carried out. A pump started moving pre-heated water through a piping system that has been cooled down before, leading to a sudden increase in temperature of approximately 70 K once the hot water has reached the point where the sensors are located. Figure 10 shows a comparison between the measured temperatures for both a fast thermocouple system as reference (diameter 0,5 mm, acquisition frequency 100 Hz, more details in Kühn 2021) as well as the FBS normalized intensity signal. A calculation of temperature values while the system is acquiring transient phenomena is not yet feasible by the current FBS model and evaluation algorithm. Clearly the responsiveness of the laser-optical system is at least on par with the conventional, intrusive thermocouple measurement.

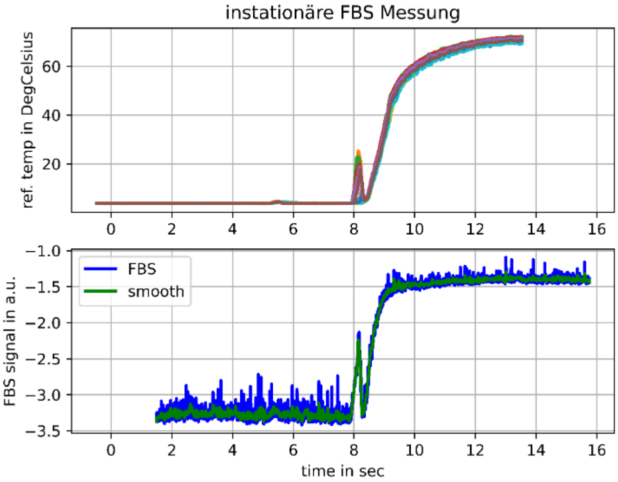

Figure 10: Results for acquiring a fast temperature transient (upper figure: temperatures measured by thermocouples, lower figure: normalized signal of the FBS system)

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