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# Investigation of New Methods and Instruments for Thermal Emissivity Measurement

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**Abstract:** This study examines the new techniques and instruments used in the measurement of thermal emissivity over the past two decades. Some of them have been evaluated with full details based on similar functions while others are not. Some devices utilize interferential filters to perform the spectral measurements which happens to be the simplest method to isolate a spectral range while others utilize spectrographs or monochromators that choose a narrower wave band compared to the filters. Lastly, others utilize the Fourier Transform Infrared (FTIR) spectrometer that measures the entire spectral range under study in each method of measurement and maximizes the ratio of signal to noise. Studying these devices with similar features can lead to building a better device that optimizes all the advantages from these other devices.

**Key words:** Thermal emissivity, infrared, blackbody, directional, instruments

## INTRODUCTION

Infrared emissivity is a relative physical parameter that refers to the method whereby an object expels electromagnetic radiation that is thermal infrared. This refers to the ratio of the quantity of emitted radiation from an object and the radiation emitted from a blackbody at similar temperatures with spectral as well as geometrical conditions (Siegel and Howell, 2002). These days, most technical applications are dependent on the sound knowledge of the properties of the radiative surface. Transfers in rediative energy are critical for space technologies, high temperature heat transfer technologies and the entire types of solar energy technologies (Gengenbach *et al*., 2004).

Based on the experimental perspective, it should be noted that a material's emissivity is dependent on the wavelength as well as the temperature and differs according to the angle of the emission. In addition, the emissivity can drastically change according to the roughness and oxidation state of the surface as well as the existence of grain, pollutants among others (Sabuga and Todtenhaupt, 2001; Mehling *et al*., 1998). Emissivity is directly measured based on either calorimetric or radiometric. In the measurement of calorimetric emissivity, the radiant heat transference rate of a sample is calculated based on the sample's lost heat. The ratio between the calculated heat transfer rate and that of the blackbody radiator based on similar conditions is equivalent to the emissivity. The total sum of the hemispherical emissivity is normally the assessed emissivity. On the other hand, the assessment of the direct radiometric emissivity is carried out by calculating the heated specimen's radiance and a blackbody under similar temperature with the sample under similar geometric as well as spectral conditions and by measuring the emissivity as the two radiances' ratio (DeWitt and Richmond, 1988; Richmond and Harrison, 1960; Furukawa and Iuchi, 2000).

The radiative heat transfer calculation was mainly affected by the radiation intensity's direction and spectral distribution in the infrared wavelength ranges. The directional spectral emissivity can be used to express these distributions. The thermal radiation's direction and spectral control was among the critical issues of efficiency improvement and the reduction of energy usage in different thermal systems. A popular method of controlling the properties of the direction and spectral radiative of a surface was the periodic surface microstructures concept. Current research findings in the area of micromachining allowed the production of periodic microstructures with geometrical dimensions of similar magnitudes as the thermal radiation wavelengths. The effects of interference were expected between the electromagnetic waves and the structure which were believed to lead to the increase in the emissivity (Gengenbach *et al*., 2004). Various possibilities are revealed in related literature on methods of measuring the

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spectral directional emissivity using the method of direct radiometric (Lopes *et al*., 2000; Ishii and Ono, 2001). There are three different options to choose from when it comes to measurements of directional emissivity namely tilting the sample, moving the detection system and locating some detectors at various angles. A blackbody radiator is used as a source of reference in many experimental setups; however, various sources of identified emissivity could be utilized (Mehling *et al*., 1998; Lopes *et al*., 2000; Pantinakis and Kortsalioudakis, 2001). An additional crucial trait in the measurement of emissivity is related to the heating control. The heating technique is dependent on the kind of sample insulation or metal used and the required maximal temperature. Hence, the Joule effect can be used to heat up the conductors; however, radiation or contact electrical heaters also permit the heating up non-conducting samples. Other alternatives methods are available at higher temperatures including the laser heating, acetylene torch and the electron beam heating among others. A thermostatic fluid that is in contact with the sample could be as well if the temperatures to be reached are not very high (Mehling *et al*., 1998; Lopes *et al*., 2000; Oertel and Bauer, 1998).

**Investigation of recent works:** In this study, we investigate an overview on a number of the new techniques and instruments used in the measurement of thermal emissivity with a particular focus on infrared radiation applications and discuss their advantages and disadvantages.

New experimental device for infrared spectral directional emissivity measurements in a controlled environment (Campo *et al*., 2006). The following presented the new experimental device for measurements of infrared spectral directional emissivity. This sample holder allowed the measurement of the spectral directional emissivity as high as 1050 K and it was put within a chamber of stainless steel sample which could be filled up with various gases or evacuated. A Fourier transform infrared spectrometer was utilized to detect the signal. The experimental results emphasized on the device's capacity to carry out measurements on emissivity as functions of emission angle, temperature and in situ surface state evolution.

A thorough research has been carried out on the homogeneity of the sample's temperature and the measurement approach such as the background radiation, the function of the apparatus response as well as differences in temperature between the blackbody radiator and the sample. Consequently, a compact expression for the emissivity of the sample that generalized the direct radiometric measurement technique obtained previously was identified. The assessment of error revealed that the key contribution to the uncertainty of the emissivity was linked to the temperature of the sample.

The general uncertainty at the intermediate temperature was projected to be approximately 3% at wavelengths that were short. The measurements of emissivity of the Armco iron were utilized to monitor the experimental device's accuracy. The experimental results revealed a perfect fit with the direct emissivity data available in related studies and with the theoretical emissivity retrieved from the Hagen-Rubens relations.

Table 1 reveal a summary of the range of measurement for the major parameters in the emissometer. The range of the spectral included much (>90%) of the thermal energy that was emitted in the measuring range of the temperature. Figure 1 display the experimental device with four major modules arranged in a T-form: a sample chamber, a FTIR spectrometer, a blackbody as well as an optical entrance box which leads the radiation emitted by the sources (blackbody and sample) in the direction of the spectrometer.

The equivalence of the optical path from both the blackbody and the sample to the detector in this experimental configuration was achieved. A tiny infrared source was utilized to align the optical path and every module was supported by the independent linear guide that was connected to the optical bench to enable the alignment to be simpler as every module was rather heavy. The whole optical path from the sources to the detector was independent of $CO_2$ and $H_2O$ gases to prevent the unwanted absorptions of radiation.

The FTIR spectrometer the optical entrance box and the sample chamber could be purged or evacuated while the blackbody could just be purged. After the experimental device was mounted as well as aligned, it was not necessary to move the modules to carry out the measurements. This was crucial as it stopped the device from misalignments as well as thermal instability caused by the movements of the components. Moreover, this minimized the room and simplifies the process of automation.

Table 1: Summary of the measuring parameter ranges: wavelength Δ, emission angle Θ, temperature T and sample chamber pressure P. (Campo *et al*., 2006)

| Parameters | Ranges |
|---|---|
| λ (μm) | 1.28-25 |
| θ (deg) | 0-80 |
| T (K) | $T_{amb}$-1050 |
| P (Pa) | 0.3-1.013×$10^5$ |

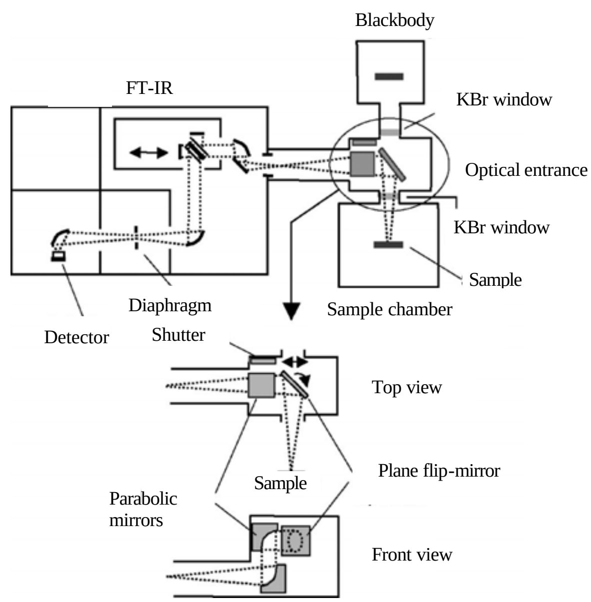


Fig. 1: Schematic view of the emissivity measurement experimental device with its four main modules (Campo *et al*., 2006)

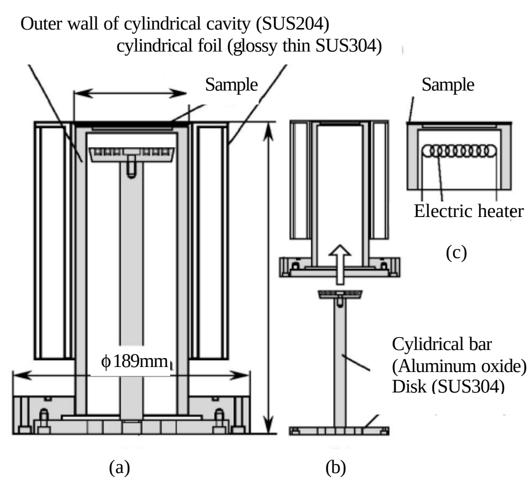


Fig. 2: Schematic of the heater for sample (Furukawa and Iuchi, 2000)

Experimental apparatus for radiometric emissivity measurements of metals (Furukawa and Iuchi, 2000). The following presented the new experimental device for the measurement of infrared spectral directional emissivity in an atmosphere that was controlled. Equipment to measure radiometric emissivity of a metal was designed.

The equipment included certain traits that permitted the metallic sample to be kept within particular conditions including atmospheres that were a vacuum, oxidized and deoxidized. Spectral (from wavelengths that were visible to 10 imm infrared), polarized emissivity (polarized p and s) and directional (normal as well as 80°) metals could be measured by utilizing this equipment which could be used to examine the emissivity of the specimen's behavior.

The structure of the equipment for emissivity measurement of a metal was thoroughly explained in this section. The equipment comprised of two sections namely the heater and the chamber with controlled atmosphere for the sample and the internal space which was controlled under particular atmospheric conditions including vacuum, oxidation or reduction. A schematic diagram of the heater section of the sample is demonstrated in Fig. 2.

The heater's features were listed as shown in the following: double structures of outer wall and heater;

outer wall material: SUS304; heater: Kanthal A-1, 1.2 mm φ, 10 U; maximal sample temperature: 1023 K; maximal sample diameter: 88 mm φ and sample's distribution of temperature: +3 K within 30 mm in diameter from the sample's center. The double structure comprising of the outer wall and heater as reveal in Fig. 2 was the most distinctive feature in this section. The outer wall was represented by a cavity that was cylindrical. The cavity's edge facing the internal space of the chamber that was atmospherically controlled was closed while the sample was located on this surface. The Kanthal A-1 wire (10 Ω) electric heater was inserted in the cavity that was cylindrical from the external side and placed close to the cavity's upper edge. Hence, this isolated the heater from the chamber's internal space. The sample within the chamber's internal space was heated using the surface's radiant heat from the cylindrical cavity's edge; the radiant heat of the electric heater in turn heated this area since there were tiny gaps between the surface edge and the sample as well as between the electric heater and the surface edge (Fig. 2c).

This radiant heating structure for the sample assisted in achieving a uniform temperature in the sample's surface. This happened to be the structure's advantage. Based on the experiment, the distribution of temperature was controlled at 63 K in a 30 mm diameter from the sample surface's center. The sample's maximal temperature obtained from this structure had a limitation of 1023 K due to the indirect radiant heating. This happened to be the structure's disadvantage. Since, the cylindrical cavity's outer surface that faced the internal chamber space was assumed to be a potential source of radiation noise as the cavity was heated up at high temperatures, cylindrical foil of glossy thin stainless steel sheets were used to surround the surface to protect the noise radiation (Fig. 2a, b).

The broken heater that occurred at times due to the overheating was removed easily to the external area and a properly working heater was inserted back into the cylindrical cavity with no effect on the internal conditions of the chamber (Fig. 2b). This happened to be the structure's additional advantage. New experimental apparatus for measurement of spectral emissivity of opaque materials using a reflector as the dummy light source (Shi *et al*., 2012).

New experimental equipment has been designed that was able to measure the spectral emissivity of opaque materials precisely by utilizing a reflector as the dummy source of light. The experimental equipment comprised mainly of the systems for optical detection, heating, temperature control, angle adjustment, signal control and data computation. The optical system functioned at 1.5 μm with a 20 nm bandwidth. The sample could reach heating of up to 1200 K by the heater sample. The sample's surface temperature was calculated using two very precise platinum-rhodium thermocouples and controlled using a device including a microcomputer controlled proportional (integral) derivative.

The error for temperature control was within 2 K more than the experimental range of 700-1200 K. A reflector was utilized as the dummy source of light to establish the measurements of the single-wavelength of the spectral emissivity. The current equipment could be utilized to carry out the spectral emissivity measurement as a function of the emission angles as well as temperatures.

This equipment measured the spectral emissivity of some of the opaque materials. For instance, the results of spectral emissivity for polished aluminum sheets at temperature ranging from 788-1028 K have been documented. The analytic dependency has been determined between the spectral emissivity with the temperature. The temperature was established based on the two thermocouples utilized to evaluate the precision of the measured spectral emissivity.

Comparing the measured temperatures by the thermocouples and the emissivity gained here showed that the results that were measured by the equipment had reached a higher accuracy and the reliability of the proposed technique of measurement is good.

The method of positioning of the reflector is revealed in Fig. 3. It was observed here that the detector and the reflector are placed at the zygomorphic sites of the regular sample surface direction.

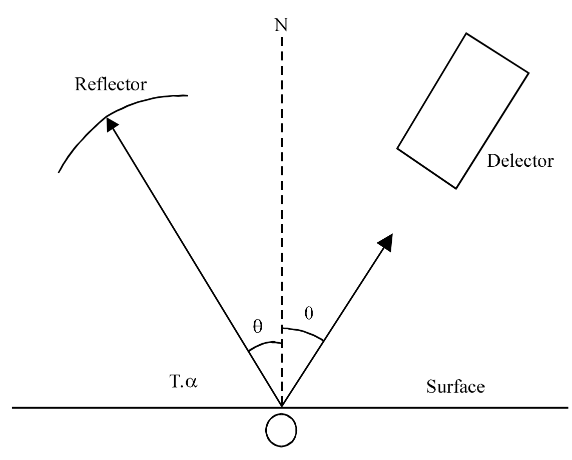


Fig. 3: Positioning method of reflector and detector (Shi *et al*., 2012)

It was seen that the optical paths were symmetrical from the sample to the reflector and from the sample to the detector in the regular sample surface direction. An infrared laser diode was utilized in the experimental configuration to ensure a geometrical symmetry. The angle h must be as tiny as possible to calculate the regular spectral emissivity as precisely as possible. A modulating disk controlled the reflector's working state. The modulating disk was positioned at the front of the reflector and the speed of rotation is 1200 r $min^{-1}$.

Figure 4 demonstrate that there are only two working states for the disk. One denoted ''light pass'' and the other denoted ''light shelter''. The reflector was operating when the disk denotes the ''light pass'' and the sample's radiant energy could arrive completely at the reflector; after that it was reflected back to the sample's surface alongside the original optical path. The reflector was not operating when the disk denotes the ''light shelter'' and the sample surface's radiant energy was not able to reach the reflector.

Measurement of directional spectral emissivities of microstructured surfaces (Gengenbach *et al*., 2004). The presented equipment was able to measure the directional spectral emissivity of solid surfaces at moderate temperatures from 330-500 K. The directional distribution is evaluated for polar angles from 0°-70° and for azimuth angles from 0-90°.

The intensity of radiation was identified using an FTIR-spectrometer in the ranges of wavelength from 4-24 μm. Precise knowledge of the temperature on the surface was critical to evaluate the emissivity, given its huge effect on the intensity of the radiation. A few

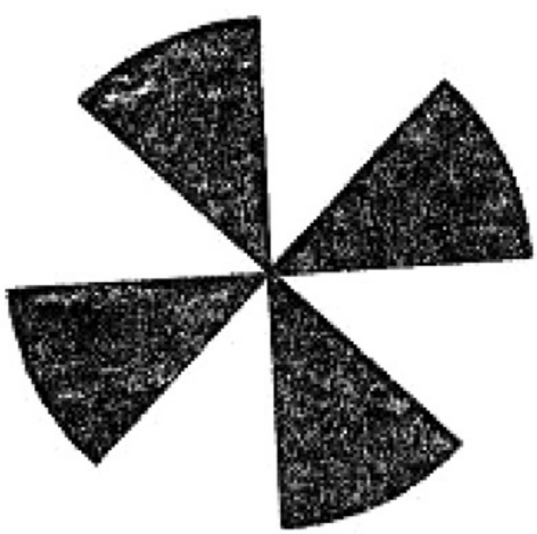

Fig. 4: Schematic diagram of the disk (Shi *et al*., 2012)

techniques were suggested to establish the surface temperature without directly utilizing a temperature probe on the surface of the sample. Experimental data was reported for the validation of samples and for different surfaces that were microstructured.

An FTIR system was utilized to carry out the measurements of directional and spectral emissivity. This system comprised two chambers namely the vacuum and equipment chambers, as observed in Fig. 5.

These chambers were connected optically to a KBr window. The equipment chamber had a fourier transform infrared spectrometer (EQUINOX 55) produced by Bruker Optik GmbH. This spectrometer was able to carry out multi measurements of wavelengths in the ranges of 0.8 and 27 μm. It contained an inlet window to allow for an external radiation source and the sample chamber is connected to it through a pipe. The spectrometer was emptied out dry with carbon dioxide-free air to reduce the impact of water and carbon dioxide on the spectrum that was measured. The Deuterated Triglycine Sulfate (DTGS) detector that was utilized had a high sensitivity at a temperature of 12°C. The radiative transfer of heat between the chamber walls and the detector was removed by tempering the sample and equipment's chambers at a constant similar 12°C temperature. The sample's chamber had various components namely a sample holder system, a cylinder cavity acting as a blackbody radiator with a rotating attachment of plain mirror between them. The sample's chamber was emptied out using a vacuum pump to remove convective transfer of heat from the sample.

The sample chamber's inner walls were colored with black lacquer with the total hemispherical emissivity of 0.94 to reflect the radiation striking the chamber walls from the heated components only in small quantities. Components close to the electrical heating systems in the sample's holder and in the blackbody radiator were covered with polished chromium or they were manufactured from materials of low emissivity values to lower the surfaces emissivity. A rotating mirror attachment was attached in the chamber at equal distance from the sample's surface and the opening of the blackbody to ensure similar optical path lengths for both the sources. It was utilized to switch from the sample's radiation and the blackbody's radiation as the FTIR-spectrometer input signal.

An aperture was positioned between the spectrometer and the mirror attachment to use up similar measuring areas of radiation from the surface of the sample and the blackbody's radiator to the detector. The optical axes' adjustment between the detector and the radiation sources was carried out after each sample transformation by utilizing an auto-collimation telescope.

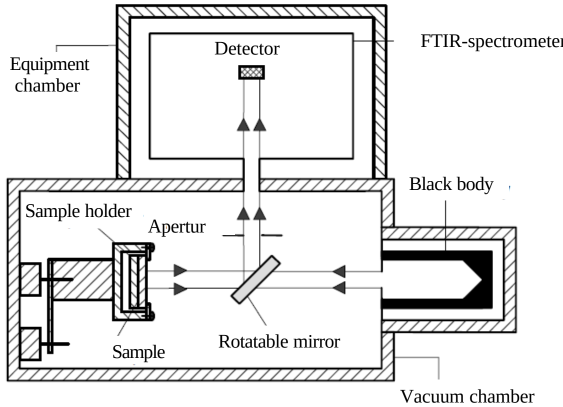


Fig. 5: Measurement equipment for the determination of the directional, spectral emissivity (Gengenbach *et al*., 2004)

The sample's holder was capable of setting the sample's polar and azimuthal angles to assess the directional features of the radiation from the surface of the sample.

This was established using the assistance of the DC-bar armature motors along with the line coded absolute rotating transducers. The sample and the blackbody radiator's temperatures were maintained using two different electrical heating systems that were PID-controlled. The sample and the blackbody radiator's measurement of temperature were performed utilizing the calibrated platinum resistance thermometers Pt-100. The temperatures of the other components were measured using the thermocouples. The entire measured data was documented in a personal computer to carry out further evaluations as described in the following. An experimental method for making spectral emittance and surface temperature measurements of opaque surfaces (Moore *et al*., 2011).

An experimental process has been designed to create the measurements of spectral emittance and temperature. An object's spectral emittance was measure utilizing the measurements of spectral emissive power and the object's surface temperature retrieved utilizing the Fourier Transform Infrared (FTIR) spectrometer.

The calibration process was thoroughly described, which explains the detector's temperature dependency. The techniques utilized to retrieve the power of spectral emissive and the surface temperatures from the measured infrared spectra were validated by utilizing a blackbody radiator at the set temperatures. The measured spectral emittance's average error was 2.1% and the average variation of the inferred temperature and the recorded spectra and the indicated temperature on the blackbody radiator was 1.2%. The technique was utilized to calculate the oxidized copper's spectral emittance at different temperatures.

Measurement of the spectral emissivity of solid materials (Redgrove, 1990). A unique technique has been utilized to accurately calculate the spectral emissivity of a variety of solid materials of metal and non-metal origins. The technique was especially suitable for weak thermal conductors with a high level of emissivity as normally they could not be accurately calculated due to huge uncertainties linked to the surface temperature measurement.

Findings were documented on two reference materials with NBS standards. Several preliminary measurements on specimens of aluminium that were bare or coated V-grooved were also documented and these findings were compared with a theoretical assumption of perfectly specular or diffused reflecting surfaces. This design specimen was selected to allow the impacts of the V-groove shape and the surface emissivity to be experimentally differentiated.

System for measuring the spectral distribution of normal emissivity of metals with direct current heating (Kobayashi *et al*., 1999). A technique was designed to measure the time differences of the regular spectral emissivity at wavelengths of 0.55-5.3 μm and applied to metal specimens in environments of vacuum and oxidization in the range of temperatures from 780-1200° C. The specimen was heated up to high temperatures using a direct current passed through a vacuum chamber and the surface oxidation was maintained using oxidizing gas of low-pressure. The specimen's temperature was calculated using a single-band (0.9 μm) radiation thermometer observed from a cavity developed from the rear of the specimen.

The specimen's front surface was observed using a multiband (112-wavelength) radiation thermometer to calculate the regular spectral emissivity. The efficacy of the specimen cavity's regular spectral emissivity was

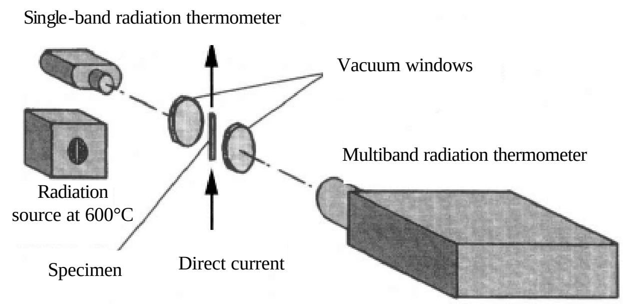


Fig. 6: Schematic of measurement system (Kobayashi *et al.*, 1999)

measured to be 0.94+0.05 at a wavelength of 0.9 μm compared to a metal tube with a tiny blackbody hole on the back. The uncertainty of measurement of by the system's regular spectral emissivity was projected to be 5-10% of the value of emissivity in many of the attractive ranges of temperature, emissivity and wavelength.

The system of measurement contained specimens, a multi-band radiation thermometer for measurement of specimen radiance, a single-band radiation thermometer for measurement of specimen temperature and a specimen system for environmental/heating control. A schematic measurement system is demonstrated in Fig. 6. The specimen's front surface heated by running a direct current was seen at the centre of the specimen by the multiband radiation thermometer to calculate the spectral radiance. The specimen's temperature was calculated from the back using a radiation thermometer of single-band (0.9 μm). The specimen's regular spectral emissivity was taken from the temperature calculated using the radiation thermometer of a single-band and the specimen's spectral radiance on the front surface at the regular direction calculated by the radiation thermometer of multiband. The specimen's surface oxidation was maintained by introducing oxidizing gases into the vacuum chamber. A change in absorption in the atmospheric caused by water vapor and carbon dioxide on the multiband radiation thermometer's optical path was corrected using a radiation source with a small black plate heated to 600°C and situated in the atmosphere close to the chambers' vacuum windows and it was periodically found by the multiband radiation thermometer.

## RESULTS AND DISCUSSION

**Analysing and modelling:** Emissivity is the ratio of the quantity of emitted radiation from an object and the radiation emitted from a blackbody that FTIR (Fourier Transform Infrared) spectrometer is used to measure both. The radiation emitted by a blackbody is determined by using of Planck's law as fallows:

$$E(\lambda, T) = \frac{2d}{\lambda^5\left(e^{b/\lambda T} - 1\right)} \tag{1}$$

where, $a = hc^2$ and $b = hc/k$, h, k, c are Planck's constant, the Boltzmann constant and the speed of light in vacuum, respectively. The measured signal for the blackbody at temperature $T_{bb}$ is:

$$E_{bb}(\lambda, T_{bb}) = R(\lambda)\left[E(\lambda, T_{bb}) + E_0(\lambda)\right] \tag{2}$$

where, R (λ) and $E_0$ (λ) are the response function of the apparatus and the background radiation, respectively. The signal of sample at temperature $T_s$ is expressed in similar method as follows:

$$E_s(\lambda, T_s) = R(\lambda)\left[\varepsilon_s(\lambda, T)E(\lambda, T) + \varepsilon_{sur}E(\lambda, T_{sur})\rho_s(\lambda, T_s) + E_0(\lambda)\right] \tag{3}$$

where, $\varepsilon_s(\lambda, T_s)\, E(\lambda, T_s)$, $\varepsilon_{sur}\, E(\lambda, T_{sur})\, \rho(\lambda, T_s)$, $\varepsilon_s(\lambda, T_s)$ $\rho(\lambda, T_s)$, $\varepsilon_{sur}$ and $T_{sur}$ are the radiation emitted by the sample, the fraction of the emitted surroundings radiation reflected by the sample, the emissivity of the sample, sample reflectivity, the surroundings emissivity and temperature, respectively. Using Eq. 2 and 3, the emissivity of the sample can be obtained as follows:

$$\varepsilon_s(\lambda, T_s) = \frac{E_s - E'_{bb}\, E(T_{bb}) - E(T'_{bb})}{E_{bb} - E'_{bb}\, E(T_s) - \varepsilon_{sur}E(T_{sur})} + \frac{E(T'_{bb}) - \varepsilon_{sur}E(T_{sur})}{E(T_s) - \varepsilon_{sur}E(T_{sur})} \tag{4}$$

where, $E'_{bb}$ is the blackbody signal at a different temperature $T'_{bb}$.

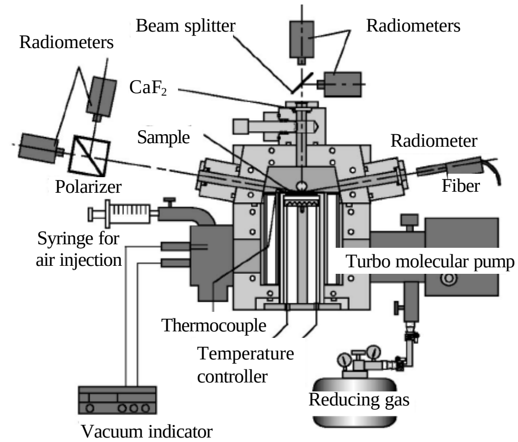


Fig. 7: Schematic of the system of emissivity measurement (Furukawa and Iuchi, 2000)

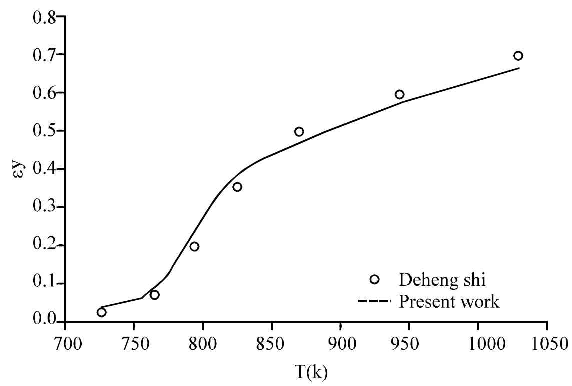


Fig. 8: Spectral emissivity of aluminum sheet as a function of temperature

The proposed device is achieved by combination of devices shown in Fig. 3, 4 and 7. After achieving the analyzing of the compound device, obtained spectral emissivity of aluminum sheet for different temperatures is compared with work of (Shi *et al*., 2012) and shown in Fig. 8 which shows a good compatibility. So, with this assessment it can be concluded that the compound device has the benefits of both devices and it can be used for a variety of applications.

## CONCLUSION

In this study, we give an extensive overview on a number of the new techniques and instruments used in the measurement of thermal emissivity with a particular focus on infrared radiation applications and discuss their advantages and disadvantages. We introduced several proposal to measure emissivity. Furthermore, we shortly report on thermal emissivity measurement as well as implementation details and optimization issues.

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