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TABLE OF CONTENTS

1 Executive Summary

Introduction

Large scale power plants based on nuclear or conventional fuel provide about 80 % of generated electricity and nearly 90 % of hot water used for district heating in the EU. Despite the efforts to increase renewable energy by 10 % by 2020 power plants will still form the backbone of energy supply for the foreseeable future. This demonstrates the importance to continue improving the energy efficiency of nuclear, coal and gas plants which in turn will contribute to energy conservation, preservation of natural resources, reduction of emissions and protection of environment.

The Problem

In order to improve the energy efficiency of existing power plants, the measurement uncertainty of the important control parameters (temperature, flow, thermal energy and electrical output) has to be reduced. For future power plants, establishing metrological infrastructure and methods is vital in order to perform the necessary developments for advanced materials (Ni-base alloys and Thermal Barrier Coatings) used in gas turbines.

The Solution

The project reduced the measurement uncertainty of the above important control parameters (temperature, flow, thermal energy and electrical output) by at least a factor of 2. A metrological infrastructure was explored in order to investigate Ni-base alloys and Thermal Barrier Coatings (TBCs) under the temperature conditions encountered in gas turbines.

Impact

The project has already generated impact via the early adoption of its results by companies responsible for construction, instrumentation and operation of power plants:

- Manufacturers of thermometers used in power plants are now able to develop thermometers with low uncertainties of 3 K instead of 8 K. One manufacturers already offers commercially thermometers with these specifications.
- Manufacturers of flow sensors are now able to offer flow sensors with an uncertainty of 0.5 % instead of 3 %. One manufacturer already sells an ultrasound based flow meter for the use in power plants with this specification.
- During the final stage of the project, some findings concerning temperature and flow rate measurements of this project were applied in the field. As performance tests in power plants are subject to strict confidentiality, it can only be stated, that after applying the findings of the project, two operators of power plants assume that the energy efficiency of each power plant could be enhanced by 1,5 percentage points as now the energy production processes can be optimised based on the low uncertainty measurements of flow rate and temperature.

Further impact is expected via:

- Manufacturers of on-site electricity power meters are now able to offer commercially measurement equipment with uncertainties of < 0.1 % instead of 0.5 %.
- Manufacturers of sensors for temperature measurement of turbine blades now have access to metrological infrastructure for further developments of the technique.
- Operators of power plants are aware of the project’s outputs and there are significant opportunities for impact as the results are adopted more widely.

All the above lead to the conclusion that the original aim of this project, to enhance the energy efficiency of power plants by 2-3 percentage points, became a reality.

2 Project context, rationale and objectives

The guiding principles of the European energy and climate policy are security of supply, economic efficiency and environmental protection. As electric energy cannot be stored in significant amounts it has to be generated at the time of use. Consequently, a mix of basic, medium and peak load power plants are necessary to balance consumption and production. Although, renewable energy is necessary and of high priority, large scale power plants, which currently provide around 40 % of generated electricity, will continue to play an important role for the next few decades. It is therefore important to increase the energy efficiency of such power plants.

The need to improve energy efficiency and reduce energy consumption is recognised in a number of European Directives (e.g. 2006/32/EC: Directive on the promotion of End-use efficiency and Energy Services[1]) and national government policies dealing with energy (e.g. "National Energy Efficiency Action Plan[2]" of the German government). The European Commission's Policy on Energy Efficiency[3] showed the importance of this goal. Across Europe industry faces a common problem: how to measure accurately energy loss and how to improve processes within a defined budget and production constraints.

In Europe steam power plants are an important source of electricity and whilst a considerable number of them are due for replacement in the next decade it is generally expected that by 2020 around 40 % of electricity will still be produced by conventional power plants[4]. The average efficiency of steam power plants across Europe is 36 %, to 46 %. By increasing the steam temperature of the next-generation power plants from the current 540 - 600 °C to 700 °C an improvement in efficiency of around 50 % is possible, resulting in 25 % CO_2 reductions per MWh of generated electricity[5]. In order to increase the efficiency of gas turbines above 60 % an increase of the typical gas inlet temperature from the current 1300 °C to 1500 °C is necessary. Across the whole world the situation is even more demanding with the mean efficiency of coal power plants of around 30 %. Typically 0.48 kg coal is necessary to produce one kilowatt hour and this is associated by an emission of about 1.116 kg CO_2. For a 700 °C power plant operating at 50 – 55 % efficiency the required coal consumption could be reduced to about 0.288 kg coal with a resulting emission of 669 kg CO_2. Overall, for a typical coal power, plant a 1 % increase in efficiency will reduce the coal consumption by 16 x 10^6 kg per year reducing the CO_2 emission by 43 x 10^6 kg per year.

Improving the efficiency of conventional power plants raises a number of significant metrological challenges not only related to the measurement of temperature at higher operational temperature but also to the performance of materials at these higher temperatures as well as energy flow within plants and overall efficiency assessments based on electrical power measurements.

2.1 Objective 1: Temperature Measurement

Thermometers used in power plants or in thermal energy distribution networks are not and cannot be calibrated directly, at the operation conditions (e.g. flow-rates up to 5000 m³/h, temperatures at least 280 °C to above 1500 °C, pressures up to 25 MPa are and will not be realised in any calibration laboratory in the world. The challenge lies in establishing metrologically sound and accepted models of the influence of process conditions on temperature metering with the aim to reduce the uncertainty from 8 K to 3 K. A further important challenge is the development of drift free (<1 K/year) and vibration-resistant temperature sensors for use at these operating temperatures.

For a future hard coal power plant the requirements to the control system will be 5 - 7 % power change within one minute for the secondary load control and up to 10 % within 10 s for the primary control. This requires considerable effort to optimise the positioning, contacting and the dynamic behaviour of the temperature sensors.

[1] Directive 2006/32/EC of the European Parliament and the Council of 5 April 2006 on energy end-use efficiency and energy services, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:114:0064:0064:EN:PDF
[2] Bundesministerium für Wirtschaft und Technologie (BMWi), November 2007, (http://www.bmwi.de/BMWi/Navigation/energie,did=223436.html)
[3] European Commission's Policy on Energy Efficiency, (http://ec.europa.eu/energy/efficiency/index_en.htm)
[4] Federal Ministry for the environment, nature conservation and nuclear safety, Germany, Neues Denken - Neue Energie Roadmap Energiepolitik 2020 (http://www.bmu.de/energieeffizienz/downloads/doc/43103.php)
[5] VGB PowerTech e. V; http://www.vgb.org/fue_projekt297.html

A further aim is an optimised dynamic “two-shifting” behaviour of a power plant in order to compensate for power-grid loads. These grid loads are caused by both consumer behaviour as well as the increasing amount of power generation by renewable energy sources, e.g. wind or solar energy, which makes the power output inevitably dependant on weather conditions.

2.2 Objective 2: Thermophysical Property Measurement

Increasing the steam and gas temperatures requires novel materials with improved durability to thermal load and corrosion. Corrosion resistant and thermal barrier materials are essential for operation at temperatures up to 720 °C and water vapour pressures of about 35 MPa for steam power plants. To increase the efficiency of gas turbines to above 60 % an increase of the typical gas inlet temperature from currently 1300 °C to 1500 °C is necessary, which sets high demands on the thermal barrier protection materials, as this temperature is significantly higher than the melting temperatures of the base material. This requires improved measurement techniques to investigate flue gas corrosion and the high-temperature oxidation behaviour of the most promising Ni-based alloys and predict their behaviour for working lifetimes of at least $2x10^5$ hours. In addition the measurement of emissivity, which governs the radiative heat exchange with the environment, is exceedingly challenging at elevated temperatures.

2.3 Objective 3: Flow measurement

Energy flow normally equates to fluid flow at some point. Energy is generated by steam, transported as hydrocarbon fluid and consumed through heating and cooling fluids. Measurements are required within industry to quantify inefficiencies, measure improvements and to meet regulation. These measurements require to be carried out at extremes of viscosity, temperature, pressure, and on multiphase and multi component mixtures. Conditions are often outside the scope of conventional techniques and sensors. Measurement of energy flow has to encompass novel integration of sensors for flow, temperature, pressure, composition and fluid parameters operating in field and industrial conditions at economic cost.

The lack of precise flow rate measurements currently limits the efficiency of power plants and thermal energy distribution networks. For example, to fulfil safety regulations in nuclear power plants the permitted thermal power output is reduced to a value 2 % below the nominal maximum power to account for the uncertainty of 2 % of the flow rate measurements. Reducing the flow rate measurement uncertainties to 0.5 % would directly enhances the power output by the same amount. Additionally, for all types of power plants the uncertainties in flow rate measurements lead to non-perfect steering and control mechanisms. Recent studies indicate that efficiency enhancement due to optimised control and operation modes based on precise flow rate measurements sum up to an efficiency gain of approximately 2 %.

Flow meters used in power plants or in thermal energy distribution networks are not and cannot be calibrated directly, as the operation conditions (e.g. flow-rates up to 5000 m^3/h, temperatures at least 280 °C to above 700 °C, pressures up to 20 MPa) are and will not be realised in any calibration laboratory in the world. The challenge lies in establishing metrologically sound and accepted models of the influence of process conditions on flow metering with the aim to reduce the uncertainty of flow metering from around 2 % to approx. 0.5 %. To achieve this aim, different flow meters were characterized with uncertainties below 0,3 % at primary measurement facilities of PTB, SP, BEV/PTP and DTI. To investigate viscosity effects and influences of the pipe geometry on the uncertainty of the meters the flow velocity distributions in the meters have to be measured by means of Laser-Doppler-Velocimetry investigations.

2.4 Objective 4: On-site electrical power measurement

A final need relates to the actual determination of the effect of all measures taken to increase the efficiency of power plants via on-site measurements of the electrical power output of the plants, particularly the dynamic measurements necessary to balance variable net load due to the discontinuous nature of renewable energy sources (wind and solar). In the field of the on-site electricity measurements the task was to realise a complete system to perform fast and reliable electrical output measurements of a power plant with low uncertainty (better than 0.1% under laboratory conditions and 0.15 % on-site)

3 Research results

3.1 Results for Objective 1: Temperature measurements

The most important aim of this work package was a better understanding of the contributions influencing the temperature measurement in power plants and the improvements of the used methods. These include both contact thermometers for steam power plants with operation temperatures up to 700 °C and non-contact radiation thermometers for gas power plants and temperatures up to 1500 °C.

Within this project the following significant contributions were identified and analysed:

- Instability of contact thermometers during operation in power plants due to mechanical shock and vibration
- Drift of resistance thermometers due to oxidation and/or contamination of the the sensor
- Influence of parasitic heat exchange with the environment (stem conduction) and dynamical errors of contact thermometers and related calibration uncertainties
- Large measurement uncertainties of radiation thermometers due to insufficient knowledge of the emissivity (details see objective 2) and suitable high-temperature calibration facilities

The results are used to provide recommendations for improved temperature measurements, i.e. design (protection), testing and pre-treatment, characterization, calibration and application of temperature sensors in power plants.

Influence of vibrations and sensor characterization

Measurement of vibration loads were carried out at different steam power plants in the Czech Republic, Finland and Germany Fig. 1.

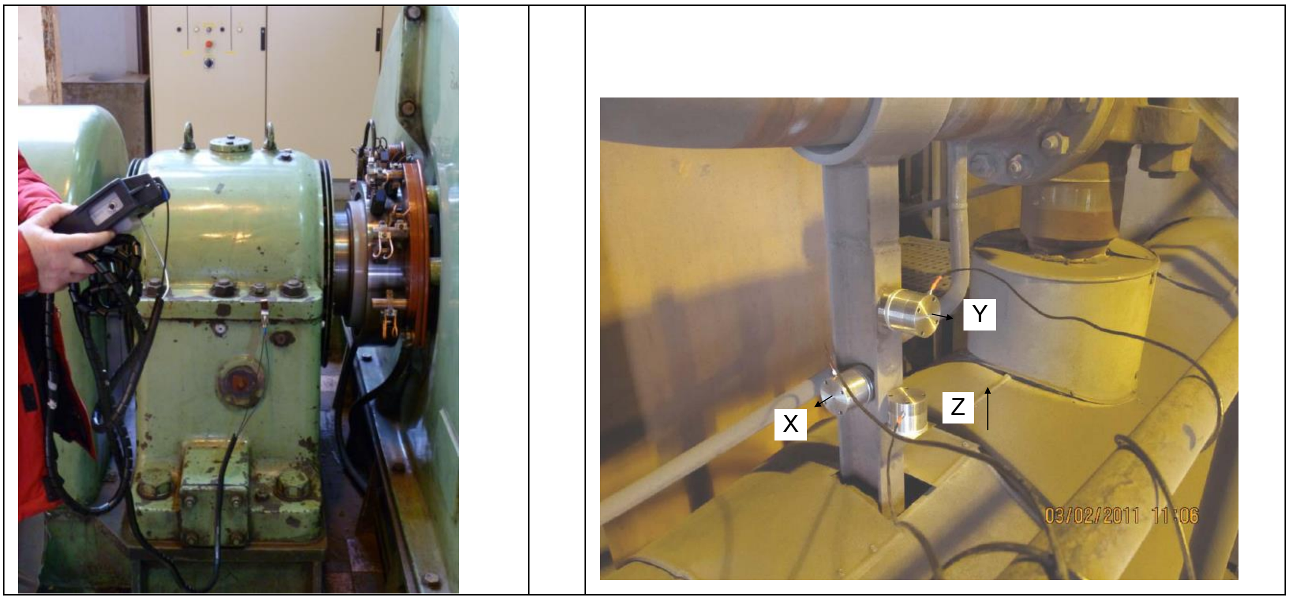
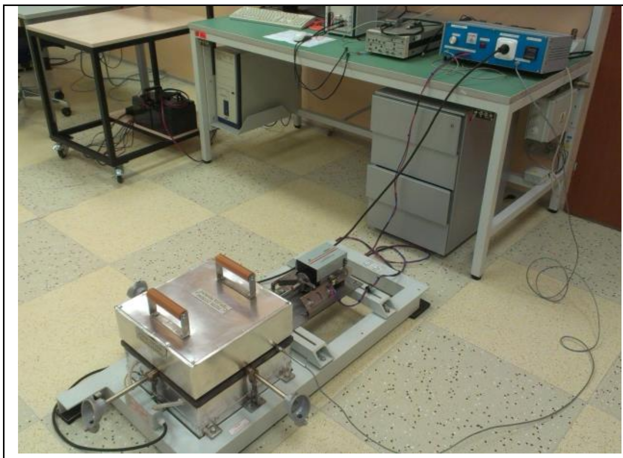


Fig. 1: Measurement setups for vibration loads at a steam power plant in the Czech Republic (left) and in Finland (right)

The evaluation of the investigations showed that the measured vibration loads to the thermometers in the investigated power plants were below 10 m/s^2 in the frequency range between 1 Hz and 1000 Hz.

So far vibration load measurements of industrial thermometers were carried out according to IEC 60751:2009 at room temperature in the frequency range from 10 Hz to 500 Hz. Within this project a new setup was developed at CMI (Fig. 2) which allows vibration loads up to 40 m/s² (in longitudinal and lateral direction) in the frequency range between 10 Hz and 2000 Hz and temperatures up to 700 °C.



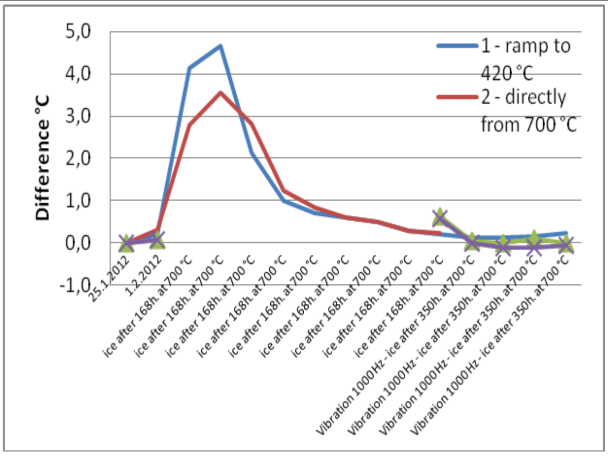


Fig. 2: Measurement setup for high-temperature (700 °C) vibration load measurements developed at CMI and results of investigations for an accelerated sensor stabilization

This setup was successfully used for combined temperature and vibration tests of prototypes of improved resistance thermometers for power plants. Co-operations with different manufacturers of industrial thermometers for further investigations started in 2013. A new type of resistance thermometer for application in steam power plants was investigated by means of this setup. It's stability under vibration load was validated for temperatures up to 700 °C (figure 2).

At MIKES (Finland) two experimental setups based on a vertical cesium heat-pipe furnace and a horizontal sodium heat pipe furnace were developed. These were used to calibrate industrial grade thermometers in the temperature range between 200 °C and 700 °C and to carry out various thermal tests such as immersion measurements, thermal cycling (hysteresis) and the investigation of the dynamic behavior. From the results recommendations for the proper choice of the thermometer characteristics were derived. It was shown that depending on the type of the resistance thermometer (e.g. wire wound or thin film) different characteristics should be used.

The following investigations were carried out at PTB:

- High-temperature contamination of thin-film sensors by surrounding materials used in thermometers by means of an XRF analysis of the Pt-film and the ceramic substrate
- Oxidation of platinum and reduction of PtO_2, by means of Simultaneous Thermal Analysis (STA)
- Ageing experiments in order to study the influence of temperature and applied current on the stabilization time of platinum thin-film sensors

Contamination of platinum thin-film sensors

The contamination of the platinum sensor of resistance thermometers by impurities is considered as the most important source of drift and measurement uncertainty for temperatures above 400 °C. In order to develop suitable solutions to protect the sensor the source and species of impurities have to be identified. In a first series of investigations uncoated platinum thin-film sensors were exposed to a high-temperature ageing process (72 hours at 700 °C) in air and in MgO-powder which is the common filling and insulation material for industrial resistance thermometers.

The characterization of the sensors was carried out by two different methods. The first one was a thermometric method by the quantification of changes in the sensor characteristics. To identify species causing the contamination of the platinum X-ray fluorescence investigations were performed out at the sensors before and after the ageing process (figure 3). These investigations were carried out at the electron storage ring BESSY II.

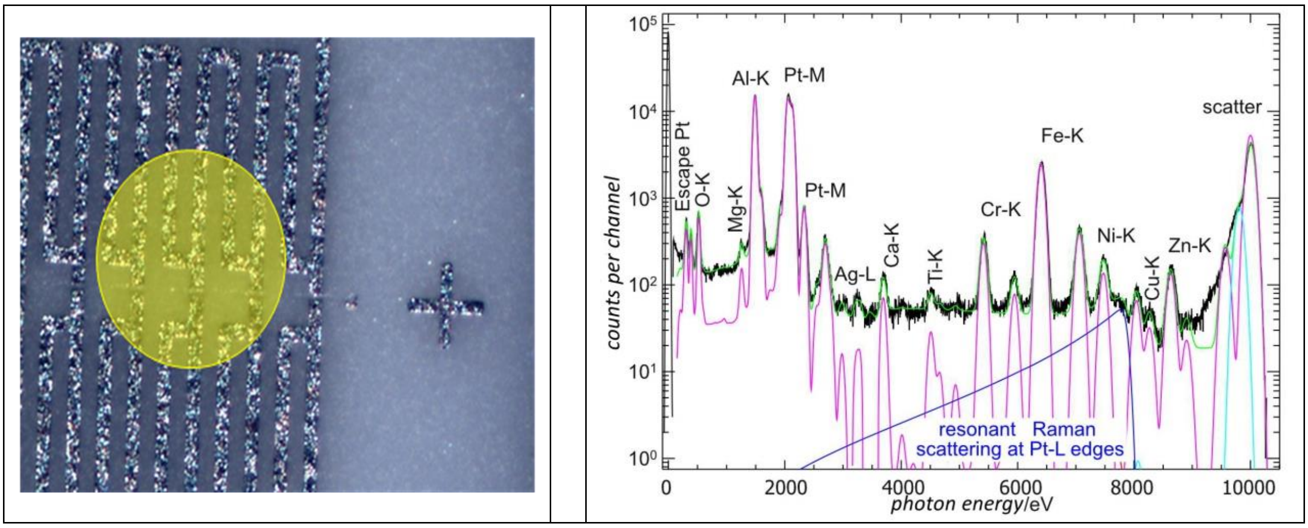


Fig. 3: left: Microscope image of the thin-film sensor with XRF measurement section (yellow circle) and right: typical XRF spectrum

The sensors which were aged in MgO powder showed a large drift of both the sensor resistance at the ice point (up to 3 K) and of its temperature coefficient. In contrast the sensors which were aged in air showed a considerably smaller drift (<0.7 K). By means of the XRF-analysis Si, Ca, K, Ti, Zn, Cu, Fe, Cr and Ni were found as impurities in the ceramic substrate of the sensors. Silicon, Ca, K, Ti and Zn are common impurities in alumina, because of their use in the sintering process. Iron, Cr, Ni, Cu, Mg and Ag were identified as impurities in the Pt strip line of the sensors. The presence of Fe, Cr, Ni, Cu in the substrate as well as in the film complicated the quantification of weight percentages of the impurity content. The determination of the mass occupancy implies that Mg was the largest impurity in the sensors and Ag is the second biggest impurity. Mg is not only the largest impurity in sensors aged in MgO powder, it's also dominant in those sensors which were aged in air.

Oxidation of platinum and reduction of PtO_2

The oxidation of platinum and the reduction of PtO2 as a function of temperature and oxygen partial pressure is a further important influencing quantity for the stability and interpolation uncertainty of platinum resistance thermometers in the temperature range between 100 °C and 600 °C. Due to the large surface to volume ratio of thin-film sensors surface oxidation does have a considerable larger effect, compared with wire-wound sensors.

Therefore, at PTB simultaneous thermal analysis and mass spectrometry measurents were carried out on PtO_2 (figure 4).

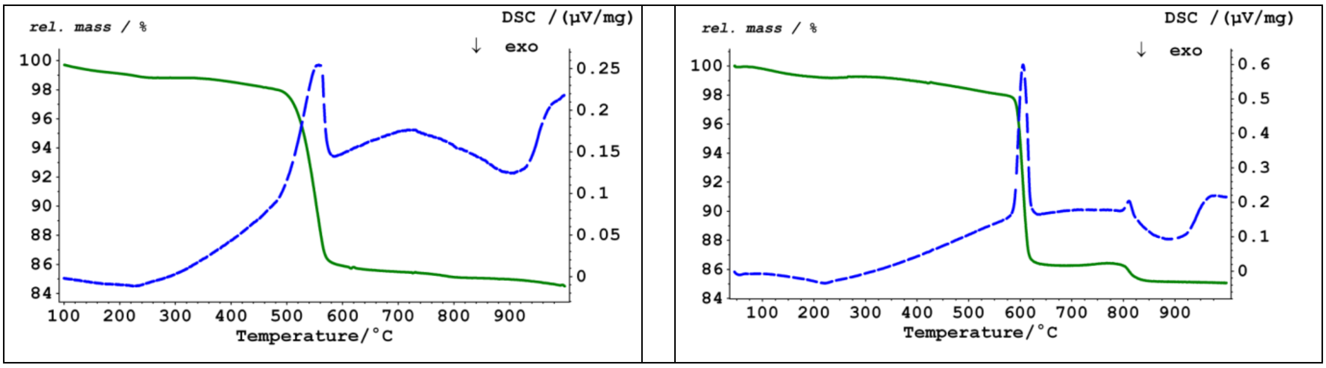


Fig. 4: Thermogravimetric (relative mass; green solid line) and differential scanning calorimetry signal (DSC, blue broken curve) of PtO_2 from 100 °C to 1000 °C , left in helium atmosphere, right in synthetic air.

The experiments on the reduction of PtO_2 were conducted in different atmospheres, in order to investigate the dependence on the partial pressure of oxygen. The main decomposition of the PtO_2 starts at the decomposition temperature T_D = 595 °C in synthetic air, i.e. a water free nitrogen oxygen mixture. In helium atmosphere the decomposition shifts to T_D = 490 °C. This strong oxygen dependency of the stability of PtO_2 is of special interest as the temperature region above 450 °C is known to be causing problems in industrial temperature measurement utilising resistance thermometers, especially when thin film sensors are being used.

Furthermore it was shown that in contrast to the current knowledge of the processes in Standard Platinum Resistance Thermometers a further oxidation is still present after the decomposition of PtO_2. This is evidenced by another decomposition process above T_D in synthetic air. There is a small mass increase (0.2 %) above 600 °C observed with thermogravimetry followed by a bigger mass (1.2 %) loss at 800 °C. In helium atmosphere this oxidation is strongly suppressed, but a small decomposition is still present at approx. 800 °C. This is interpreted as an incomplete decomposition at T_D so that another form of platinum oxide remains.

Influence of temperature and applied current on the stabilization time of platinum thin-film sensors

For any resistance thermometer an initial pre-treatment is required in order to achieve sufficient stability of its resistance vs. temperature relationship. Depending on the temperature range, type of sensor and specific aspects of the thermometer construction different ageing (pre-treatment) procedures are in use. For vibration resistant thin-film based thermometers there is insufficient knowledge about suitable methods to achieve the best possible stabilization. Therefore a series of measurements was carried out to investigate the influence of a current (range from 1 mA to 10 mA) during the thermal pre-treatment of thin-film based resistance thermometers.

After an initial characterisation at the ice point (0 °C) and at 200 °C, 400 °C and 600 °C, the thermometers were aged for one week at 600 °C. To check the long term influence of the measurement current during the normal operation of a thermometer in a power plant some of the thermometers were aged with an applied current of 1 mA another set was aged without a current. A current of 1 mA is a typical for the operation of 100 Ohm resistance thermometers. To test the dependency of the stability of the thermometer on the current two other sets were aged with an applied current of 3.16 mA and 10 mA.

The results of the ageing experiments showed that the current had a considerable effect on the stability of the thermometers. Sensors without any current applied drifted by the smallest values, but they didn't stabilise over a time of three weeks. On the other hand the sensors with an operation current of 1 mA stabilized after two weeks of ageing, but drifted after one week of ageing by about 1 °C (at 0 °C). Applying a higher current is clearly stressing the film and the thermometers which were aged with 3.16 mA didn't stabilise and drifted by more than 5 °C. The sensors with an applied current of 10 mA though showed a different behaviour. One sensor drifted after one week of ageing by more than 7 °C, but recovered over time to a drift of less than

2 °C compared to its initial ice point value. While this thermometer recovered, two others started to drift again by more than 7 °C and two others drifted only by approx. 2 °C. These findings point to electromigration being another process involved in the drift of thermometers.

Summarizing, a small current of 1 mA during ageing leads to a stabilisation of the thermometer after an initial drift, while an intermediate current of 3.16 mA leads to no stabilisation or recovery of the thermometer. For a stable operation of a platinum resistance thermometer it seems therefore advisable to either stress it during ageing with a low current or with a high current. When the processes during this stressing are better understood the latter is interesting, because the initial drift is recovered and all damaging and recovery effects seem to be accelerated compared to the low current stressing.

Radiation temperature measures up to 1500 °C
Over the last 15 years high-temperature fixed points have become metrological tools that allow to improve and test the realization and dissemination of the temperature scale. While the temperature scale itself is defined and realized using a number and dedicated measurement techniques, above the freezing temperature of Cu 1084.6 °C the currently valid international temperature scale of 1990 (ITS-90) is defined by extrapolation using a ratio measurement based on Plancks law of thermal radiation. For a primary realization this is connected with an increasing measurement uncertainty towards higher temperatures. A solution was found around 15 years ago in the development of high-temperature fixed-points based on metal-carbon eutectic alloys. These artefacts have been intensively investigated and are nowadays technologically advanced tools for NMI level calibration labs. However up to now, their acceptance is limited to laboratories equipped with expensive high-temperature furnaces, optimized for the operation as a fixed-point furnace.

For this reason, two high-temperature fixed points were manufactured by PTB for KE Technologie GmbH, a SME and manufacturer of radiation thermometers that has also been involved in the calibration of radiation thermometers for more than two decades.

A dedicated high- temperature fixed point cell was developed for the high-temperature furnace available at KE Technologie GmbH. The high temperature furnace used in the calibration laboratory of KE Technologie GmbH is equipped with a graphite heater tube of 20 mm inner diameter. As the rear side of the heater is formed into a conical bottom, the heater itself forms a radiating cavity of high emissivity. For this cavity an only 19 mm outer diameter fixed point cell was developed. The cell design is depicted in figure. 5.

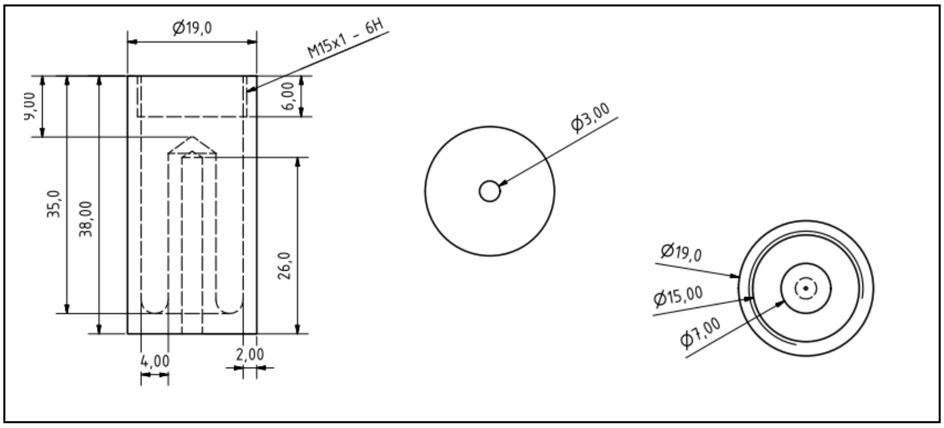


Fig. 5: Schematics of the fixed point design

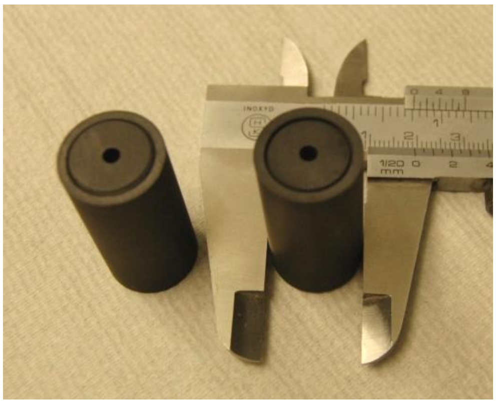


Fig. 6: A Cu and a Fe-C high-temperature fixed point cell were manufactured.

The dedicated fixed-point cells were installed into the furnace at a position ca. 20 mm to the furnace bottom, without wrapping the cells additionally into graphite paper or graphite felt. The furnace was heated by directional changing the power setting without additional temperature control. A KE radiation thermometerLP5 was aligned to the HTFP cell opening and measured the radiation of the fixed point cell through a quartz window. The radiation temperatures given below have not been corrected for the influence of the quartz window. Figure 7 shows the high-temperature and the radiation thermometer LP5.

Fig. 7: Calibration laboratory of KE Technologie GmbH with KE high temperature blackbody furnace and KE radiation thermometer LP5

A typical melt freeze diagram for Cu is depicted in figure 8. For an furnace offset of around +/- 20 K relative to the materials melting and freezing temperature a freezing plateau of around 15 min duration was observed.

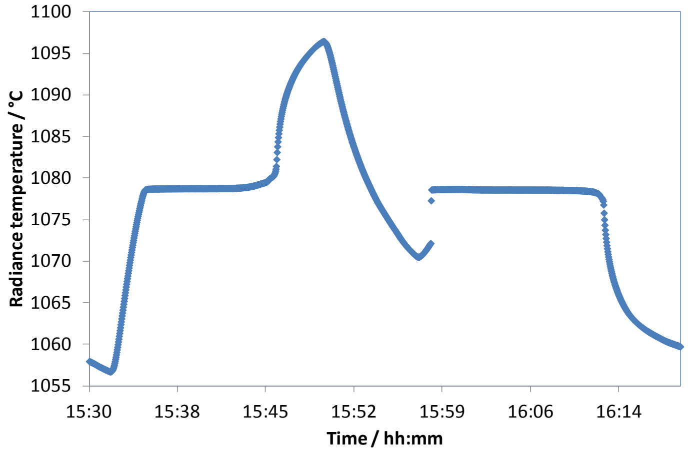


Fig. 8: Overview of the melt/freeze plateaus for the Cu HTFP cell

The observed freezing plateau is stable to within 200 mK during 15 min (figure 9). The slight in the freeze plateau origins in a change of furnace settings during the freeze by the operator.

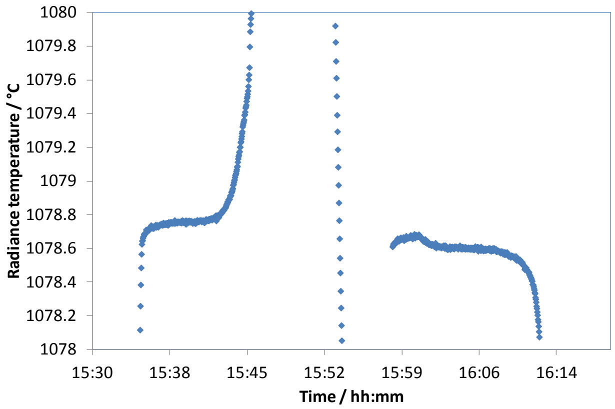


Fig. 9: Detail of the melt/freeze plateaus for the Cu HTFP cell

A typical melt freeze diagram for Fe-C is depicted in figure 10. For a furnace offset of around +20 K / -25 K relative to the materials melting and freezing temperature a melting plateau of around 10 min duration was observed.

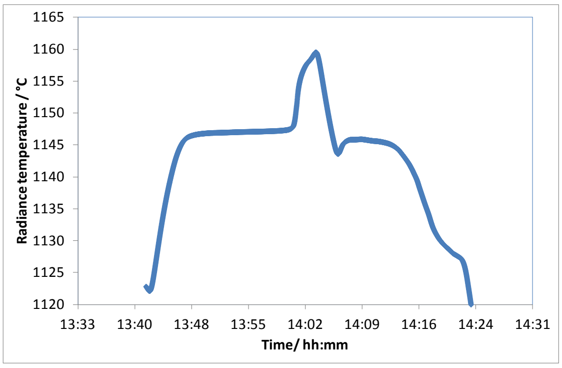


Fig. 10: Overview of the melt/freeze plateaus for the Fe-C HTFP cell

The observed freezing plateau is stable to within 200 mK during 10 min (figure 11).

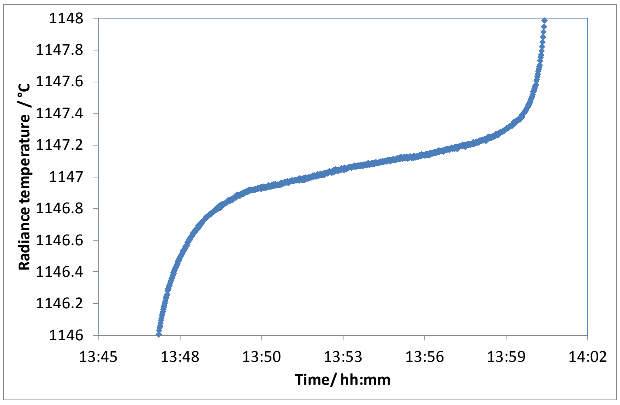


Fig. 11: Detail of the melt/freeze plateaus for the Fe-C HTFP cell

Compared to the standard well characterized laboratory furnaces available at NMIs the available industrial furnace differs largely in terms of inner cavity dimensions and temperature uniformity. Here, it could be demonstrated that it is possible to establish a high temperature fixed-point cell under the non-ideal conditions of an industrial environment to test and evaluate the stability of high-temperature radiation thermometers using dedicated high-temperature fixed-points.

To summarize the work, In the field of temperature measurements, resistance thermometers for use in power plants were developed, which solved problems of platinum poisoning and vibration loads.

3.2 Results for Objective 2: Thermophysical properties

The second area of interest concerns research on thermophysical properties of high performance materials as they are used in turbines of gas power plants. The task was to develop and improve accurate reference facilities and methods for the measurement of thermal properties (thermal diffusivity, emissivity and specific heat) of homogeneous solid materials and Thermal Barrier Coatings (TBCs) at high temperature.

Two complementary facilities based on different metrological approaches (calorimetric and radiometric methods) for the measurement of normal spectral emissivity of solid materials up to 1500 °C, as well as a very high temperature diffusivimeter have been developed for this project. Methods and calorimeters for the measurement of specific heat up to 1500 °C have also been improved.

The directional spectral emissivity $\varepsilon_\lambda(\lambda,T)$, at wavelength λ and temperature T is a dimensionless quantity, and is for a thermally radiating specimen defined as the ratio of the spectral radiance $L_{\lambda,\mathrm{Specimen}}$ of the specimen in a particular direction to the spectral radiance of an ideal blackbody $L_{\lambda,\mathrm{BB}}$ at the same temperature T:

$$\varepsilon_\lambda(\lambda,T)=\frac{L_{\lambda,\mathrm{Specimen}}(\lambda,T)}{L_{\lambda,\mathrm{BB}}(\lambda,T)} \quad (1)$$

The measurement capabilities of the existing setups in these NMIs were limited respectively to 850 °C for LNE and 500 °C for PTB at the start of the project, and new ones were therefore developed for enabling spectral emissivity measurements of solid materials up to 1500 °C.

The method selected by PTB is based on a dynamic emissivity measurement using an adaptation of the laser flash technique Its principle is given by the following relation, which states that the energy absorbed by the specimen (left hand term of equation 2) causes an increase of its internal energy (right side of equation 2).

$$\varepsilon_{\lambda}(\lambda,T)\cdot E_{\lambda}=m\cdot c_{p}(T)\cdot\Delta T(T) \qquad (2)$$

If the specific heat $c_p(T)$ and the mass m of the specimen are known then its spectral emissivity $\varepsilon_\lambda(\lambda,T)$ can be determined by measuring the energy E_λ deposited by the laser pulse on its front face, and its increase of temperature ΔT. Figure 2 shows a general scheme of the apparatus (called AD□M) used by PTB for the dynamic emissivity measurement. It is based on a commercial laser-flash apparatus *Netzsch* LFA 427, which has been greatly modified to measure both the laser pulse energy and the resulting temperature rise.

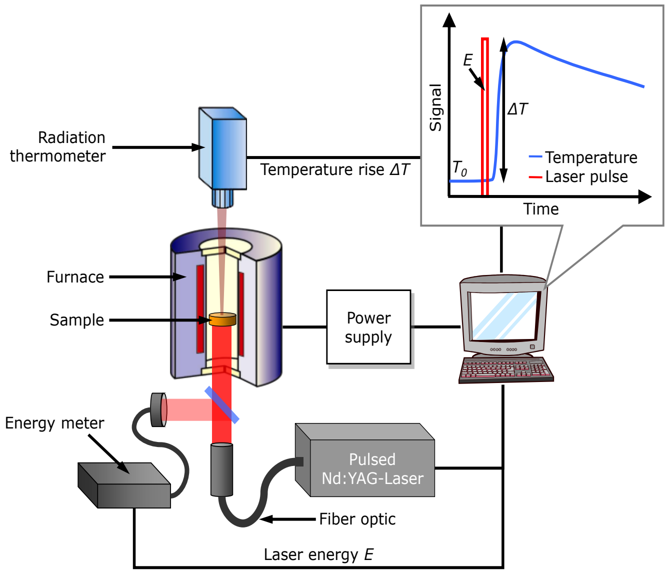


Fig. 12: Schematic of the reference apparatus of PTB for the dynamic emissivity measurement (ADεM).

It basically consists of a pulsed Nd:YAG laser (1064 nm), a high temperature resistive furnace that contains the specimen, and a radiation thermometer. The laser fires single pulses with a tunable pulse energy of approx. 1 J to 15 J and a duration between 0.3 ms to 1.2 ms. The absolute value of the temperature rise ΔT at the rear face of the specimen is measured by a calibrated fast response radiation thermometer LP5HS, having a narrow bandwith spectral responsivity at the wavelength of the laser pulse and with a temporal resolution of 1 ms. The surface temperature sensed by the radiation thermometer is corrected for the influence of the hot surrounding furnace (cavity effect). The laser beam was characterized in respect to its spatial energy distribution because this parameter critically affects the measured temperature rise. The absolute energy E_λ of the incident laser radiation is measured via a beam splitter, which reflects a part of the laser pulse (around 3 %) toward a calibrated laser energy meter.

LNE designed a new optical facility for measuring the directional spectral emissivity of solid materials up to 1500 °C in the spectral range from 0.8 µm to 10 µm with a spectral resolution of 1 cm^{-1}. The general principle of the technique is directly based on the definition of directional spectral emissivity (cf. equation 1), i.e. a comparison of the spectral radiance of the specimen at a temperature T to that of a reference blackbody at the same temperature.

Figure 13 shows a schematic diagram of the LNE facility. The specimen (typically a disc of 25 mm in diameter and 10 mm thickness) is located in a vacuum chamber with a controlled atmosphere to avoid oxidation at high temperature. It is heated by a lamp image furnace constituted of a set of seven halogen lamps of 400 W, equipped each with an ellipsoidal mirror that focuses radiation on the rear side of the specimen. The reference blackbody is equipped with a silicon carbide cavity that can be used in a large spectral range from 0.8 µm up to 10 µm. Silicon carbide was selected for its ability to be heated in air up to 1500 °C, its high thermal conductivity and its high spectral emissivity (above 0.8) for wavelengths below 10 µm. Spectral emissivity of silicone carbide decreases dramatically above 10 µm, thus the spectral range is limited below 10 µm. The temperature of the blackbody is measured with a type S thermocouple or a pyrometer. A blackbody at room temperature is also used for the correction of background radiation.

The spectral radiances of the specimen and of the blackbodies are measured with a Fourier transform infrared spectrometer (Vertex 70 manufactured by Bruker) in the wavelength range 0.85 µm to 10 µm. An optical system is used to collect the radiation emitted by the blackbodies or specimen by keeping constant the measurement spot size and the numerical aperture. Blackbodies and specimen heating system move laterally, in order to be positioned in front of the radiation measurement system (spectrometer and optical system) that is maintained in a fixed position in order to avoid any variation of sensitivity.

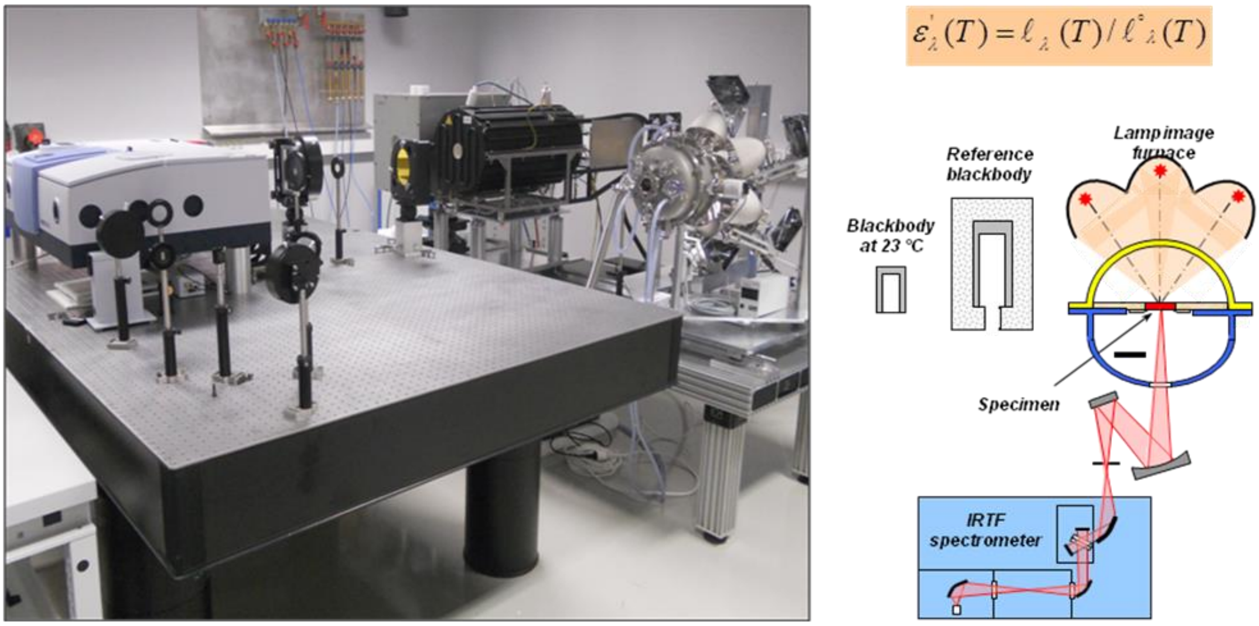


Fig.13: Photograph and schematic diagram of the new metrological facility of LNE for the measurement of directional spectral emissivity at high temperature.

The chamber has a quartz hemispherical dome transparent to the radiation of the lamps. Radiance measurements on the front face of the specimen are made through a CaF_2 or a ZnSe window depending on the wavelength range. The walls of the chamber are water cooled and coated with high emissivity paint in order to control the background radiation on the front face of the specimen. A thermostated movable shutter limits the heating of the window during the measurements of the spectral radiances of the blackbodies. The surface temperature of the specimen can be measured either by contact thermometry or bichromatic radiation thermometry.

The above described setups have been validated at high temperature by measuring normal spectral emissivity of an isostatic graphite grade R6650P5 from *SGL Carbon group.* Figure 14 shows the agreement between results of PTB and LNE for a broad wavelength range between 1064 nm to 3500 nm at a temperature of 1250 °C.

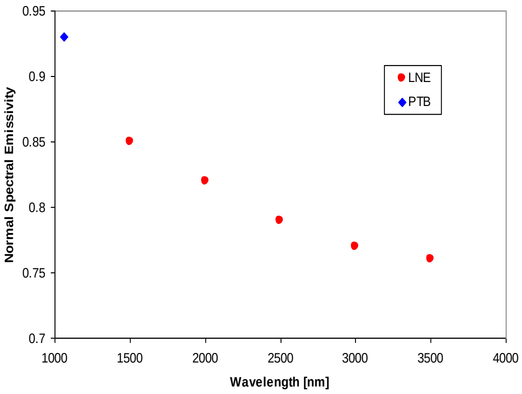


Fig. 141 : Consistency of the results obtained by PTB and LNE at 1250 °C for different wavelengths (1064 nm for PTB, from 1500 nm to 3500 nm for LNE) for graphite

Besides the importance of spectral emissivity for precise temperature measurement, thermal diffusivity at high temperatures is a crucial material parameter for development and optimization of the super alloys used in modern power plant technology.

LNE has used for many years a homemade diffusivimeter based on the principle of the laser-flash method. A cylindrical specimen is heated on its front face by a short energy pulse, and the induced transient temperature rise on its rear face is measured versus time. The thermal diffusivity is determined with an estimation procedure based on minimizing the difference between the experimental temperature-time curve and the same curve given by a theoretical model. This versatile reference apparatus was used for example in the certification process of Pyroceram 9606 as BCR-724 reference material, in the first international interlaboratory comparison on thermal diffusivity measurements organized by the Bureau International des Poids et Mesures (BIPM), or for the characterization of the thermal diffusivity of thick coatings up to 800 °C.

Using a resistive furnace, the maximum operating temperature of this facility is limited to 1400 °C. The facility has been strongly modified to enable measurement of thermal diffusivity of solid materials up to 2000 °C under inert atmosphere (argon or helium). Figure 15 shows a scheme of the new configuration of this apparatus. An inductive furnace equipped with two CaF_2 windows has been designed and fitted to this diffusivimeter.

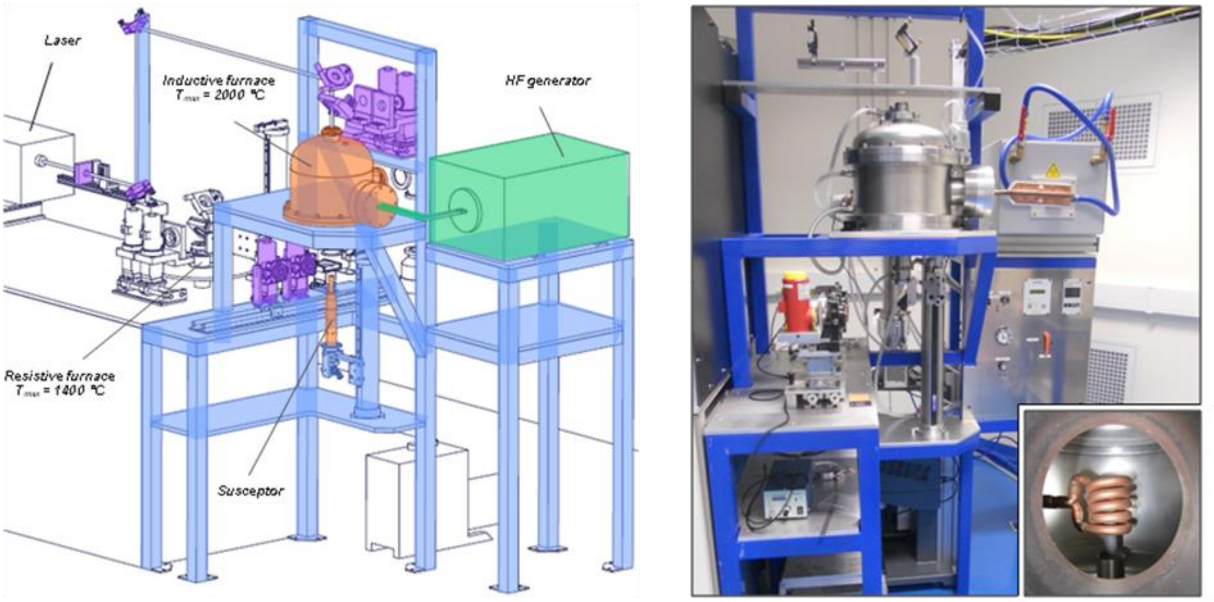


Fig. 15: Scheme of the new high temperature diffusivimeter of LNE.

It consists of an airtight enclosure cooled by water in the centre of which a copper inductive coil (connected to a 50 kW high frequency generator) and a movable graphite sample holder are placed on a vertical axis. The specimen, which is a disk of 10 mm in diameter and 1 mm to 5 mm thick, is placed at mid-height inside the sample holder. Its steady state temperature before the pulse is measured with an infrared bi-chromatic pyrometer (0.90 µm and 1.05 µm). The energy pulse is generated by a Nd:phosphate glass laser at 1054 nm wavelength, whose beam is formed by a set of lenses and mirrors so that its diameter is about 10 mm on the front face of the specimen. The transient temperature rise of the specimen rear face is measured with infrared detectors (InGaAs and HgCdTe). An optical system made of lenses is associated to each IR detector in order to collect the infrared radiation emitted by the specimen.

These new metrological setups have been validated at high temperature by measuring the thermal diffusivity and normal spectral emissivity of an isostatic graphite grade R6650P5 from *SGL Carbon group* and used for the measurement of thermophysical properties of Ni base alloys such as Nimonic 101.

The thermal diffusivity results obtained with the new diffusivimeter have been compared with the measurements performed by LNE with its current reference bench.
The relative expanded uncertainty (k=2) on thermal-diffusivity measurements of homogeneous materials with this facility has been estimated to be between 3 % and 6 % over the temperature range 23 °C to 1400 °C , depending on the material and the temperature level. Thermal diffusivity was also measured by NPL and PTB with commercial apparatus (**LFA** 427 laser flash system). The obtained results for isostatic graphite and Nimonic 101 are presented in Figure 16 and Figure 17.

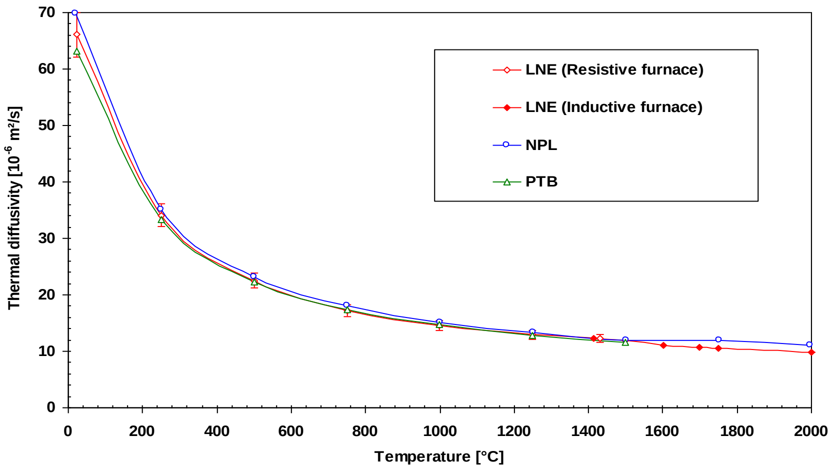


Fig. 16: Thermal diffusivity of isostatic graphite measured at LNE (with different heating systems), NPL and PTB

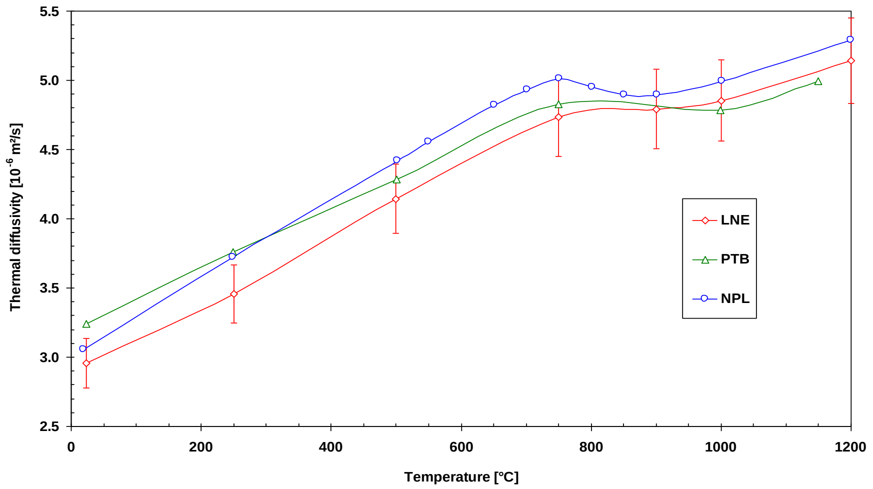


Fig. 17: Thermal diffusivity of Ni base alloy Nimonic 101

To summarize the work enabled to increase the capabilities of European NMIs for the measurement of high temperature thermophysical properties of refractory alloys and ceramic coatings. Before the beginning of this project, there were no possibility of ensuring the traceability to the SI of these types of measurement above 800 °C. The facilities that were developed in the framework of this project are enabling to perform these measurements up to 1500 °C. The facilities were used for characterization measurements on Ni-base alloys and TBCs. These metrological developments will therefore allow to better characterise the thermal properties of new high performance materials used in gas turbines, in order to increase efficiency of fossil fuel power plants.

3.3 Results for Objective 3: Flow measurements

Main issue of the research concerning flow measurements in power plants was to build up extrapolation models for different commonly used flow sensors in order to account for the fact, that there exist no facilities to calibrate the flow sensors at the high temperatures, flow rates and pressures that occur in power plants. The developed extrapolation models could be proven experimentally to be metrologically valid and allow for a reduction of the uncertainty of flow rate measurements from approx. 2 % to 0,5 %. Especially the separation of effects due to temperature and flow profiles will result in improved parameter sets of the flow meters and will lead to smaller measurement uncertainties. This is an important feature to optimize the process control of power plants with direct and high impact for the energy efficiency of power plants.

The extrapolation model for the ultrasound meter

The new 10-beam ultrasound flow meter already has a correction function implemented in the flow computer. The meters raw data of the measured flow velocity w_{RAW} is corrected in dependence of pressure *p*, temperature *T* and Reynolds number *Re* to determine the volume flow rate q_v. The refined equation has the following form

$$q_V = k_m \cdot k_h(Re) \cdot k_t(T) \cdot k_p(p) \cdot w_{RAW} + Q_0(Re) \qquad (3)$$

The first term, the meter constant k_m is independent of *p*, *T* and *Re* and is generally determined by calibration. It also includes geometrical parameters such as the internal cross-section and path angles that cannot easily be determined by other methods with sufficient accuracy. The hydraulic correction term k_h was determined in advance by a factory calibration at 20 °C and was later updated based on the available calibration results at PTB. In the refined model the initial hydraulic correction k_h was therefore not used in the measurement campaign but the updated correction was applied a posteriori. For the thermal expansion constant k_t a linear expansion model including a linear expansion coefficient was used. The pressure expansion factor k_p was not used in this study since a low and constant pressure of 0.2 MPa was provided during all measurements. In addition to these already known parameters it was found necessary to also include an offset term $Q_0(Re)$ in the correction, because the UFM exhibited a clear flow velocity dependency. This behaviour led to a spread of measured deviations at fixed Reynolds numbers and different temperatures and flow velocities. $Q_0(Re)$ was determined by a least squares method based on reducing the spread of the measured deviations at the fixed Reynolds numbers. The measurements of the UFM include 5 Reynolds numbers and 8 temperatures between 10 and 80 °C. As shown in figure 12 the resulting deviations after applying all corrections vary about ±0.05 % for all Reynolds numbers. This result implies that the systematic effects are well covered by the presented refined correction function given in equation (3).

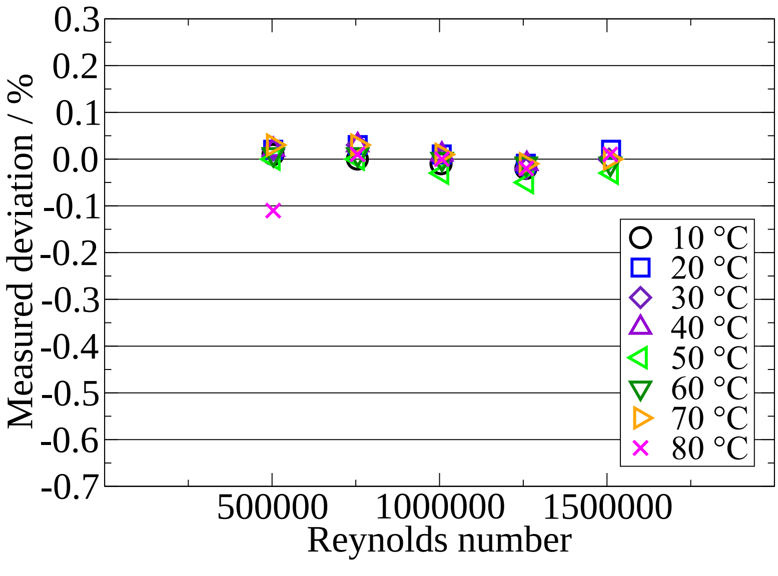


Fig. 18: Measured deviation of the UFM in dependence of Reynolds number at different temperatures after applying equation (1)

For very high Reynolds numbers it is expected that $Q_0(Re)$ and $k_h(Re)$ converge to an asymptotic value. The measured values of $Q_0(Re) = 0.335\ m^3h^{-1}$ and $k_h(Re) = 0.9964$ at Re = 1.5 x 10^6 are therefore used for all high Reynolds numbers, e.g. for Re = 6 x 10^6 at the new high temperature flow rig at PTB.

The extrapolation model for the magnetic induction meter
In the electromagnetic flow measurement an electrical voltage *U* is generated due to the interaction of the velocity w_{vol} of a fluid with a magnetic field *B*. In this case the average flow-rate is proportional to the electrical voltage tapped between the electrodes. For a rotationally symmetric velocity profile and an infinitely long homogeneous magnetic field the measuring principle of an EMF is given by the following equation:

$$U = k_m \cdot B \cdot D \cdot w_{vol} \qquad (4)$$

Since the volume flow rate q_v is the product of the volumetric flow rate w_{vol} and the cross-sectional area *A* the equation results in:

$$q_v = \frac{\pi \cdot D}{4 \cdot k_m \cdot B} \cdot U \qquad \text{with: } 0.8 \le k_m \le 1.0. \qquad (5)$$

The values of diameter *D* and $k_m \cdot B$ for the reduced measuring sensitivity are implemented in the electronics of the flow meter by the manufacturer. In general also temperature dependencies, e.g. of diameter *D(T)* are mostly implemented. But it is impossible to have access to the raw data since these are corporate secrets.
Therefore the magnetic inductive meter has been calibrated in terms of the Reynolds numbers corresponding to 5 flow rates and 9 temperatures between 11 and 85 °C. It could earlier be shown that the measurement deviation is a linear function of the temperature. This means this meter has more or less no compensation for temperature effects. This is very clearly demonstrated in figure 19.

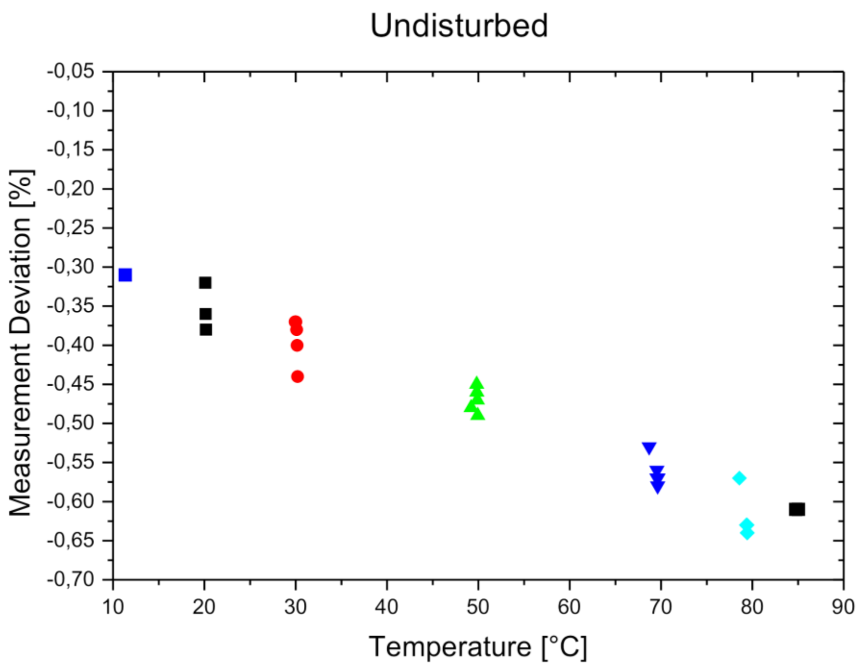


Fig. 19: Measurement deviation of the MID in direct dependence of the temperature for all performed flow rates.

As best refined model for the temperature dependency used for extrapolation to high Reynolds numbers in order to predict a measurement error at temperatures exceeding 200 °C the following equation was obtained:
Refined model undisturbed flow: $E[\%] = -0.37598 - 3.45812 \times 10^{-9} \times Re$ (6)

The effect of the implementing this as temperature correction to the original measurement data (undisturbed case) is demonstrated in figure 19, where the variation in measurement error can be suppressed to lie within a small range of around ±0.05 % with an offset of about -0.37 %. The result is almost the same for the disturbed case. The investigated meter innately has a conical reduction of the measuring cross-section to provide rotationally symmetric velocity profiles nearly independent from the upstream condition.

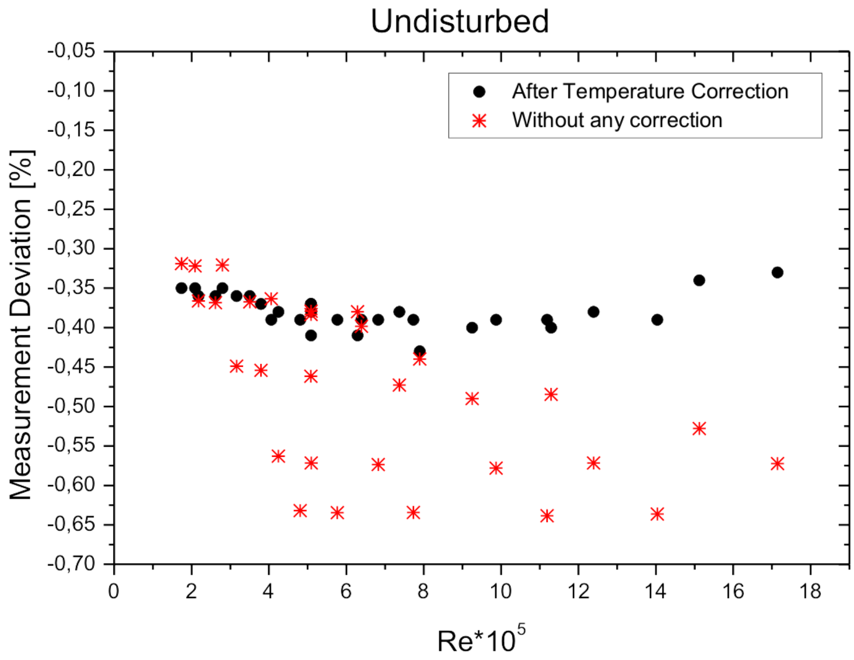


Fig. 20: Measurement deviation of the EMF in dependence of Reynolds number at different temperatures before and after temperature correction.

The extrapolation model for the Venturi tube

The measurement principle for the Venturi tube, as for all other differential pressure flow meters, follows from the continuity equation (law of the conservation of mass) and from Bernoulli´s equation. The final measurement equation deduced from these relates the interesting mass flow q_m to the square rot of the pressure difference dp according to ISO standard 5167

$$q_m = C \cdot \frac{d_o^2 \cdot \pi \cdot \varepsilon}{4 \cdot \sqrt{1-\beta^2}} \cdot \sqrt{2 \cdot \rho \cdot dp} \qquad (7)$$

For an incompressible medium □=1. The deduction implies the introduction of an additional factor C relating the actual operating flow rate to the theoretical ideal case, e.g. frictionless flow rate from Bernoulli's equation. For the classical Venturi tube the value of this flow rate coefficient C also known as discharge coefficient is close to a value of 1.0, but it is not a complete constant.

The calibration of the used classical Venturi tube flow meter with a machined convergent section included 8 temperatures and a number of different flow rates. The resulting discharge coefficient showed a slight linear dependency with Reynolds number. All measuring results were mainly within the uncertainty limits stated by the standard. In the undisturbed case the discharge coefficient exceeded the value of one. With a disturber in front in form of an asymmetric swirl generator a slightly lower discharge coefficient was measured providing less spread.

In the refined form after having removed data of higher uncertainty the extrapolation to the higher Reynolds numbers found is given by the fitting equation (8) for the undisturbed and (9) for the disturbed case.

Refined model undisturbed: C = 1.0016 + 2.940 x 10^{-9} (8)

Refined model disturbed: C = 0.9970 + 1,059 x 10^{-9} (9)

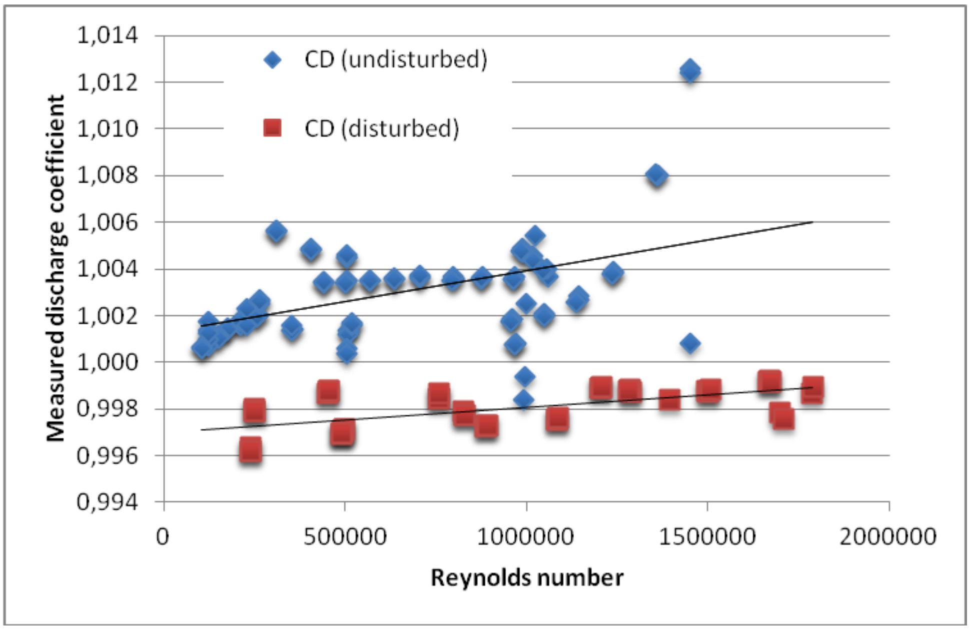


Fig. 21: The calibration data of the discharge coefficient for a classical Venturi tube at 8 temperatures and several flow rates with and without a disturber upstream fitted with a linear model.

The extrapolation model for the orifice plate

The principle relation between the measured differential pressure *dp* and the interesting mass flow rate q_m is given by the general equation.
In words the flow rate changes with the square of the throat diameter d_o of the constriction and the square root of the measured differential pressure. The temperature dependence of diameter d_o and that of the of the fluid density □□are generally well known and can be compensated for. For liquids the expansibility factor is a constant □ = 1 and can be neglected. As long as the pipe and the orifice are made of the same material, which is most common, the relation $\beta = \mathrm{d_o}/\mathrm{D}$ between the throat d_o and pipe diameter *D* is not explicitly temperature dependent.
For a temperature extrapolation the interesting parameter is the discharge coefficient C that is a function of Reynolds number. Thus C is indirectly temperature dependent via the viscosity of the medium.

$$Re_D = \frac{4 \cdot q_m}{\pi \cdot D(T) \cdot \mu(T)} \qquad (10)$$

The outcome of the calibration i.e. the discharge coefficient as a function of Reynolds number determined at 5 temperatures under undisturbed flow conditions was discussed in deliverable report D3.2.
Within the measured flow range the fitted curve follows reasonably the expected dependency given by the Reader-Harris Gallagher equation. There is a variable offset of roughly 0.3 to 0.4 %, which is within the accepted uncertainty of 0.5 % of the RHG-equation. The first applied best fit found used a linear term.

$$C = m_1 + m_2 \cdot Re_D^{-0.5} + m_3 \cdot Re_D \qquad (11)$$

At very large Reynolds numbers, that in practice cannot be reached because of cavitation, the linear term would give too low values for the discharge coefficients. There is much evidence that the discharge coefficient cannot continue to decrease but needs to approach a final value.
A refined model taking care of this aspect can be achieved in several ways. The first is simply to remove the linear term.

Refined model 1: $$C = m_1 + m_2 \cdot Re_D^{-0.5} \qquad (12)$$

The second model would be to exchange the linear term with a different one.

Refined model 2: $$C = m_1 + m_2 \cdot Re_D^{-0.5} + m_3 \cdot Re_D^{0.01} \qquad (13)$$

The third approach is to use the priciple RHG-equation model using the different Reynolds number terms with their respective exponents. This equation contains totally four terms containing the pipe Reynoldsnumber Re_D. However, for an orifice with corner tapping the fitting of the experimental data can be compressed to

Refined model 3: $$C = m_1 + m_2 \cdot Re_D^{-0.7} + m_3 \cdot Re_D^{-1.1} \qquad (14)$$

The result of the fitting with respect to higher Reynolds numbers, i.e. higher temperatures is for model 1 and 3 shown in figure 22

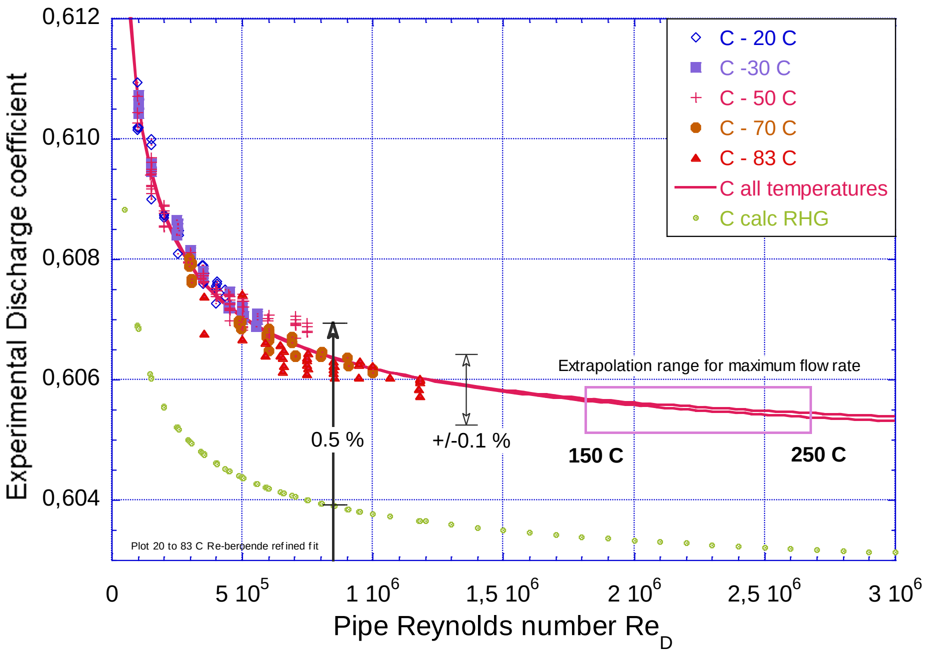


Fig. 22: The calibration data at 5 temperatures fitted with refined extrapolation models 1 (lower line) and 3 (upper line). For comparison discharge coefficient values calculated with the Reader Harris Gallagher equation below.

These fits follow well the curvature of the expected dependence according to the standard. Except these three approaches the refined model 1 was also tested with exponents -0.4 and -0,6 for Re_D leading to very comparable values in the interesting temperature range of 150 to 250 °C (corresponding to a Reynoldsnumber of 1.8 to 2.7*10^6). The refined model 3 seems to be the most resonable one, because it reflects the experience from high Reynolds numbers and it is further valid for all types of standardised orifice plates, not only corner tappings. Thus the suggestion is to adopt the refined model 3 as the most suitable one for temperature extension purposes. The corresponding coefficient are collected in table 1.

	$C = m_0 + m_1 \cdot Re_D{}^x + m_2\, Re_D{}^y + m_3\, Re_D{}^z + m_4\, Re_D{}^v$			
Model	1	2	**3**	3 general
Exponent x Exponent y Exponent z Exponent v	-0.5	-0.5 0.01	**-0.7** **-1.1**	-0.3 -0.7 -0.8 -1.1
Coefficient m_0 Coefficient m_1 Coefficient m_2 Coefficient m_3 Coefficient m_4	0.6040972 2.086789 -	0.6593323 1.524957 - 0.04772729 - -	**0.6046178** **28.51499** **-930.8763** **-** **-**	0.602756 0.19303 5.10305 -0.001 53.451
Difference from model **3** at Re_D = 2 500 000	-0.01 %	-0.18 %	**-**	-0.04 %

Table 1: Fitting coefficients for a refined extrapolation model – undisturbed flow

Besides the mentioned approches other exponent combinations have been tested too. As the data behaves so nice small variations in the exponents achieve quite similar calculation results for C including the general model 3 with four Re_D-terms. This also means the extrapolation is not so critical. Figure 22 displays six curvatures that all fit the data with almost the same quality (correlation coefficient). Several of them differ less than 0.1 % from model 3 even at very high reynolds numbers. Thus the extrapolation should not add sincere uncertainty to the experimental data having a calibration uncertainty of ±0,1 %.

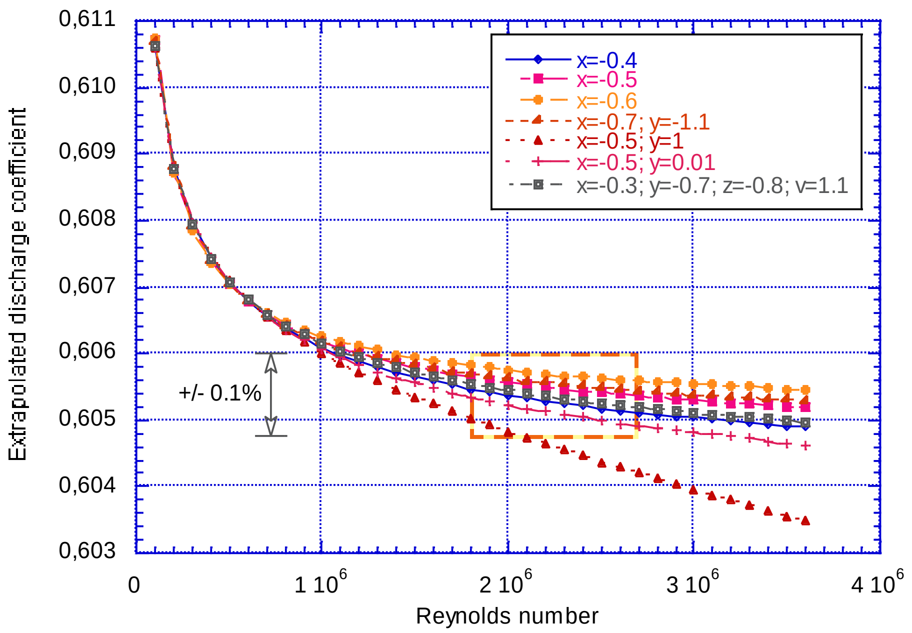


Fig. 22: Seven varying approaches to fit the calibration data according to the basic form $C=m_0+m_1Re_D{}^x+m_2Re_D{}^y$ and the resulting curvature of the calculated discharge coefficient C for high Reynolds numbers.

The ISO 5167 standard also treats the situation where no ideal profile can be expected. The Reader-Harris Gallager equation is still recommended for determining the discharge coefficient suggesting C decreases with increasing Reynolds number. But extra uncertainty is added to the basic one of 0.5 %.

The test program also contained a test if the extrapolation model can be used when the demands for an ideal flow profile is violated. Figure 23 displays the calibration results after a sincere flow disturbance achieved by an asymmetric swirl generator. In contrast to the undisturbed case the discharge coefficient now increases with increasing Reynolds number. In fact the Reader Harris Gallagher equation cannot be applied for this conditions. However, as shown in figure 23 the same refined extrapolation model is also able to fit the disturbed measurement. Due to the larger spread caused by the swirl generator the fit is not as good as in the undisturbed case. Again model 3 using the exponents according to Reader Harris Gallagher shows the most reasonable form for the extrapolation. This is a strong argument for the technique to calibrate at reasonable laboratory temperatures and use the fitted equation for temperature expansion purposes.

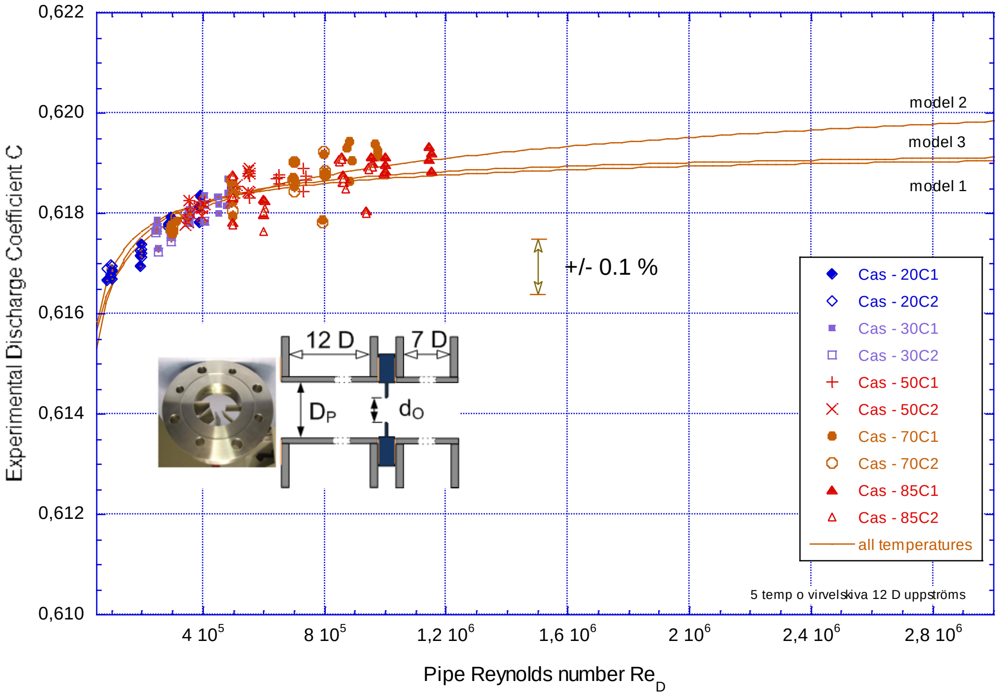


Fig. 23: The measured discharge coefficient at 5 temperatures from 20 to 85 °C and several flow rates at each temperature and a disturbing asymmetric swirl generator in front.

Table 2 contains the coefficients found for the three fitting models with model 3 as the most suitable one.

	$C = m_0 + m_1 \cdot Re_D{}^x + m_2\, Re_D{}^y$		
Refined fitting model	1	2	**3**
Exponent x Exponent y	-0.5	-0.5 0.01	**-0.7** **-1.1**
Coefficient m0 Coefficient m1 Coefficient m2	0.6195355 -0.8410177 -	0.5534742 -0.3857435 0.05736015	**0.6194499** **-12.16081** **309.7903**
Difference from model **3** at Re_D = 2 500 000	-0.01 %	0.10 %	**-**

Table 2: Fitting coefficients for a refined extrapolation model – disturbed flow

Again the difference between the three models is relative small even at high Reynolds numbers. A conclusion of this is that the temperature extrapolation does not add much extra uncertainty to that of the calibration it self.

Scaling and validity of extrapolation

Meters cannot be calibrated at conditions typical for feed water in power plants. In specifying measurement uncertainties suppliers of flow meters need to allow for possible errors that cannot be tested experimentally. These uncertainties must take into consideration the various parameters involved (spread in machining, reproducibility, pressure and temperature effects as well as unknown dynamic interactions with medium and pipe work etc. at working conditions) with maximum uncertainty contributions combined linearly not in a statistic way.
In four cases with four different meters it could be shown that extrapolation to temperatures higher than 90 °C is possible and leads to improved flow metering even at conditions beyond those achieved in laboratory. In calibration, even if the interesting flow conditions cannot fully be reached, the effect of several of these parameters can be determined under such conditions that an extrapolation is possible and reasonable.
However, the meters tested in this project were much smaller than those installed in power plants. Does this mean the results are only valid for the tested meters on an individual basis? Of course the extrapolations based on the coefficients found for the fitting are only valid for the individual meters. The important conclusion, however, is the following. It has been shown possible to produce fully developed flow conditions and to calibrate with the temperature as a direct or indirect independent variable. Thus some of the uncertainties like spread in manufacturing and reproducibility could be drastically reduced. The range of data was such that all meters could be fitted with a really simple or reasonable simple model equation. These equations all behaved in a smooth and monotone way so that extrapolation to higher temperature is reasonably well predictable without adding much extra uncertainty.

To summarize the results: The four meters, perhaps with the exception of the magnetic inductive meter, can be scaled up easily, which means characteristic measures like diameters etc. will be different but the extrapolation models as such will still hold. As a consequence the work performed in this work package can be repeated with larger meters and the same fitting and extrapolation procedure can be applied on the calibration data achieved. A further conclusion is that if high Reynolds numbers cannot be achieved by increased temperature they can be realized with increased flow rate. This is probably the closest one can come up to concerning traceability in flow at feed water conditions. For the four meters the models allow to lower the measurement uncertainties under operation conditions by at least a factor of 2

3.4 Results for Objective 4: On-site Measurement of the Electrical Output of Power Plants

One of the major aims of the JRP was to realise a metrology-grade reference set-up to perform fast, reliable and accurate on-site measurement of the electrical power output of generating plants at high voltage (three phase, up to 150 kV grid voltage and 2 kA current). The required accuracy must be better than 0.1 %, since the reference set-up should at least be a factor 5 better than the commercial systems presently in use to measure the electrical output of power plants. The approach taken in practice is that the reference set-up will be placed in parallel with the revenue metering set-up that measures the electrical energy generated by the power plant, in order to validate its accuracy.
The realized reference set-up is based on three custom-made current transformers (CTs), three custom-made voltage transformers (VTs) and a reference power/energy meter. In discussions with power plant operators they showed interest in this setup especially for acceptance tests of power plants. Validation of a new power plant with better accuracy will allow for increased confidence that a plant meets its specifications.

System requirements

In order to meet the demand for a total system accuracy of better than 0.1 %, the individual components each must have an accuracy of better than 0.05 %. Another factor to take into account is that for grid revenue metering set-ups, grid metering codes require the instrument transformers have an accuracy of 0.2 % or better. For that reason, it is chosen to search for instrument transformers for the reference set-up with an accuracy of better than 0.02 % (200 ppm). The power/energy meter was selected based on its accuracy and its stability for use in different temperatures, since under on-site conditions at a power plant the temperature variations will be significantly more than under laboratory conditions.

Reference system components

After an extensive study, the choice was made to use the following components for the reference set-up (the manufacturers and equipment mentioned are not necessarily the best and certainly not the only option available):

- Current transformers: Alstom, OSKF 170
- Voltage transformers: Alstom, OTEF 245
- Power/energy meter: Radian, RD33

The voltage transformers can be set to be used for a line voltage of 110 kV, 150 kV or 220 kV (line to line voltage). The corresponding ratios are 1100:1, 1500:1 and 2200:1, resulting in an output voltage for each setting of 100 V ‘line to line’. In practice the output is measured line to ground, resulting in a nominal voltage of 100/√3 V (approximately 57.7 V). The guaranteed accuracy by the manufacturer is 0.02 % for ratio and 1 min (~300 µrad) in phase. In total four voltage transformers have been purchased in order to have one spare.
The current transformers can be set to a ratio of 600:1 for a nominal primary current of 600 A (range 6-1500 A) or to a ratio of 2000:1 for a nominal primary current of 2000 A (range 20-5000 A). With the correct settings, the nominal output current is 1 A (range 0.01-2.5 A). The accuracy provided by the manufacturer is 0.02 % for both settings, 1 min (~300 µrad) in phase for a ratio of 2000:1 and 3 min (900 µrad) in phase for a ratio of 600:1. In total four current transformers have been purchased in order to have one spare.
The power/energy meter has a voltage range from 30 V to 525 V (specified uncertainty 0.005 %, 50 ppm) and a current range from 0.02 A to 120 A (specified uncertainty 0.007 %, 70 ppm). For currents less than 0.02 A the device is still functioning but with worse accuracy than for the normal range. The specified accuracy in power and energy is 0.01 % (100 ppm).

Calibration and test of system components

After purchase, all instrument transformers have been calibrated to determine their actual accuracy and performance behaviour.
The calibration of the current transformers was performed with an uncertainty (k=2) of 0.002 % (20 ppm) for ratio and for phase displacement. The maximum burden is 1 VA, since the cables and power meter input connected to it have a resistance of less than 1 Ω. Based on the calibration results and taking into account the current meter accuracy, the CTs should always be used at a ratio of 2000:1. In that case the ratio error is less than 5 µA/A and the phase displacement is less than 30 µrad. In practice the current transformers will operate with the primary terminals at high voltage. Applying a high voltage introduces a capacitive induced “error” current in the secondary winding. In a test measurement, with 60 kV and 100 kV, it has been verified that this current is orthogonal (90 deg out of phase) with the applied voltage and therefore does not have a measurable effect on active power measurements.
The calibration of the voltage transformers was performed with an uncertainty (k=2) of 0.002 % (20 ppm) for ratio and for phase displacement. The burden is 0 VA, since the power meter connected to the VTs has a voltage input impedance of 1 MΩ. The VTs have been calibrated for the 1500:1 and the 1100:1 ratios. The table 3 below shows an overview of the results.

VT-724108301 (“VT1”)			
Ratio	$V_{\text{line to line}}$ [kV]	R [µV/V]	Phase [µrad]
1500:1	150	40	-96
1500:1	110	10	-105
VT-724108302 (“VT2”)			
Ratio	$V_{\text{line to line}}$ [kV]	R [µV/V]	Phase [µrad]
1500:1	150	0	-122

1100:1	110	-30	-119
VT-724108303 (“VT3”)			
Ratio	$V_{line\ to\ line}$ [kV]	R [µV/V]	Phase [µrad]
1500:1	150	-20	-108
1100:1	110	-40	-113
VT-724108304 (“VT4”)			
Ratio	$V_{line\ to\ line}$ [kV]	R [µV/V]	Phase [µrad]
1500:1	150	10	-105
1100:1	110	-20	-105

Table 3: Ratio error and phase displacement of the four reference VTs for two different nominal ratios and at 0 VA burden.

In general it can be stated that the voltage transformers are within 0.004 % (40 ppm) equal to their nominal magnitude ratio and have a phase displacement of approximately -100 µrad.
The power/energy meter has been calibrated at 57.7 V (100/√3 V) for currents from 1 mA up to 120 A, and for phases between voltage and current from -1/2 π to +1/2 π rad. In the range of 10 mA to 2.5 A the accuracy of the power/energy meter generally is better than 40 µW/VA. In the range from 32 mA to 65 mA the accuracy of channel one is the worst, having a deviation from nominal up to 80 µW/VA (see figures below). The power / energy meter never deviates more than the 100 µW/VA specified by the manufacturer.

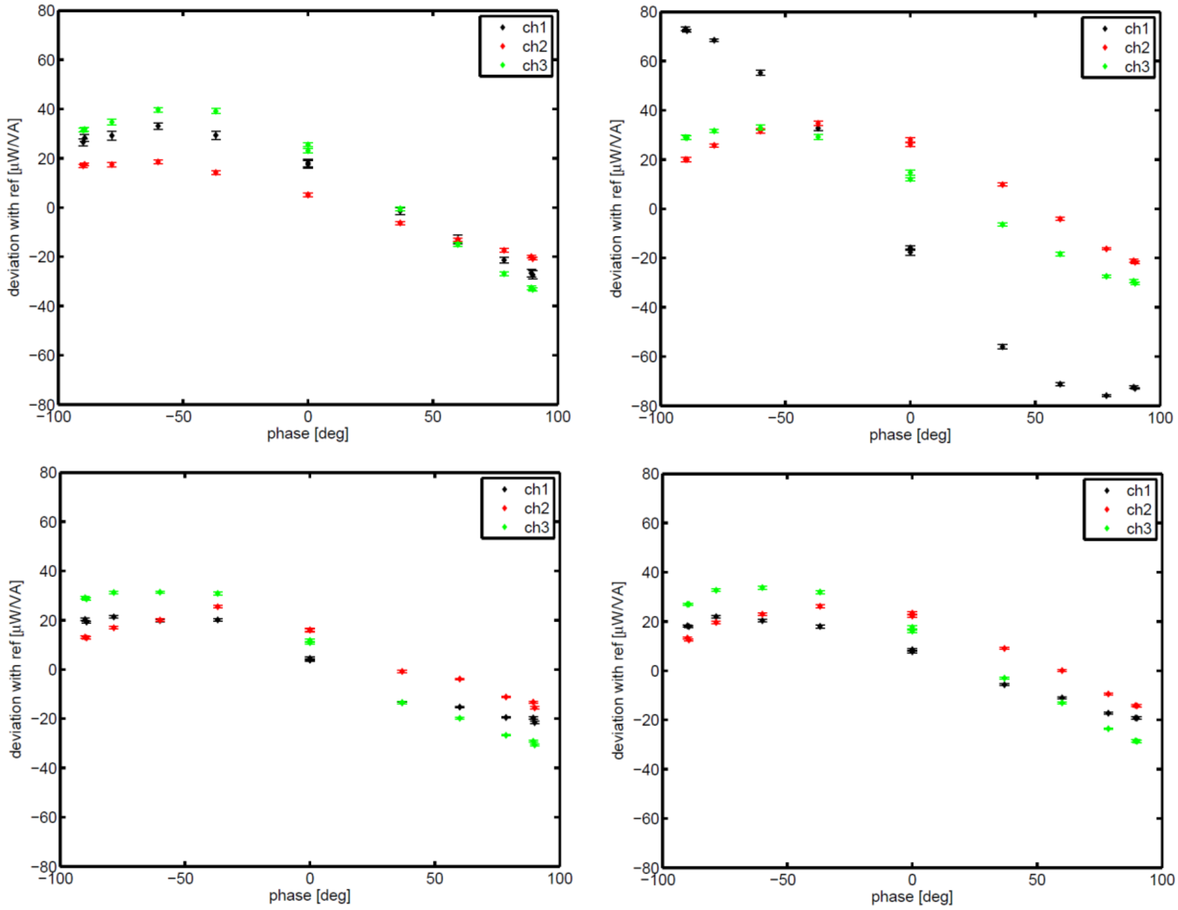


Fig. 24: Relative deviation from nominal value of the three input channels of the reference power / energy meter for four different currents as a function of phase angle between voltage and current.

Top left: 10 mA, the minimum for which the current transformers are calibrated. Top right: 50 mA, showing the larger deviation of channel one. Bottom left: 1A, nominal current. Bottom right:, 2.5 A the maximum current for which the current transformers are calibrated.

The effects of harmonic signals on the accuracy of the power/energy meter have been measured and these appear to be negligible for conditions as they appear on the power grid in practice (up to 10 % total harmonic distortion (THD)). The temperature dependency was found to be less than 2 µW/VA/°C.
Special attention was paid to the wiring that connects the instrument transformers to the power/energy meter, since it is well known that these can have quite detrimental effects on the overall system uncertainty. The instrument transformers are connected with 20 m long double-shielded twisted pair cables. The twisted pair carries the signal, the inner shield is connected to ground at the power/energy meter for signal shielding and the outer shield is connected to ground at both sides (safety ground). In this way, both a safe and accurate measurement was assured. This was verified in a test where a ground loop current of more than 0.8 A was induced in the outer shield, resulting in no measurable effects on the power reading of the power / energy meter.

System validation at NRC

A full system validation was performed at NRC, Canada, in order to verify that all components brought together perform according expectation. The picture below shows the system during testing at the NRC laboratory.

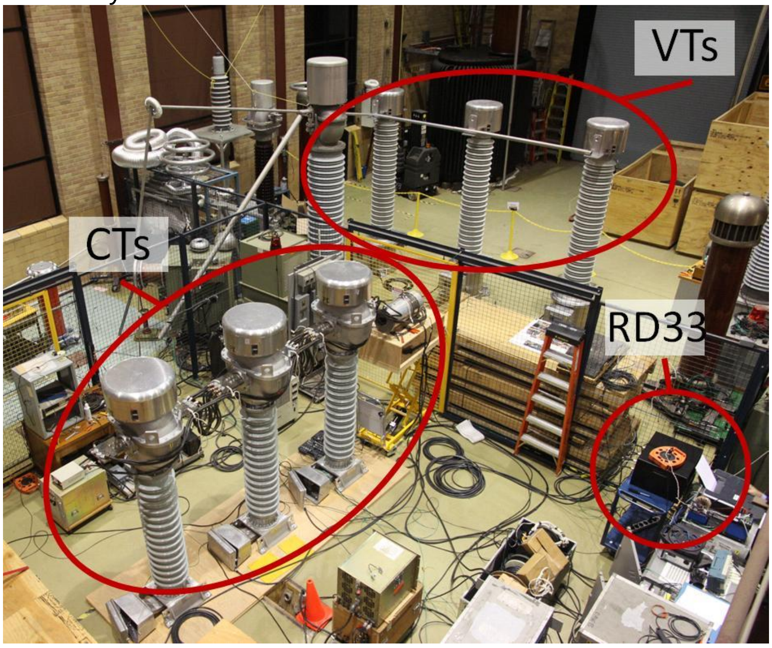


Fig. 25: Picture of the complete VSL reference set-up during testing in the NRC laboratory. The RD33 is the power/energy meter. The current through the CTs is generated at low potential, separately from high voltage to the VTs. This allows the use of conventional current generator and measurement techniques. The phase between current and voltage test signals can be set at will.

In the complete VSL system the deviations of all individual components add up to a total system deviation. The expectation is that the complete system has a deviation of approximately 0.001 % (10 ppm) in magnitude and 150 µrad in phase (the latter mainly caused by the voltage transformers).

This indeed was confirmed by the NRC system validation. The results of the tests were excellent: the difference between the readings of the VSL system and the NRC reference was at most 0.003 % (30 ppm) from the expected deviation. The measurement results were reproducible within 0.002 % (20 ppm), meaning that – if needed – the deviations can be corrected with an uncertainty of 0.002 %.

As an example, the figure below shows the results of channel 1 at 1000 A primary current (1 A going to the power/energy meter). From these results we conclude that under lab conditions the total expanded uncertainty of the system is 0.004 % (k = 2).

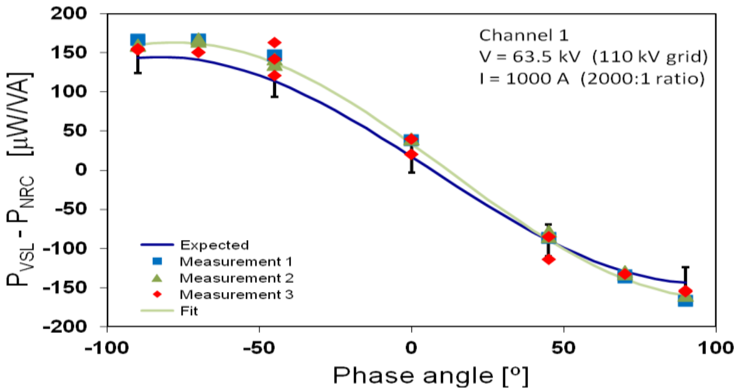


Fig. 26: Difference in measured real power between the VSL revenue metering set-up and the NRC set-up. The blue line is the expected deviation based on the calibration of CT1, VT1 and channel 1 of the RD33. The measurements were repeated with intervals a few days apart (symbols). The green line is the best fit through the measurement data.

Full on-site system description

In practice the reference power/energy meter will be placed outdoors, close to the instrument transformers. To protect the meter and peripheral equipment, the equipment is mounted inside a flight case. Inside the flight case the temperature is kept at (30 ± 2) °C for outdoor temperatures between 0 °C and 28 °C by means of a controlled airflow.

The results of the VSL reference system must be compared to the kWh meter under test. In practice the blinking LED or rotating disc of the kWh meter under test will be used as the “meter-under-test signal” to be measured. The power/energy meter is set to generate pulses like the kWh meter does. The time between pulses from the reference and kWh meter (i.e. the two ‘frequencies’) are compared simultaneously by using two timers/pulse counters that are read out by a computer. A computer stores the data in a database which can be accessed from a remote location. In addition to the two pulse rates, the computer also stores the other data from the power/energy meter like current, voltage, instantaneous power, etc. Also the temperature en humidity in and outside the flight case are recorded. The figure below show a sketch of the layout of the complete set-up.

The system, complete with peripheral equipment, can calibrate a kWh meter under laboratory conditions with an uncertainty of 0.005 % (50 ppm). In the field the uncertainty is estimated to be less than 0.03 % (300 ppm).

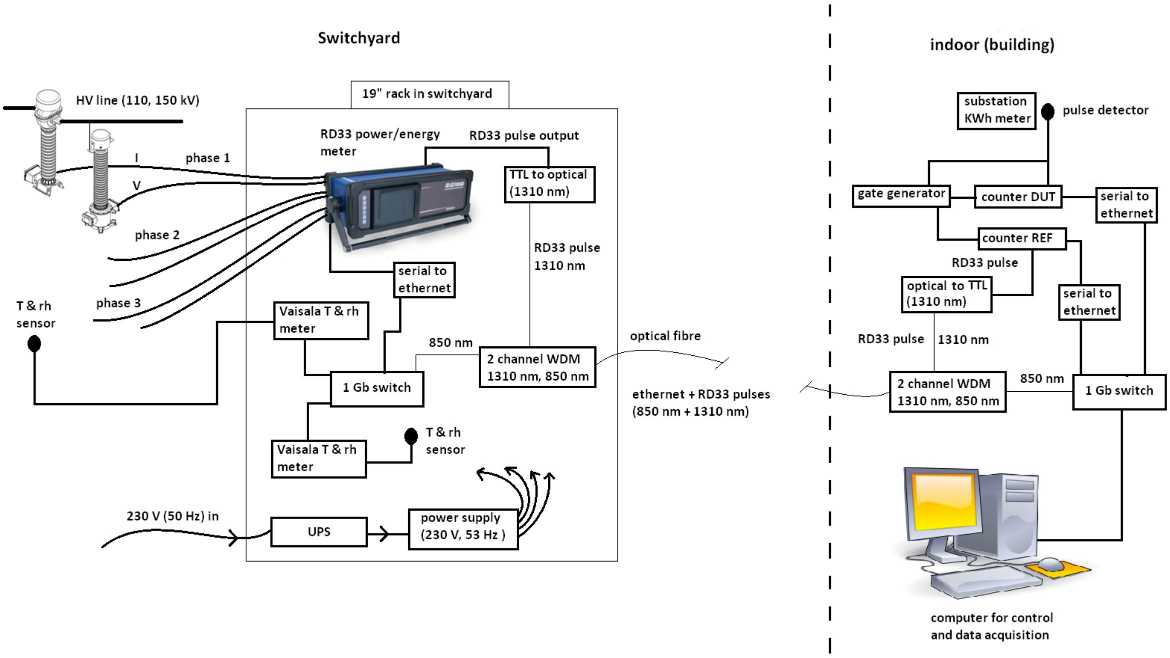


Fig. 27: Sketch of the VSL reference set-up as used on-site to verify the existing power plant revenue metering system. The reference outdoor equipment (except CTs and VTs) is placed inside a temperature controlled flight case with 19" rack in the substation switch yard. The other equipment is placed inside the substation control building, close to the kWh meter. An optical fibre is used to eliminate electromagnetic interference with the signals between the two sections of the set-up.

As a result of this EMRP project a three-phase reference system has been realized by VSL for on-site verification of the installation that measures the energy delivered by a power plant. The VSL reference system has an uncertainty of less than 0.03 % for 110 kV and 150 kV installations for currents between 20 and 5000 A (corresponding to a total power of 1.3 GW). This is a 3 times larger measurement range, at a three times lower uncertainty than the original project aim.

4 Conclusions

The collaboration of the NMIs resulted in considerable success in the four metrological fields addressed by the joint research project:

- In the field of **temperature measurements**, resistance thermometers for use in power plants were developed, which solved problems of platinum poisoning and vibration loads. There were two main problems. The first one was that until now vibration investigations could only be carried out at room temperature. With the new setup at CMI, vibration measurements were now possible at temperatures up to 700 °C. The second challenge was the understanding of contamination (poisoning) of platinum thermometers and its relation to oxidation. This was solved by chemical analysis by means of synchrotron radiation and by simultaneous thermal analysis.

- In the field of **thermophysical properties**, by developing and validating reference facilities for the measurement of spectral emissivity, heat capacity and thermal diffusivity up to temperatures of 1500 °C the foundations for an accurate radiation thermometric temperature measurement of high performance Ni base alloys were established. Such facilities did not exist at the beginning of the project.

- In the field of **flow measurement**, metrologically valid extrapolation models were established for flow sensors to be used in power plants to lower the uncertainty for flow rate measurements from 3 % to below 0.5 %. Extrapolation models were also designed to establish ultrasound based temperature sensing in the pipes of the power plant. These types of models did not exist before the project.

- In the field of **on-site electrical power measurement**, fast voltage and current meters were set up with unique low uncertainties of less than 0.15 % of electrical on-site power measurement. This measurement technique was not available at the beginning of the project

5 Actual and potential impact

The project is directly related to the important European political issues concerning the enhancement of energy efficiency in order to save natural resources, promote the protection of environment and lower the emission of greenhouse gases.

The results of the project are relevant to a wide community of different and competitive companies responsible for construction, instrumentation and operation of power plants. In order to disseminate the findings of the project as fast as possible, high level representatives of these stakeholders formed an Advisory Committee.

Among this group of stakeholders the project is already creating impact:

- Manufacturers of thermometers used in power plants are now able to develop thermometers with low uncertainties of 3 K instead of 8 K. One of the manufacturers already offers commercially thermometers with these specifications.
- Manufacturers of flow sensors are now able to offer flow sensors with an uncertainty of 0.5 % instead of 3 %. Especially one manufacturer already sells an ultrasound based flow meter for the use in power plants with this specification.
- During the final stage of the project, some findings concerning temperature and flow rate measurements of this project were applied in the field. As performance tests in power plants are subject to strict confidentiality, it can only be stated, that after applying the findings of the project, two operators of power plants assume that the energy efficiency of each power plant could be enhanced by 1,5 percentage points as now the energy production processes can be optimised based on the low uncertainty measurements of flow rate and temperature.
- Three power plants in Germany replaced their thermocouples with resistance thermometers whereas two power plants also installed low-uncertainty flow rate measurements

Further impact is expected via:

- Manufacturers of on-site electricity power meters are now able to offer commercially measurement equipment with uncertainties of < 0.1 % instead of 0.5 %.
- Manufacturers of sensors for temperature measurement of turbine blades now have access to metrological infrastructure for further developments of the technique.
- Operators of power plants are aware of the project's outputs and there are significant opportunities for impact as the results are adopted more widely.

As there exists a strong economic interest for enhancing the energy efficiency in power plants, and the results have already been shared with the stakeholders during the lifetime of the project, it can be expected, that the aim of the project, enhancing the energy efficiency of power plants by 2-3 percentage points, will become reality within the next couple of years.

As mentioned above, the Advisory Committee of this project included stakeholders from power plant manufacturers, operators,, instrumentation companies but also from corresponding regulative bodies. Due to the participation of these representatives, the results of this project were easily adopted by industry: These stakeholders also influenced discussions within the normative bodies such as EURAMET FC-F. EURAMET TC-T. Industry as result will act as a pacemaker ensuring adoption of the findings by the regulative bodies. This is very important as the procedure for incorporating new scientific results into internationally valid standardisation documents is time consuming.
In this sense, the partners of this project have delivered essential input to several normative bodies such as:

- EURAMET TC-F (the project provided information on the flow profile influence on flow meters)

- EURAMET TC-T (the project provided supplementary investigations for the EURAMET guide for the calibration of industrial resistance thermometers)
- EURAMET TC-T WG “Thermophysical Properties of Materials”. EURAMET TC-T WG TP, the Technical Committee of Thermometry of EURAMET is concerned with all issues of measurement of temperature, humidity and moisture, and thermophysical properties of materials. During the annual meeting of this technical committee in April 2013 in Prague, CZ, both PTB and LNE presented the measurement facilities for thermophysical properties, which have been developed within in the frame of this project.
- EMATEM - the European Metrology Association for Thermal Energy Metering (the project provided information on the flow rate dependency of flow sensors to the discussion forum for the EN 1434 Heat Meters)
- CEN TC 176 (the project provided information on the flow profile influence on flow meters, with a special flow disturber (developed within the project) generating an asymmetric profile with a swirl included in the EN 1434)
- VDI Technical Committees for “Applied Radiation Thermometry” 2.51 is a German national committee concerned with standardisation in the field of radiation thermometry. On May 13th 2013, PTB presented and discussed their plans to develop a new set-up for the measurement of spectral emissivity at elevated temperatures.

With 12 publications and more than 50 talks and poster presentations the project demonstrated considerably high scientific impact reflecting the common interest for the projects’ findings.

For the NMIs there also exists considerable impact, as this project joined together – one the one hand - a group of NMIs with measurement capabilities, technical knowledge and scientific excellence in the fields of temperature measurement, thermophysical properties, flow rate measurement and electrical measurement. On the other hand, none of the NMIs could work out the tasks alone. As a result, a stable metrology network was established among the partners, which allows for further collaboration.

As stated above, the project was related directly to European energy policy. On a long term, after a representative number of power plants were operated at higher energy efficiency using the finding of this project, it might be possible that the use of better measurement techniques might be subject of European Legislation.

The environmental impact of energy efficiency gains is enormous, as it results directly in a lowering CO_2 emission and other greenhouse gasses. Currently, power plants, driven by fossil fuels, contribute to approximately 34 % of the CO_2 emissions and 40 % of the electricity worldwide. Improving the efficiency by 2 % will reduce at least 2 % of the CO_2 emissions worldwide. In addition, efficiency gains will preserve natural resources (gas, coal, nuclear fuel). This is has a social impact element as by reducing the pollution it will improve the health of European citizens. It can be expected that a more efficient production of energy will also lower energy prices; for example a reduction of 2 % (related to the efficiency gain) means that the 196 million private households in EU27 will be unburdened by 2 400 M€ per year.

6 Website address and contact details

The work of the project is documented within the web-site: www.powerplant-efficiency.de

Further information concerning the project can be obtained via the coordinator Dr Thomas Lederer, thomas.lederer@ptb.de

7 List of publications

No	Authors	Title	Journal	Details
1	B. Hay, J. Hameury, N. Fleurence, P. Lacipiere, M. Grelard, V. Scoarnec and G. Davée	New facilities for the measurements of high temperature thermophysical properties at LNE	International journal of thermophysics	DOI 10.1007/s10765-013-1400-8 (2013)
2	O. Büker, P. Lau and K. Tawackolian	Reynolds number dependence of an orifice plate	Flow measurement and instrumentation	30, 123-132, 2013
3	P. Klason, A. Andersson, M. Holmsten, P. Lau, G. Kok	A Speed Of Sound Based Feed Water Temperature Sensor	American Institute of Physics Volume 8 of Temperature: Its Measurement and Control in Science and Industry	AIP Conf. Proc. 1552, 925 (2013)
4	P. Klason, A. Andersson, M. Holmsten, P. Lau, G. Kok	Temperature Measurement In Flow Pipes – Comparison With Single Pt-100 And Multi Sensors	American Institute of Physics Volume 8 of Temperature: Its Measurement and Control in Science and Industry	AIP Conf. Proc. 1552, 987 (2013)
5	P. Klason, A. Andersson, M. Holmsten, P. Lau, G. Kok	Measuring temperature distributions in pipe flows	Advanced Mathematical and Computational Tools in Metrology and Testing IX, Series on Advances in Mathematics for Applied Sciences	vol. 84, Singapore, 2012, 20120404
6	K. Tawackolian, O. Büker, J. Hogendoorn and T. Lederer	Investigation of a 10-path Ultrasonic Flow Meter for Accurate Feedwater Measurements	Measurement Science and Technology	Vol. 25, No. 7, 075304
7	P. Klason, G. Kok, N. Pelevic, M. Holmsten, S. Ljungblad, P. Lau	Measuring Temperature in Pipe Flow with Non-Homogeneous Temperature Distribution	International Journal of Thermophysics	Vol. 35, Issue 3-4, pp 712-724 2014
8	T. Lederer, P. Klason et al.	Metrology for improved power plant efficiency the power plant project	Procc. ISFFM	Online available on: www.isffm.org June 2012
9	G. Rietveld, F. Diouf, X. Guo, E. So	The Establishment of a Reference System at VSL for On-Site Calibration of HV Revenue Metering Systems	CPEM 2012 conference digest	July 2012, 130 – 131
10	Ivan Jursic and Steffen Rudtsch	Thermal Stability of b-PtO_2 Investigated by Simultaneous Thermal Analysis and Its Influence on Platinum Resistance Thermometry	International Journal Thermophysics 35 (2014), 1055-1066	DOI 10.1007/s10765-014-1695-0 (2014)
11	B. Hay, J. Hameury, N. Fleurence, P. Lacipiere, M. Grelard, V. Scoarnec and G. Davée	New facilities for the measurements of high temperature thermophysical properties at LNE	International journal of thermophysics	DOI 10.1007/s10765-013-1400-8 (2013)
12	G. Rietveld, M. Fransen, E. Houtzager, and E. So	Reference system for on-site verification of HV revenu metering systems	Proc. Conference on Precision Electromagnetic Measurements (CEPM)	DOI 10.1109/CEPM.2014.6898436
13	R. Strnad, S. Rudtsch, K. Riski, M. Šindelář, M.	Vibration Behaviour of a Thin-film Sensors in Power Plants	submitted to International Journal of Thermophysics	in the review process

	Jelínek			