Measurement techniques for investigation of heat transfer processes at European Research and Technology Test Facility P8

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Abstract

Optimization of heat transfer management is a key issue in designing a rocket combustion chamber. Therefore heat transport processes have been an ongoing interest at the DLR Institute of Space Propulsion. This paper gives short overview of experimental methods and test specimens used by Institute of Space Propulsion for heat transfer investigations at European Research and Technology Test Facility P8 for the abovementioned investigations.

Introduction

Today rocket engines using high-energy cryogenic propellants (LOX and LH_2) play a major role due to the high combustion enthalpy (13.4 kJ/kg) and the high specific impulse of these propellants. The combustion chamber wall material used is a copper alloy with a good thermal conductivity, $k \sim 350 Wm^{-1}K^{-1}$. High temperature differences between the hot combustor gases and the cooling fluid in combination with high heat transfer coefficients yield extreme heat flux levels through the combustion chamber wall. Typical values for the Vulcain main engine at 10.5 MPa chamber pressure are up to 80 MW/m^2 and for the Space Shuttle Main Engine at 20.5 MPa heat fluxes up to 160 MW/m^2 are experienced. The reliable operation of rocket combustion chambers at such high thermal and mechanical loads is achieved with highly efficient cooling. For optimal cooling design with minimal hydrodynamic losses the precise knowledge of heat transfer processes in rocket engines is important. Despite substantial progress in numerical simulations still exist needs on realistic experimental data at representative conditions both at hot gas and at coolant side for verification and development of numerical design tools. The importance of these data is confirmed by the fact that life cycle prediction of rocket engines strongly depends on the accuracy of wall temperature prediction, an error of 40K leads to 50% life reduction [1].

In the past decades various different methods to determine local heat transfer measurement methods were developed and applied. The methods are based on different physical effects, but a common feature is that the detection of the necessary gas and surface temperatures is relatively simple whereas the realization of the correct heat flux is substantially more difficult.

Most of the known methods can be sorted according to the following major categories:

- *Transient method:* Transient measurements with help of impressing a sudden change of the flow temperature.
- Measuring by different *heat flux sensors*
- *Caloric method*: Direct measurement of the thermal energy input. Typically the easy measurable enthalpy increase of cooling fluids is used as energy measurement method.
- *Inverse method*: Determination of the heat flux from the temperature field within the test body with a known thermal resistance

According to this survey, this paper will only give an overview about the mentioned methods with respect to application for heat transfer measurement in subscale rocket engines The transient method [2] is used predominantly in short tests (ca. 5s) and rarely on high pressure subscale combustion chambers. The measurements with heat flux sensors are very perspective because they allow defining local heat transfer by steady state and transient conditions. But it needs some development to reach the necessary level of accuracy and reliability at measurement conditions typical for rocket engines, i.e. extremly high level of heat flux. Therefore both methods have not been used in the tests presented in this report.

The measurement techniques used were developed and optimised for detailed investigations of heat transfer processes in the combustion chamber and in the cooling channels on subscale models at conditions representative for real rocket engines. For the investigations the calorimetric method and the inverse method were selected.

A conventional *calorimetric method* allows the determination of integral heat fluxes derived from calorimetric measurements taken at the inlet and outlet positions for each test segment or cooling channel [4]. Using the calorimetric technique, global heat transfer properties can be determined with good accuracy however local behaviour of heat transfer can not be resolved.

The *inverse method* is based on direct determination of the temperature field in a solid wall of a combustion chamber. This method allows the essential, more detailed investigations of thermal processes and particularly the 2D effects related to thermal stratification in cooling channels [6]. This method is very sensitive to accuracy implementing of measurement technique and disturbance of temperature field in combustion chamber wall.

Test specimen

All investigations presented here were performed at the European Research and Technology Test Facility P8 (Fig. 1). This test facility enables investigations with liquid and gaseous hydrogen and typical rocket engine operating conditions [2]. Supply systems of P8 are operated in a controlled blow-down mode. The high pressure propellant supply systems for LH_2 and LOX are designed for interface pressures at the experimental test specimen of up to 360bar with mass flow rates from 0.05kg/s to 3.0 kg/s, from 0.05kg/s to 1.5 kg/s for LH_2 and GH_2 respectively from 0.2kg/s to 8kg/s for LOX.

Fig. 1: European Research and Technology Test Facility P8

For the tests presented, the typically high heat flux through the chamber walls is of primary interest. Due to the enormous energy requirements, these conditions cannot be simulated under laboratory conditions.

Conbustion chamber	internal diameter	nozzle throat diameter	P_{max} MPa
“B”	50mm	28mm	11.5
“L42”	80mm	50mm	9.5

Table 1: Main parameters of DLR subscale combustion chambers

The experimental studies were performed on two different combustion chambers: Combustion chamber “B”, a segmented, water cooled model combsutor (Fig. 2) and the L42-combustor, a segmented model combustor, regenratively cooled with LH_2 (Fig.5). These combustion chambers were designed at the DLR Institute of Space Propulsion especially for studies with inter-changeable combustor segments. A segmented design enables implementation of various test equipment without the additional expenditure. Table 1 shows the parameters of both combustion chambers.

Combustion chamber Model „B“

Combustions chamber model “B” is used predominantly to study the heat transfer on the hot gas wall of the combustion chamber and the influence of different design solutions (for e. thermal barrier coating) on the thermal loads on the combustion chamber wall. In these investigations solely the calorimetric measurement method was applied.

Fig. 2: Subscale tests with DLR combustuon chamber “B” at the European Research and Technology Test Facility P8

Combustion chamber "B" consists of cylindrical elements, each of 50mm length, with separate cooling supply (Fig. 3). The cooling occurs due to row of cylindrical channels.

Two collectors provide a uniform mass flow through all cooling channels. Precise temperature and pressure measurement in inlet and outlet collectors allow determining the increase of coolant enthalpy und following the integral heat flux. An additional temperature sensor measures the surface temperature on hot gas side. The separate supply of the segments allows the use of different coolant fluids in different segments. For example for realizing real transient thermal conditions in testing of thermal barrier coatings LH_2 was used as coolant in the segment with the TBC deposit. In Fig. 4 a typical heat flux distribution in the cylindrical part of combustion chamber “B” is presented.

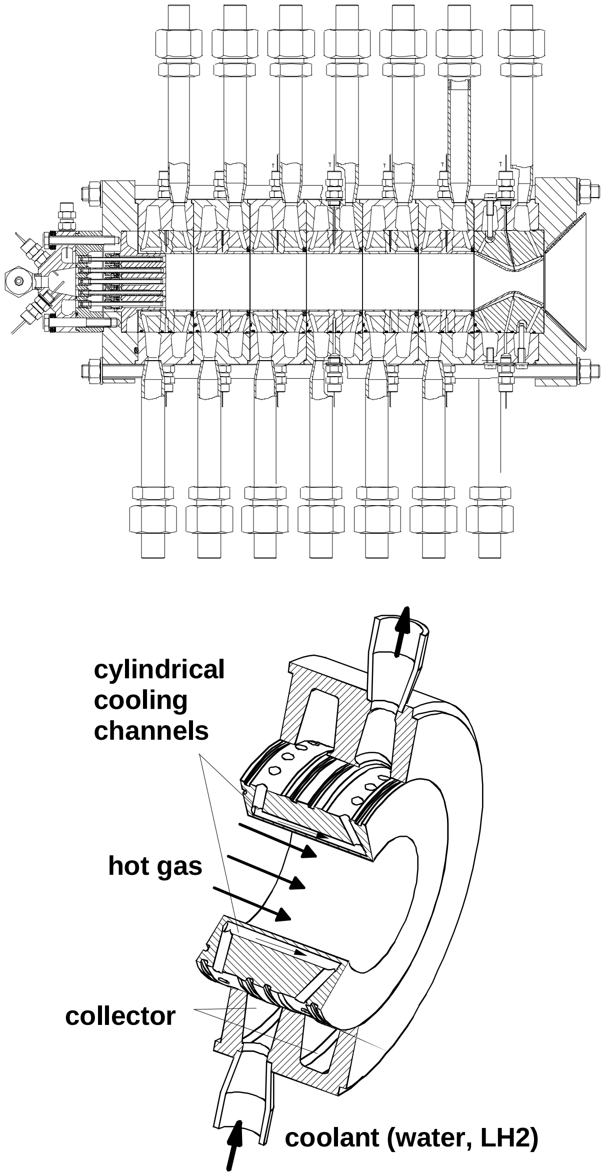


Fig. 3: Cross section of combustion chamber “B” and test segment for calorimetrical measurement of hest transfer

Combustion chamber Model „L42“

Combustion chamber „L42“ is applied mainly for heat transfer investigations in cooling channels. The use of liquid hydrogen as a coolant made it possible to investigate the influence of the fluid parameters that are strongly dependent on temperature and pressure which exhibit real gas behaviour throughout the operating range investigated. Experimental simulation this behaviour with substitude fluids was deemed not possible. A segmented design enables implementation of various test equipment without additional expenditure. The injector head contains 42 small coaxial injectors supporting a homogenous distribution of propellants in the combustion chamber.

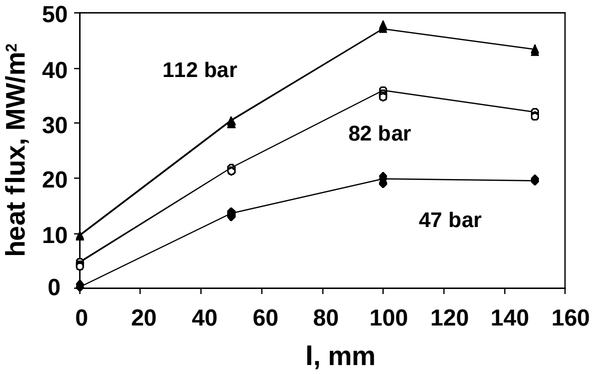


Fig. 4: heat flux distribution in cylindrical part DLR combustion chamber "B"

To perform the experimental study, a unique High Aspect Ratio Cooling Channel segment (HARCC) was designed and developed. The test segment was mounted at a position of 2.5 injector head diameters downstream. This again ensures homogeneous flow conditions with the uniform distribution of velocity and temperature at the segment of interest.

The HARCC-segment is a single cylindrical segment with 200mm length. Production of a longer segment was not possible for technical reasons. The test segment had on its circumference four different cooling channel geometries, in each 90°-sector the cooling ducts have a different aspect ratio. This construction on one hand reduced the number of tests and the associated expense. On the other hand, such a construction with circumferential positioning of the cooling channel sectors ensures each cooling channel design experiences the same conditions. The hot-gas side of each cooling channel sector in an axisymmetric arrangement experiences identical physical and thermal conditions during a combustion test. This fact enables direct evaluation and comparison of the behaviour and response of the various cooling channel designs on a test-to-test basis.

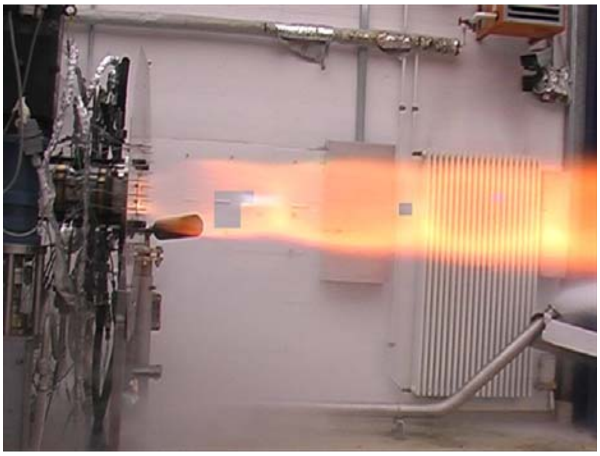


Fig. 5: Subscale tests DLR combustuon chamber "L42" at the European Research and Technology Test Facility P8

For investigation the heat transfer processes both calorimetric and inverse methods were used simultaneously. A conventional calorimetric method was used for the determination of integral heat fluxes derived from calorimetric measurements taken at the inlet and outlet positions for each sector. This method was used essentially as a reference for the inverse measurement technique.

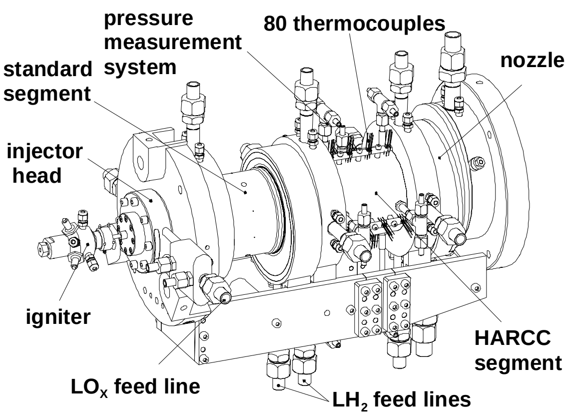
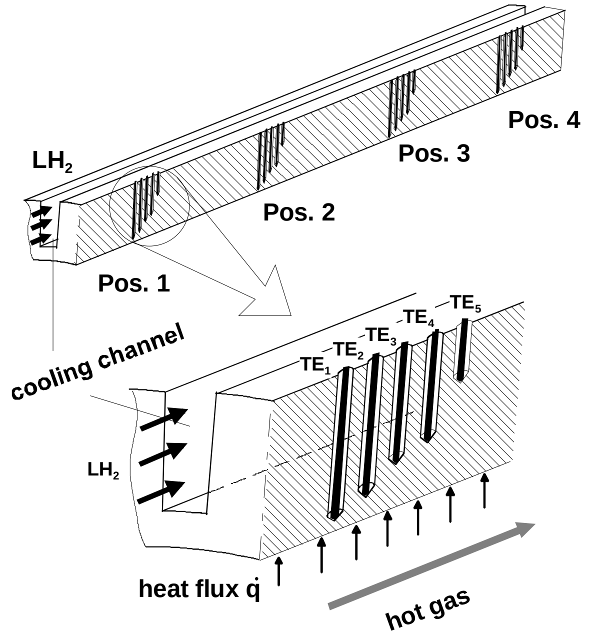


Fig. 6: DLR combustuon chamber "L42" with implemented HARCC-segment

The temperature field inside the combustion chamber wall was determined from measurements at 4 locations along the main chamber axis for each sector (Fig. 7). Such temperature measurements at different locations along the cooling channel provides important information regarding the emergence and development of stratification processes. At each location, a group of 5 thermocouples was integrated, each at a predefined, precise distance from the interior chamber surface.

The development and successful implementation of a method for determining the temperature field in cooling duct walls presents a difficult task. One must ensure on the one hand, exact temperature measurement with extremely high heat flows (i.e. high spatial temperature gradients) and, on the other hand good handling and minimum influence of the wall structure with the integration of the thermocouples.



Thermocouple	TE_1	TE_2	TE_3	TE_4	TE_4
Distance from hot gas side (mm)	0.7	1.1	1.5	1.9	7.5

Fig. 7: Position of thermocouples in wall of cooling duct

For these reasons, soldering or welding techniques were deemed inappropriate. Such operations would lead to thermal deformation of the partition wall. The thermocouples were inserted into precisely manufactured cylindrical holes and pressed with the assistance of a special springing system. The spring system provided a constant force (F=3.3N) and thus constant surface contact between the thermocouple and the base of the hole bored for the thermocouple (Fig. 8).

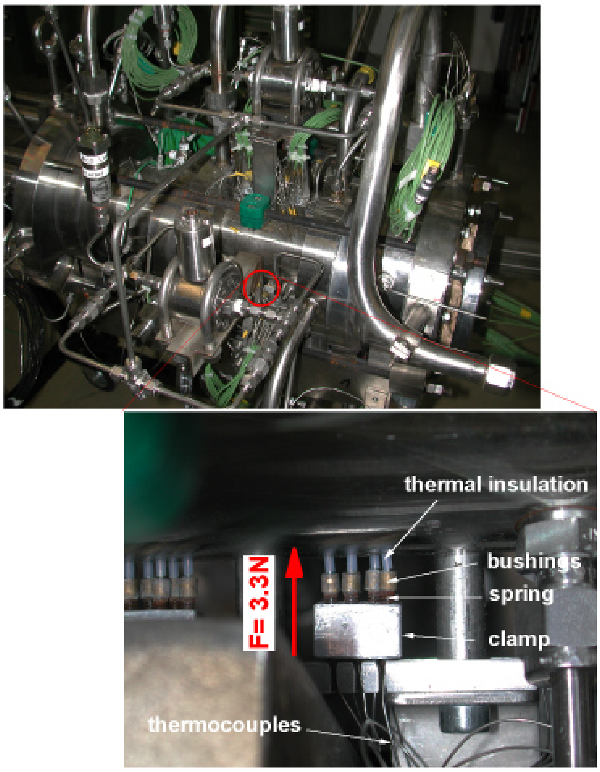


Fig. 8: Fitting system for integration of thermocouples

This setup avoids change of thermocouple contact area and potential loss of contact as the materials undergo expansion and contraction due to changes in temperature. The pressed force supplied by the spring was kept constant during all tests. Thermally insulating each thermocouple avoids the emergence of heat flux along the sensor with a negative influence on measurement values.

The simultaneous recording of signals from conventionally mounted thermocouples which adjust to temperature change through deflection, and the spring mounted thermocouples showed that the new design drastically reduced the level of signal fluctuation (Fig. 9). The standard deviation of the signal from spring mounted thermocouples is two times less than that from conventionally mounted thermocouples.

Another problem was achieving precise temperature measurements under cryogenic conditions. As already mentioned, thermocouples were used as temperature sensors. The use of conventional type thermocouples ensures the measurement surface area is relatively small. The size of this contact point of two thermal-active wires for selected thermocouples is about 0.1 mm. This enables to bring the measurement element very near to the selected point of interest. This characteristic makes standard type thermocouples favourable for this application.

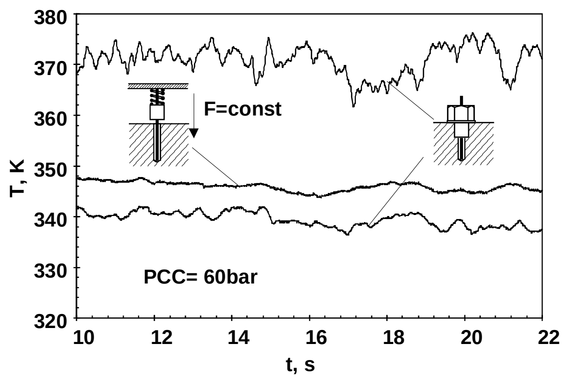


Fig. 9: Signal behaviour from spring fixed and conventionally mounted thermocouples at 60bar pressure in combustion chamber

On the other hand, thermocouples also have a substantial disadvantage. Their sensitivity drastically decreases within the low temperature range of cryogenics. To increase the measurement accuracy, the thermocouples were calibrated for temperatures in the area of 25-150K at the Cryogenic Laboratory at DLR Institute of Space Propulsion. With this calibration procedure, the complete measurement system including the analog to digital converter was adjusted. This led to substantially higher measurement accuracy as these procedures also consider the distortion of the measurement signal in all parts of measurement system. The calibration allows one to achieve high accuracy temperature measurement (± 2K at 20-40K and ± 1K in temperature area 40-300K.

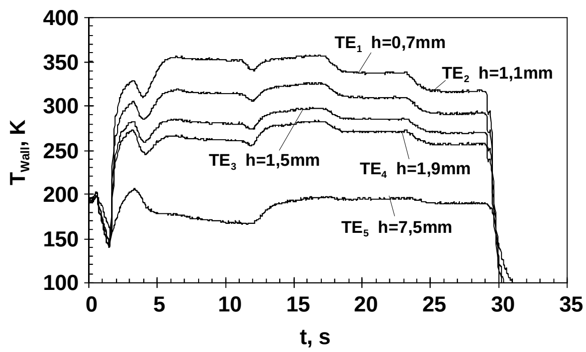


Fig. 10: Behaviour of temperature field in combustion chamber wall during the test

Fig. 10 presents the measurement temperatures at different distances from inside the combustion chamber for the 6 MPa test. These temperatures were used for determination of the heat flux using the gradient method.

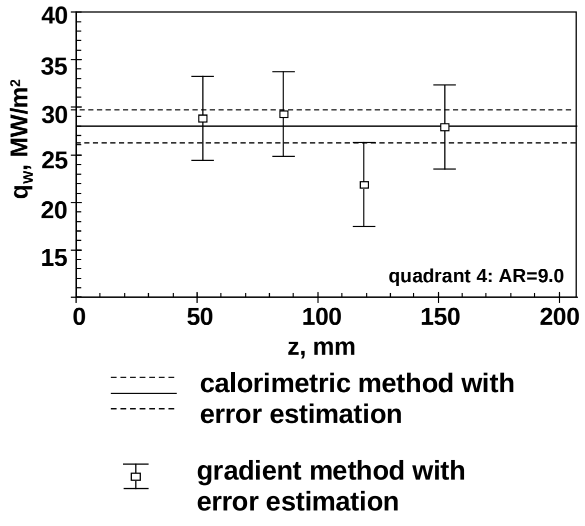


Fig. 11: Comparison of experimental determined heat fluxes from calorimetric and gradient methods at a combustion chamber pressure of 6MPa [6]

In Fig. 11 the results of the calorimetric analysis and the method of temperature gradients with estimated errors are compared. The error estimation is made accounting for the maximum temperature measurement error (ΔT_{max}) and the maximum possible deviation of the thermocouple tip from the desired position. The plots display the results of both methods as the distribution of heat flux density along the combustion chamber axis. It can be clearly seen that the calorimetric as well as the temperature gradients method have comparable results.

To improve the accuracy of the inverse method for heat transfer measurement on the hot gas side the possibility of the application of other materials for the test segment were investigated. A very interesting candidate is graphite. The material has a medium level of thermal conductivity (80-100 W/mK) and a very high temperature resistance (up to 2900°C in protective atmosphere).

These properties provide to apply the test bodies with essentially thicker wall between hot gas and coolant (10-20mm). An application of graphite test bodies for inverse method drastically reduces the influence of temperature measurement error and inaccuracy by the implementation of temperature sensors. The high surface temperature allows the application of infrared measurement techniques for the determination of surface temperatures. Investigations of the DLR Institute for Space Propulsion at P8 show that in hydrogen/oxygen combustion chambers the level of radiation intensity from graphite surface in the infrared region even at high pressure can significant prevail the radiation intensity from hot gas. The application of graphite as well allows the better simulation of heat transfer processes on ceramic surface with extremely high surface temperature.

A graphite test segment has been used in a study of cooling film efficiency downstream from the injection point. This region is characterized due to relative small heat flux and the existence the hydrogen protective atmosphere. The test segment is composed of graphite body with radial cooling channels and stainless steal ring. The ring positions the graphite part and avoids the overshooting of mechanical stress in sensitive graphite material.

The rows of thermocouples were glued with graphite adhesive with a distance of 3mm from hot gas surface and near the bottom of the cooling channel. Fig. 12 shows the typical measurement set-up for the temperature distribution in graphite body

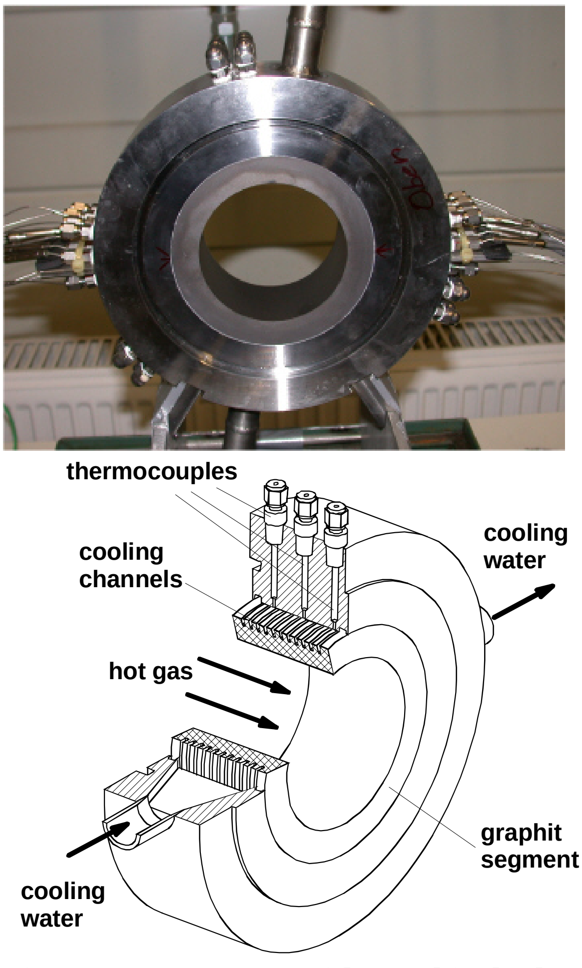


Fig. 12: Test segment with graphite body

Conclusion

Subsequent tests show that the designed test specimen provides high precision investigations of heat transfer processes at extremely high thermal loads. The combination of different measurement techniques provides detailed and quantitative information heat transfer processes on hot gas side and in cooling channel.

Reference

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