Hukseflux
Thermal Sensors

USER MANUAL

RHF SERIES

Ring heat flux sensors

Warning statements

Follow the installation instructions of this user manual.

The sensor and sensor-to-cable transition should not be exposed to significant force.

Putting more than 12 Volt across the sensor wiring can lead to permanent damage to the sensor.

Do not use “open circuit detection” when measuring the sensor output.

RHF is usually cooled using air or water. The user must keep the RHF temperature within its rated operating range.

Contents

List of symbols

Quantities	Symbol	Unit
Heat flux	Φ	W/m²
Voltage output	U	V
Sensitivity	S	V/(W/m²)
Temperature	T	°C
Resistance	R	Ω
Temperature dependence	TD	%/K
Thermal conductivity	λ	W/(m·K)

Subscripts

property of thermopile sensor	sensor
calibration reference condition	reference

Introduction

The RHF series consists of customer-specific heat flux sensors incorporated in a stainless steel ring. They are used as building blocks in larger measuring systems, for example to study fouling and slagging in combustion processes. Many RHF's are eventually part of so-called "deposition probes" or "fouling sensors" designed by the customer. It is particularly suitable for trend monitoring that is necessary for this application. A typical sensor contains 4 separate heat flux and 4 temperature sensors, so that fouling behaviour can be studied at different locations on the sensor at different angles relative to the local gas flow.

Sensors of the RHF series are used in scientific as well as operational experiments to study fouling and slagging behaviour. RHF design is user-specific; geometry and cabling are designed in cooperation with the user for the specific application.

RHF may be employed as a building block, when designing a deposition probe or a fouling sensor. Many RHF sensors are part of multi-purpose probes that also measure local gas temperature and take gas samples (so-called suction probes). RHF's can be manufactured in many different geometries and dimensions. RHF01 is a version incorporating 4 heat flux / temperature sensors. Usually the RHF is cooled by compressed air or water.

RHF measures heat flux, in W/m^2, as well as its body temperature in °C. The sensors in RHF are a thermopile and a type K thermocouple. The thermopile measures the temperature difference across the body of RHF, creating an output that is representative of the local heat flux. The thermocouple measures the approximate sensor body temperature. A thermopile and a thermocouple are passive sensors; they do not require power.

The part of the cabling closest to the sensor is a special high-temperature metal sheathed cable. The sensor as well as the high temperature cable and armour withstand temperatures up to 800 °C. The low-temperature extension cable has wire insulation and a jacket of PTFE type plastic.

Using RHF is easy. Its sensors can be connected directly to commonly used data logging systems. The heat flux, Φ, in W/m^2, is calculated by dividing the RHF sensor output, a small voltage U, by the sensitivity S, possibly applying user–determined corrections based on the temperature or flow rate measurement.

A typical measurement function of RHF, involving the temperature dependence TD, is:

$$\Phi = U/(S\cdot(1 + TD\cdot(T - T_{reference}))) \qquad \text{(Formula 0.1)}$$

The sensitivity at around 30 °C is provided with RHF on its product certificate for all sensors in the RHF.

Figure 0.1 *Example of a customer-specific RHF ring heat flux sensor with 2 x heat flux and temperature sensor, also showing high temperature cables*

RHF is most suitable for relative measurements using one sensor, i.e. monitoring of trends relative to a certain reference point in time or comparing heat flux at one location to the heat flux at another location. The heat flux sensor calibration depends on the way the sensors are built-in and may also depend on the flow rate of the gas or liquid used for cooling. RHF01 is provided with a factory calibration of every sensor which is suitable for relative measurements. If you want to perform accurate absolute measurements with RHF, as opposed to relative measurements, it is necessary to calibrate the RHF incorporated in the final design under operating conditions, possibly as a function of water or air flow. Hukseflux can provide dedicated heaters to perform such calibration.

Hukseflux can provide dedicated heaters to perform such calibration.

Suggested use of RHF:

- building block for customer-specific sensors
- deposition sensors
- fouling sensors
- heat flux sensors

See also:

- SBG01 for high accuracy radiative flux measurements
- HF03 for study of flares / mobile measurements
- HF02 for flare measurement
- view our complete product range of heat flux sensors

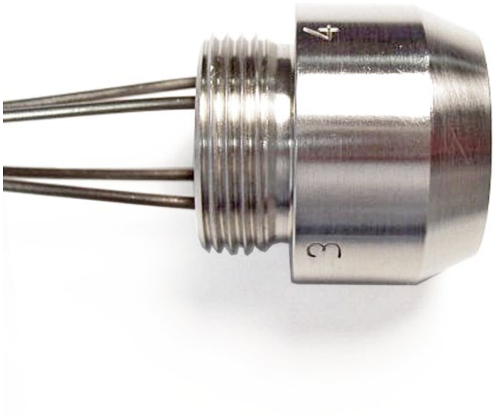

Figure 0.2 *Example of a customer-specific RHF01 ring heat flux sensor with 4 x heat flux and temperature sensor*

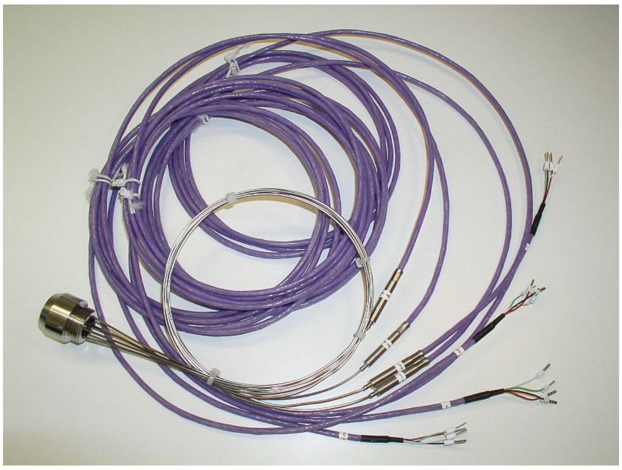

Figure 0.3 *Example of a customer-specific RHF ring heat flux sensor; the entire sensor, high temperature cable and low temperature extension cable*

1 Ordering and checking at delivery

1.1 Ordering RHF

RHF design is user-specific; geometry and cabling are designed in cooperation with the user for the specific application. Common options are:

- longer cable (specify total cable length for both cable types in m)
- connector at RHF cable end
- low temperature extension cable with 2 connectors, matching cable connector and chassis connector
- chassis connector with internal wiring
  (colour code of wiring identical to cable colour code)

1.2 Included items

Arriving at the customer, the delivery should include:

- heat flux sensor RHF according to customer-specific drawing
- cable of the lengths as ordered
- product certificate matching the instrument serial number

1.3 Quick instrument check

A quick test of the instrument can be done by connecting it to a multimeter.

1 Check the electrical resistance of the heat flux sensor between the black [-] and red [+] wires and the thermocouple between the green [+] and white [-] wires. Use a multimeter at the 100 Ω range. Measure the sensor resistance first with one polarity, then reverse the polarity. Take the average value. Typical resistance should be the nominal sensor resistance of 1 to 2 Ω for the thermopile sensor, plus for additional low temperature extension cable 0.2 Ω/m (resistance per meter cable) for the total resistance of two wires (back and forth added), for high temperature cable 13 Ω/m. For the thermocouple work with 1 to 2 Ω , plus additional low temperature extension cable 3 Ω/m resistance per meter cable), for high temperature cable 28 Ω/m. Infinite resistance indicates a broken circuit; zero or a lower than 1 Ω resistance indicates a short circuit.
2. Check if the heat flux sensor reacts to heat: put the multimeter at its most sensitive range of DC voltage measurement, typically the 100 x 10^{-3} VDC range or lower. Expose the sensor to heat, for instance exposing the sensor to the flame of a lighter. The signal should read > 0.1 x 10^{-3} V now. Also look at the reaction of the thermocouple to heat.
3. Inspect the instrument for any damage.
4. Check the sensor serial number engraved on the sensor or on the transition piece between high temperature and low temperature cable, against the certificate provided with the sensor.

2 Instrument principle and theory

A heat flux sensor measures the heat flux density through the sensor itself. This quantity, expressed in W/m^2, is usually called “heat flux”. RHF users typically assume that the measured heat flux is representative of the undisturbed heat flux at the location of the sensor though a pipe of the same temperature. Users may also apply corrections based on scientific judgement.

The heat flux sensors in RHF are thermopiles. This thermopile measures the temperature difference across the wall of the pipe. Working completely passive, the thermopile generates a small voltage that is a linear function of this temperature difference. The heat flux is proportional to the same temperature difference divided by the effective thermal conductivity of the heat flux sensor body.

Using RHF is easy. For readout the user only needs an accurate voltmeter that works in the millivolt range. To convert the measured voltage, U, to a heat flux Φ, the voltage must be divided by the sensitivity S, a constant that is supplied with each individual sensor, and correct for the temperature of the sensor.

The temperature sensor inside RHF is a type K thermocouple.

Heat flux sensors such as RHF, for use in industry at high heat flux levels, are typically calibrated under the following reference conditions:

- conductive heat flux (as opposed to radiative or convective heat flux)
- homogeneous heat flux across the sensor
- 30 °C
- heat flux in the order of 3000 W/m^2

Measuring with heat flux sensors, errors may be caused by differences between calibration reference conditions and the conditions during use. The user should analyse his own experiment and make his own uncertainty evaluation.

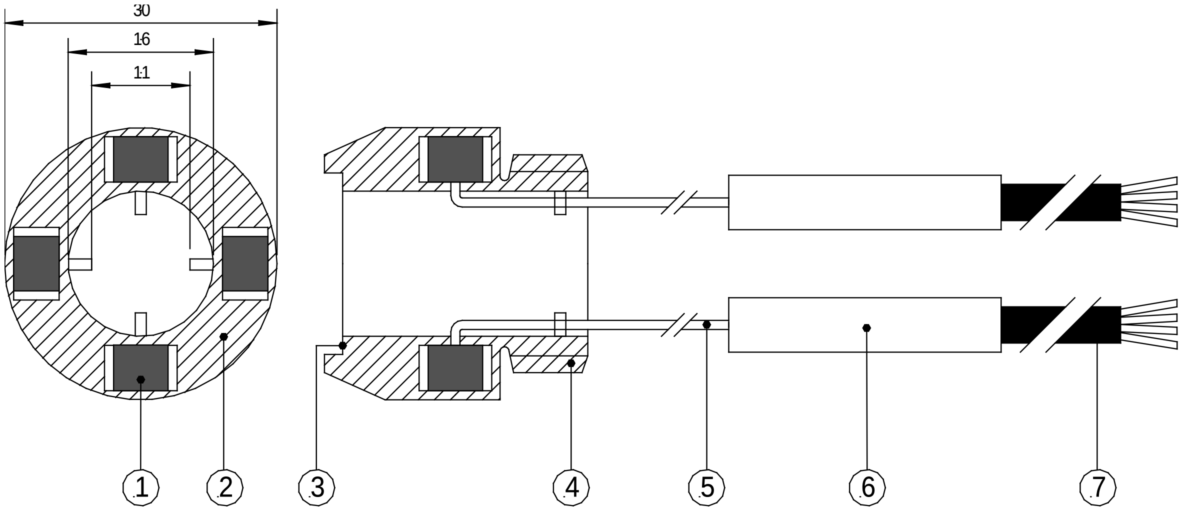

Figure 2.1 *Example of RHF01 ring heat flux sensor with 4 x heat flux / temperature sensors (1), in a stainless steel body (2), with either a flat connection for welding- (3) or a threaded connection (4). High temperature cable (5) is usually extended with low temperature extension cable (7). Cooling must be provided by air, oil or water. RHF design is user-specific. Dimensions in the drawing serve as an example only. Dimensions are in x* 10^{-3} *m.*

3 Specifications of RHF-series

3.1 RHF specifications

RHF consists of sensors embedded in a ring-shaped tube wall. They measure the heat flux density through the surface of the sensor. This quantity, expressed in W/m^2, is called heat flux. They also measure the absolute temperature of the wall. RHF design is user-specific; geometry and cabling are designed in cooperation with the user for the specific application. An RHF is passive, using thermopile and thermocouple sensors. The thermopiles generate a small output voltage proportional to the heat flux. RHF can only be used in combination with a suitable measurement system. The RHF is usually cooled by air or water. RHF sensors are typically used for trend monitoring, which does not rely on absolute calibration. For absolute measurements the user must calibrate the RHF incorporated in the final design under operating conditions, possibly as a function of water or air flow.

Table 3.1 *Specifications of RHF (continued on next page)*

RHF SPECIFICATIONS	
Sensor type	ring heat flux sensors
Sensor design	RHF design is user-specific; geometry and cabling are designed in cooperation with the user for the specific application.
Sensor type according to ASTM	heat flow sensor or heat flux transducer
Heat flux sensor	thermopile
Measurand	heat flux
Measurand in SI units	heat flux density in W/m^2
Measurement range	0 to 300 x 10^3 W/m^2
Temperature sensor	thermocouple type K
Temperature sensor specification	ANSI MC96.1-1982 / EN 60584
Measurand	temperature
Measurand in SI units	temperature in °C
Measurement function / required programming	$\Phi = U/(S\cdot(1 + TD\cdot(T - T_{reference})))$
Temperature dependence TD	- 0.013 %/K (constant value for all sensors, based on material and thermocouple specifications)
Optional measurement function / required programming	user-specific measurement equation, determined by user calibration
Recommended number of sensors	2 to 4 per ring
Sensitivity (nominal)	4 x 10^{-9} $V/(W/m^2)$
Response time (95 %)	180 s (depends on cooling)
Directional sensitivity	see product certificate
Expected voltage output	multiply the sensitivity by the maximum expected heat flux
Required readout	per heat flux and temperature sensor: heat flux sensor: 1 x differential voltage channel or 1 x single ended voltage channel temperature sensor: 1 x Type K differential thermocouple channel or 1 x Type K single ended thermocouple channel both with input resistance > 10^6 Ω

Table 3.1 *Specifications of RHF (started on previous page, continued on the next page)*

Rated operating temperature ranges: sensor and high temperature cable low temperature extension cable optional connectors	 -30 to +800 ˚C -30 to +240 ˚C -50 to +250 ˚C
IP protection class Sensor and high temperature cable Low temperature extension cable	 IP68 IP67
Rated operating relative humidity range	0 to 100 %
Required sensor power	zero (passive sensors)
Sensor diameter including guard	8×10^{-3} m (typical)
Sensor thickness	12×10^{-3} m (typical)
Sensor thermal conductivity	$\lambda = 13.2 + 0.015T$ W/(m·K) for SS316
Standard cable lengths: High temperature cable Low temperature extension cable	 1 m (see options) 3 m (see options)
Standard cable diameter: High temperature cable Low temperature extension cable	 0.15×10^{-3} m 4×10^{-3} m
High temperature cable type	metal sheathed mineral insulated signal cable
Low temperature extension cable type	PTFE signal cable with shield
Heat flux sensor resistance range	1 to 2 Ω
Low temperature extension cable: heat flux sensor cable resistance	0.2 Ω/m (nominal)
High temperature cable: heat flux sensor cable resistance	13 Ω/m (nominal)
Temperature sensor resistance range	1 to 2 Ω
Low temperature extension cable: temperature sensor cable resistance	3 Ω/m (nominal)
High temperature cable: temperature sensor cable resistance	28 Ω/m (nominal)
Low temperature extension cable diameter	4×10^{-3} m
Transition piece diameter	10×10^{-3} m
Marking	see drawing 1 x sensor serial number engraved on connection piece high temperature to low temperature cable or on the sensor body 1 to 4 x individual sensors are marked by a number engraved on the metal of the ring 1 x sensor serial number on sticker at the end of the low temperature extension cable
Gross weight	on request
Net weight	on request
Packaging	box of 300 x 320 x 60 mm (typical)
INSTALLATION AND USE	
Cooling	by air, water or oil (user responsibility)
Cooling requirements	RHF is usually cooled using air or water. The user must keep the RHF temperature within its rated operating range.
Installation	see recommendations in this user manual avoid mechanical force on the sensor body and sensor-to-cable transition.
Cable extension	see options: longer cable, extension cable and connectors

Table 3.1 *Specifications of RHF (started on previous 2 pages)*

INSTALLATION AND USE	
minimum tube outer diameter	25 x 10^{-3} m
minimum tube wall thickness	7 x 10^{-3} m
minimum tube length	50 x 10^{-3} m
ACCESSORIES	
Heater for calibration	verify heater type for the user specific RHF typical heater specifications: heater resistance 100 Ω (nominal) heater voltage 30 VDC effective surface area 0.00407 m^2
CALIBRATION	
Calibration traceability	to SI units
Product certificate	included (showing calibration result and traceability)
Calibration method	CBW01 calibration method
Calibration hierarchy	from SI through international standards and through an internal mathematical procedure
Calibration uncertainty	± 20 % (k = 2)
Calibration reference conditions	30 °C, heat flux of 3 x 10^3 W/m^2
Validity of calibration	factory calibration may be used for trend monitoring. For absolute measurements re-calibrate when the sensor is built-in.
Temperature sensor tolerance class	IEC Tolerance class EN60584-2: Type KX, class 2
Temperature sensor error limits	ASTM E230-ANSI MC96.1: Type KX, standard limits
MEASUREMENT ACCURACY	
Uncertainty of the measurement	statements about the overall measurement uncertainty can only be made on an individual basis. see the chapter on uncertainty evaluation.
VERSIONS / OPTIONS	
Order code	RHF with reference to drawing
Longer cable	longer cable (specify total cable length for both cable types in m)
Connector	connector at RHF cable ends
Extension cable	low temperature extension cable with 2 connectors with 2 connectors matching cable connector and chassis connector (specify cable length in m)
Chassis connector	chassis connector with internal wiring (colour code of wiring identical to cable colour code)

3.2 Dimensions of RHF

RHF design is user-specific; geometry and cabling are designed in cooperation with the user for the specific application.

4 Standards and recommended practices for use

Use of RHF is not subject to standardised operating procedures.

Hukseflux
Thermal Sensors

5 Installation of RHF

5.1 Installation and cooling

Table 5.1.1 *Recommendations for installation of RHF heat flux sensors*

Location	RHF sensors are often used as building blocks in larger measuring systems for example to study fouling and slagging in combustion processes. Many RHF's are eventually part of so-called "deposition probes" or "fouling sensors" designed by the customer.
Performing a representative measurement	A typical sensor contains 4 separate heat flux and 4 temperature sensors, so that fouling behaviour can be studied at different locations on the sensor at different angles relative to the local gas flow.
Cooling requirements	RHF is usually cooled using air or water. The user must keep the RHF temperature within its rated operating range. We recommend making a safety system by measuring the RHF temperature.
Mechanical mounting: avoiding strain on the sensor to cable transition	RHF is usually mounted on a probe of the user. The connection may be made by welding or screwing. In case of a welded connection, make sure that the sensor temperature during welding remains below 800 °C. The sensor-to-cable transition is vulnerable. During installation as well as operation, the user should provide proper strain relief of the cable so that transition is not exposed to significant force.

5.2 Electrical connection

A heat flux sensor should be connected to a measurement system, typically a so-called datalogger. The thermopiles of an RHF are passive sensors that do not need any power, neither for the heat flux sensor, nor for the temperature sensor. Cables may act as a source of distortion, by picking up capacitive noise. We recommend keeping the distance between a datalogger or amplifier and the sensor as short as possible. For cable extension, see the appendix on this subject.

Table 5.2.1 *The electrical connection of a single heat flux and temperature sensor of an RHF. The shield is not connected to the stainless steel sensor body.*

WIRE	
Red	heat flux signal [+]
Black	heat flux signal [−]
Green	thermocouple type K [+]
White	thermocouple type K [−]
Blank	shield

5.3 Requirements for data acquisition / amplification

The selection and programming of dataloggers is the responsibility of the user. Please contact the supplier of the data acquisition and amplification equipment to see if directions for use with the RHF are available.

Table 5.3.1 *Requirements for data acquisition and amplification equipment for a single sensor of RHF*

Capability to measure small voltage signals	preferably: < 5 x 10^{-6} V uncertainty Minimum requirement: 20 x 10^{-6} V uncertainty (valid for the entire expected temperature range of the acquisition / amplification equipment)
Capability for the data logger or the software	to store data, and to perform division by the sensitivity to calculate the heat flux. $\Phi = U/(S\cdot(1 + TD\cdot(T - T_{reference})))$ (Formula 0.1)
Capability to measure thermocouple type K	preferably: measurement uncertainty within ± 3 °C
Data acquisition input resistance	> 1 x 10^{6} Ω
Open circuit detection (WARNING)	open-circuit detection should not be used, unless this is done separately from the normal measurement by more than 5 times the sensor response time and with a small current only. Thermopile and thermocouple sensors are sensitive to the current that is used during open circuit detection. The current will generate heat, which is measured and will appear as a temporary offset.

Hukseflux
Thermal Sensors

6 Maintenance and trouble shooting

6.1 Trouble shooting

Table 6.2.1 *Trouble shooting for RHF*

General	Inspect the sensor for any damage. Inspect the quality of mounting / installation. Inspect if the wires are properly attached to the data logger. Check the condition of the cable. Inspect the connection of the shield (typically connected at the datalogger side). Check the datalogger program in particular if the right sensitivity is entered. RHF's sensor serial number is engraved on the sensor or on the transition piece between high temperature cable and low temperature extension cable. The sensitivity can be found on the calibration certificate. Check the electrical resistance of the heat flux sensor between the black [-] and red [+] wires and the thermocouple between the green [+] and white [-] wires. Use a multimeter at the 100 Ω range. Measure the sensor resistance first with one polarity, then reverse the polarity. Take the average value. Typical resistance should be the nominal sensor resistance of 1 to 2 Ω for the thermopile sensor, plus for additional low temperature extension cable 0.2 Ω/m (resistance per meter cable) for the total resistance of two wires (back and forth added), for high temperature cable 13 Ω/m. For the thermocouple work with 1 to 2 Ω , plus additional low temperature extension cable 3 Ω/m resistance per meter cable), for high temperature cable 28 Ω/m. Infinite resistance indicates a broken circuit; zero or a lower than 1 Ω resistance indicates a short circuit.
The sensor does not give any signal	Check if the heat flux sensor reacts to heat: put the multimeter at its most sensitive range of DC voltage measurement, typically the 100 x 10^{-3} VDC range or lower. Expose the sensor heat, for instance touching it with your hand. The signal should read > 2 x 10^{-3} V now. Touching or exposing the red side should generate a positive signal, doing the same at the opposite side, the sign of the output voltage reverses. Also look at the reaction of the thermocouple to heat. Check the reaction of the thermocouple sensor to heat. Check the data acquisition by replacing the sensor with a spare unit.
The sensor signal is unrealistically high or low	Check the cable condition looking for cable breaks. Check the data acquisition by applying a 1 x 10^{-6} V source to it in the 1 x 10^{-6} V range. Look at the measurement result. Check if it is as expected. Check the data acquisition by short circuiting the data acquisition input with a 10 Ω resistor. Look at the output. Check if the output is close to 0 W/m^2.
The sensor signal shows unexpected variations	Check the presence of strong sources of electromagnetic radiation (radar, radio). Check the condition and connection of the shield. Check the condition of the sensor cable. Check if the cable is not moving during the measurement.

7 Appendices

7.1 Appendix on cable extension / replacement

A heat flux and temperature sensor in an RHF is equipped with one cable that consists of a high temperature cable and a low temperature extension cable. Keep the distance between data logger or amplifier and sensor as short as possible. Cables may act as a source of distortion by picking up capacitive noise. In an electrically “quiet” environment the RHF cables may be extended without problem to 50 metres. If done properly, the sensor signal, although small, will not significantly degrade because the sensor resistance is very low (which results in good immunity to external sources) and because there is no current flowing (so no resistive losses). Cable and connection specifications are summarised below.

Table 7.1.1 *Preferred specifications for cable extension of a single sensor in RHF*

Cable	Hukseflux RHF high temperature cable (not extendable) Hukseflux RHF low temperature extension cable
Extension	use Hukseflux RHF extension cable with 2 connectors matching cable connector and chassis connector (specify cable length in m) use Hukseflux RHF cable connector at the end of the RHF low temperature extension cable to a connector of the extension cable with 2 connectors use Hukseflux RHF chassis connector
Outer diameter	4 x 10^{-3} m (low temperature extension cable)
Length	cables should be kept as short as possible, in any case the total cable length should be less than 50 m

7.2 EU declaration of conformity

We, Hukseflux Thermal Sensors B.V.
Delftechpark 31
2628 XJ Delft
The Netherlands

in accordance with the requirements of the following directive:

2014/30/EC The Electromagnetic Compatibility Directive

hereby declare under our sole responsibility that:

Product model:	RHF
Product type:	Ring heat flux sensor

has been designed to comply and is in conformity with the relevant sections and applicable requirements of the following standards:

Emission:	EN 61326-1 (2006)
Immunity:	EN 61326-1 (2006)
Emission:	EN 61000-3-2 (2006)
Emission:	EN 61000-3-3 (1995) + A1 (2001) + A2 (2005)
Report:	08C01340RPT01, 06 January 2009

Eric HOEKSEMA
Director
Delft
September 08, 2015