Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Video Inspection Probe for Deep Geothermal Boreholes - GeoKam

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Keywords: borehole tools, cooling system, lighting system, GeoKam, ZWERG, engineering

ABSTRACT

GeoKam, an online inspection probe with integrated camera which is developed at the Karlsruhe Institute of Technology will be completed after almost two years development time. The first prototype is suitable for the use in geothermal wells. It is able of transferring live pictures from up to 4000 m depth with an ambient temperature of up to 165 °C to the earth´s surface via wireline.

The developments of GeoKam are based on the ZWERG concept, which will be described in the paper of a colleague Dr. Isele: The ZWERG Project, also handed in; it stands for a platform for the fast construction of modular probes. Thus, if required, each probe can be configured individually with different components in order to obtain the desired information of a geothermal borehole. GeoKam is the first prototype. It is composed of cameras, camera electronics, transmitting electronics, cooling device, power supply and lighting system, which are mounted in housing. The housing itself consists of several segments, which are assembled with special connectors for the probe, as required.

For optimal investigation of the borehole, several cameras are installed in the GeoKam. In this case each camera is equipped with a lens, wherein the aperture and the focus are adjustable. In order to obtain high quality images, high-quality camera sensors and lenses are installed in GeoKam. By miniature electromotors the lenses can also be adjusted finely to obtain the best quality of image, which also depends on the lighting system. A high image quality, which is unique for a camera probe can be achieved by selecting suitable light sources and a proper positioning on the probe.

Due to the high hydrostatic pressure, combined with the relatively high environment temperature and the corrosive fluids in the boreholes, special materials have been selected. For the housing a nickel based superalloy has been chosen. In the area of the camera a high-performance transparent ceramic is used. Both materials with extremely different physical properties especially at high temperatures have been connected by a suitable jointing technology. To ensure a safe operation of the joint in the borehole, a thermal stress analysis, using commercial FEM software and various mechanical tests have been conducted.

1. INTRODUCTION

Despite the great potential of geothermal energy in Germany investors as well as the German Government shies at providing funds. As a cause they name the high risks of thermal energy. Experts do not only state the difficulties of searching for suitable spots but also refer to the extreme conditions, which occur when using deep thermal energy. The technologies used, e.g. borehole and exploration technology, derive from the gas and oil industry and therefore are not always suited for the cause of geothermal energy. If difficulties occur in a geothermal energy borehole, e.g. damages of the casing, they cannot be resolved because the localization of the damage is already very difficult. Therefore experts state that cause studies and cause elimination have to be central elements of the geothermal energy research and approve the developments in these fields.

The Karlsruhe Institute of Technology discovered the necessity of research in these fields five years ago and began with the development of a platform for modular probes. The ambition of this project, named "ZWERG" [Isele, 2013], is the development of a model kit for a borehole probe, in order to configure the probe individually to fit the requirements. The platform is the basis for inspection, repair and logging probes. Since many components of the different probes are identical the advantages of a common platform are clear. A first realization of a probe with ZWERG as the basis is GeoKam. GeoKam is a video inspection probe for the use within the field of geothermal energy, which allows real-time inspections of the borehole surface in depths with 48 MPa pressure and ambient temperatures of 165 °C.

Every probe from the ZWERG model kit consists of the basis module and one or many functional modules. The basis module contains the control cabinet, wireline, cable head, housing, probe to probe coupling, heat shields, cooling, internal assembly, power supply, embedded system, sensors, actuators, data storage, data transfer and the software [Isele, 2013]. Since the GeoKam is a video inspection probe it consists of a camera as functional module and the basis module.

The camera unit of the GeoKam is built up from a plurality of components. They can be divided roughly into these functional blocks: housing, heat shield, lighting system, cooling system and camera module (Figure 1). The different blocks and their state of development will be described subsequently.

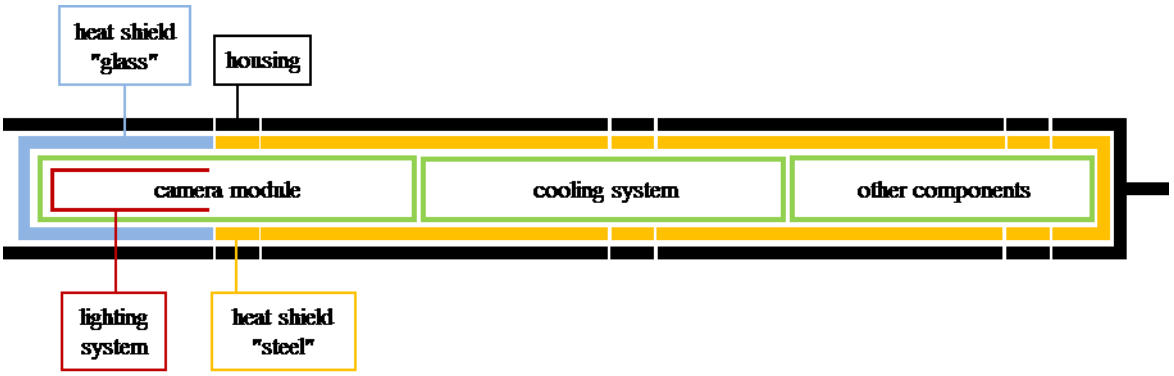

Figure 1: Schematic design of the GeoKam probe with the components of the camera unit

2. THE CAMERA UNIT OF GEOKAM – DESIGN AND FABRICATION

The development of the camera unit for GeoKam is based upon the platform ZWERG. The ZWERG platform postulates a modular buildup of the probe to obtain a high flexibility of the different modules. Every module of a probe is electrically and mechanically compatible to other modules of the platform. Each module can be roughly divided into three levels, protection layer, insulation layer and working layer (Figure 2). The first level, the protection layer, consists of the housing and protects the subjacent levels from the high pressure, corrosive thermal water and shocks during service. The housing also serves as supporting structure for the other layers. Special joints connect the different modules e.g. the camera to the cooling unit. The second level, the insulation layer, is required to protect the third level, the working layer, as good as possible from the high temperatures in the borehole.

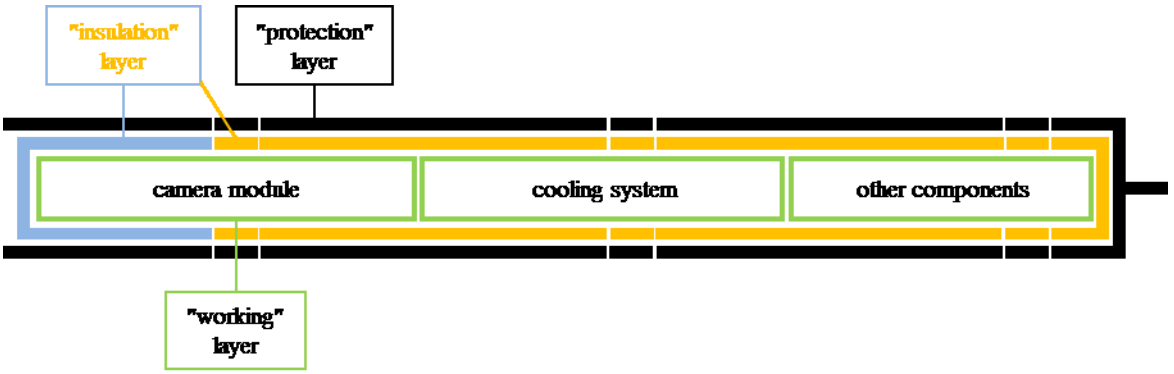

Figure 2: The three different layers of the GeoKam

2.1 Housing

The camera unit housing allows the operator sight to be redirected axially into the borehole and radially to the borehole surface. In order to allow a 360° examination of the borehole wall the camera module rotates within the camera unit. In contrast to the use of a rotating mirror, a rotating camera module will not tilt the image when inspecting another angle of the borehole wall. A a strong motor is therefore expendable, which safes power and decreases heat input. Altogether there are six lateral windows distributed over two levels. Each window is separately framed by the metal housing and therefore well protected. The multiple frames facilitate the jointing of metal and sapphire glass. The front window is inserted into the housing angular. Through purging bores close to the front window contaminations are rinsed off the window continuously during service. A screw joint connects the housing with other modules of the probe. The closeness is ensured through two O-rings. Bores and notches for a hook spanner facilitate the assembling with additional modules.

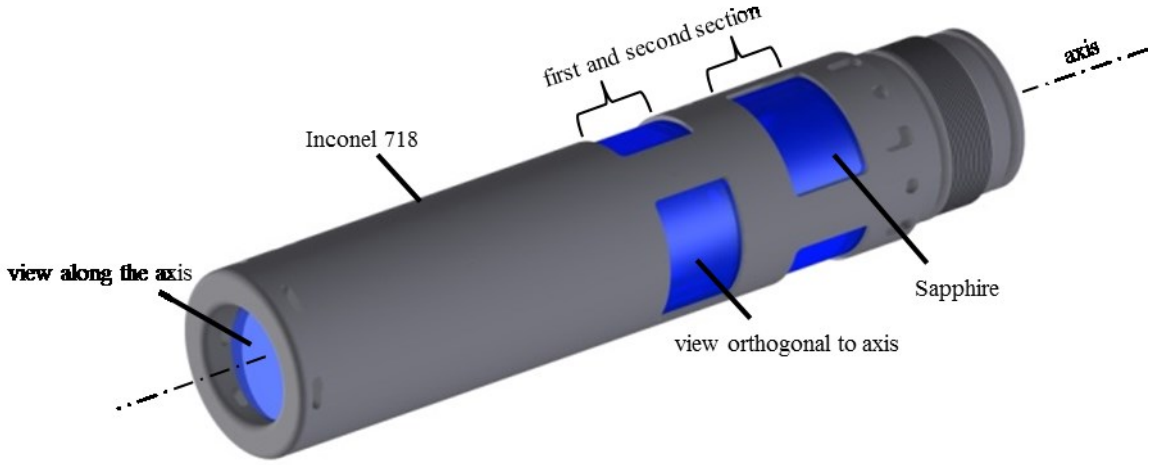

Figure 3: 3D design of the housing of the camera unit (Spatafora, 2014)

The high requirements on the housing of the GeoKam demand special materials. The material used is a nickel-base superalloy. In case of the GeoKam the material Inconel 718 [Haynes, 2001] is favored. Its high strength at high temperatures and its corrosion resistance allow a low wall thickness for the housing. For the camera unit a transparent ceramic material is needed in the areas where sight on the borehole wall is required. The transparent ceramic is also needed to withstand the high loads in the borehole. There are only a few materials, e.g. sapphire (Al_2O_3) or spinel ($MgAl_2O_4$), which fulfill these requirements. The calculations for the dimensioning of the camera unit are performed with the material resistance of the ceramics since their probability of fracture is higher and their strength is lower compared to Inconel 718. Considering the outer diameter of the GeoKam of 95 mm the calculations result in a minimum wall thickness of 15 mm (sapphire). This result is validated through a thermal stress analysis with the FEM software ANSYS Workbench. [Spatafora, 2014]

The jointing between Inconel 718 and sapphire is achieved through high temperature brazing. This holds some advantages, since it enables a bond between different materials as, in this case, metal and ceramic. The use of the braze material Incusil^{TM} ABA from Morgan Technical Ceramics [Morgan, 2013] omits the metallization of the ceramic and the materials can be jointed without pretreatment. Another advantage of brazing is the possibility of jointing complex geometries. For the GeoKam this allows relatively large side windows (Figure 3). The braze material also relieves, to a certain degree, the internal stresses, which occur due to the different thermal expansion coefficients. The prerequisite of the brazing material is a lower strength compared to that of base materials. The brazing material serves as a compensation layer between the metal and the ceramic. Another point to consider is the tightness of the jointing since it is very important that there is no leakage into the probe during service. Due to the high pressure and temperature and the corrosive thermal water in the borehole, the tightness cannot be guaranteed by sealing. Additionally it is very difficult to seal a curved plane, as the side windows.

Several high temperature brazing tests with sapphire and Incusil^{TM} ABA show a very good wettability of the sapphire with a wetting angle smaller than 2°. This is confirmed by metallographic analyses. [Spatafora, 2014]

2.2 Heat shield

The insulation layer serves the thermal insulation and has great influence on the durability of the components inside the camera unit. Combined with a cooling system the temperature within the camera unit can be kept below 90 °C at a surrounding temperature of 165 °C. A Dewar is used for insulation since it shows the best insulation capabilities compared to rockwool, polyurethane foam, polystyrene or aerogel at a smaller wall thickness [Isele, 2013]. The Dewar for the camera unit should be transparent in the area of the camera module, which is why glass Dewars (figure 4) and steel Dewars (figure 5) are used. The dimensioning of Dewars for the GeoKam has been sufficiently dealt with by Isele et. al [Isele, 2013] and is not part of this paper.

The glass Dewar is one of the most sensitive parts of the GeoKam and therefore has to be extra protected (Figure 4). In no case may it be damaged during service since a rise in temperature over 90 °C within the probe would lead to failure and destruction of the electronic parts. To avoid this problem, a cage of stainless steel (protector) surrounds the glass Dewar. The lagging also serves as connection between the housing and the Dewar. Between lagging and Dewar, a polymer [Modulor, 2013] is filled in, to cushion shocks. The glass Dewar consists of the Material Duran of Schott AG [Schott, 2013]. The manufacturing of the Dewar follows two steps. At first a small glass cylinder is fitted into another glass cylinder and they are jointed at one end. In the second step a vacuum is drawn and the opening is sealed. [Spatafora, 2014]

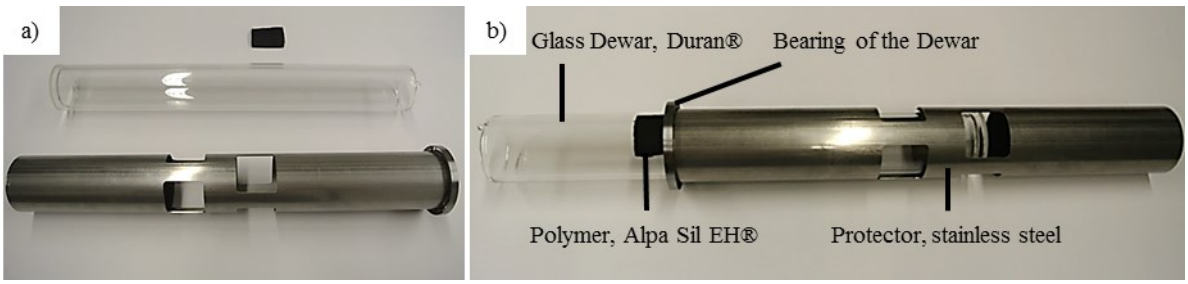

Figure 4: Components a) and assembly b) of the Glass Dewar (Spatafora, 2014)

The areas outside of the camera are insulated with steel Dewars (Figure 5). The wall of the inner cylinder of the steel Dewar has to be as thin as possible in order to limit the heat transfer from the outer cylinder through the jointing to the inner cylinder. Furthermore it has to be considered that the outer, warmer cylinder expands more than the inner cylinder. In order to prevent damage resulting from the different thermal expansions, the inner cylinder is furnished with beads (Figure 5, b)). To draw the vacuum the connecting ring are provided with bores.

The manufacturing of a steel Dewar is carried out in several steps. The pipes and the connection rings are jointed through TIG-welding. Afterwards the Dewar is heated in order to burn away the contamination in the vacuum chambers and on the outer surfaces. This step is carried out in a vacuum. After cleaning the bores at the connection rings are closed.

For the insulation in axial direction Teflon is used because of its temperature resistance and insulation properties.

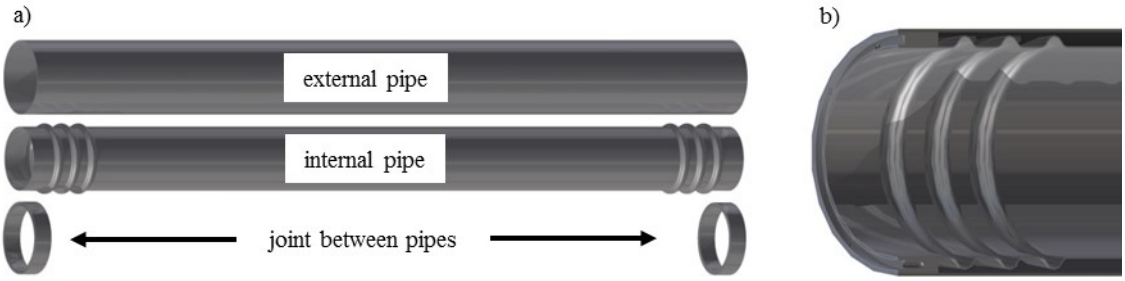

Figure 5: Components a) and cross section view b) of the Steel Dewar

2.3 Lighting system

The purpose of a video inspection probe is the capturing of images in preferably high quality. The lighting system has major influence on image quality. Through subtle positioning of the light and adequate light intensity important details of the borehole can be made visible. Therefore a completely new light management has been developed for the GeoKam.

The camera unit lighting system consists, as the GeoKam, of three levels (Figure 6). Each level is individually controllable and dimmable. The outer layer (protection layer) is equipped with two rings with 12 illuminants each. One Ring sits near the front window, the other one between the two sections of the side windows. In the intermediate layer (insulation layer) illuminants are attached between the housing and the glass Dewar, four units close to each side window and another six units close to the front window. Every Window is individually controllable and dimmable. In the inner layer (working layer) two illuminants are positioned right next to the lens of the camera module in such way that they rotate with it (Figure 7, a) b) c)).

The relatively large number of illuminants in different layers enables the operator to adjust the illumination and set the ideal lighting conditions. Reflections from the casing or from floating particles can be reduced through an indirect illumination or dimming of the illuminants.

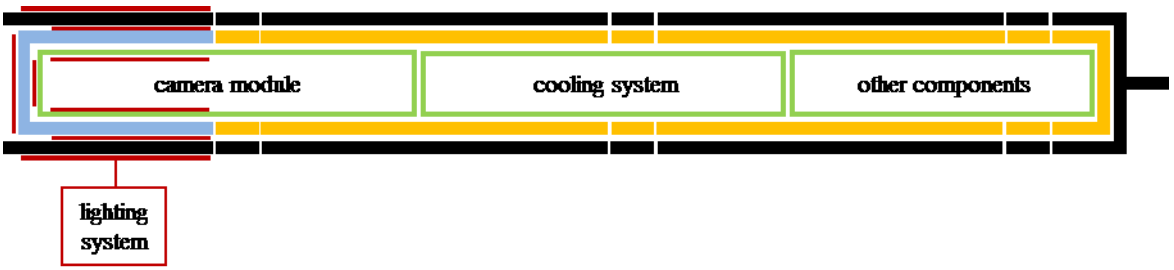

Figure 6: Position of the lighting system; lighting between the three layers of the GeoKam

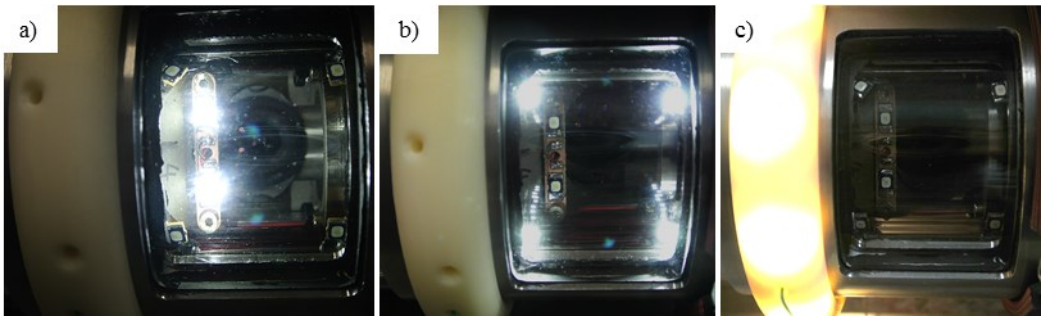

Figure 7: Position of the lighting; a) working layer, b) insulation layer, c) protection layer (figure 2)

The illuminants face different conditions depending on in which layer they are localized. The outer illumination rings are in direct contact with the environment inside the borehole and thus suffer from temperatures up to 165 °C and pressures of up to 48 MPa. Additionally the lighting housing has to be resistant to shocks and friction. The illuminants between housing and glass Dewar are only exposed to the high temperatures but need to be as flat as possible since the available space is very limited. Within the probe the heat produced by the inner illuminants has a negative influence on the temperature and thus has to be as small as possible.

To fit these high requirements LEDs (light-emitting-diode) are used. The LED is a highly efficient illuminant and very space-saving at the same time. The light intensity of the used LEDs is 26-38 candelas. This is comparable to a 20 W halogen lamp. Despite the high light intensity the power needed is only 1.5 W and therefore the amount rejected heat is also very small. Stress testing under realistic conditions proves the pressure and temperature durability. In a furnace the LEDs are exposed to a cyclic thermal load with temperatures of 55 °C and 165 °C. After a period of 56 days (1344 hours, 125 cycles) the Test ended without any failures of the LEDs. However the experiments show that the intensity of the LEDs decreases over time. During the 56 days the light intensity fell to approximately 23% of the initial value. The pressure durability is tested in an autoclave with a maximum pressure of 50 MPa. The pressure load of 50 MPa had no influence on the LEDs.

2.4 Cooling system

The GeoKam camera module consists of a multitude of actors and sensors which may not overheat. The maximal tolerable temperature for the camera module is 90 °C. Owing to the surrounding temperature of 165 °C in borehole and the generated heat of the electronic parts, a temperature of about 90 °C is fast and easily to be reached. In order to prevent the overheating, a cooling system is used. However the cooling system succumbs to some limitations. The available space is limited through the outer diameter of the probe of 95 mm, the wall thickness and the dimensions of the Dewar so that the maximal diameter of the cooling system is only 65 mm. Additionally the cooling system has to ensure a sufficient cooling throughout the whole period of use. The calculated thermal load of the GeoKam is about 100 W.

An adequate solution is the use of a PCM (phase change material), which absorbs the produced heat in form of energy when it heats and begins the phase change. Due to its high heat capacity, phase change temperature, environmental compatibility and good availability frozen water is used as PCM. The disposable heat is proportional associated with the amount of PCM used. The amount of PCM needed to keep the temperature at the critical parts below 90 °C for the requested time can be calculated, if the system boundaries are identified. The heat transfer from the critical zones to the PCM is realized with heat pipes. The heat pipes contain smallest amounts of a refrigerant. At the end of the heat pipe, close to the critical zones, the refrigerant vaporizes and transports heat from the system. At the other end, which is embedded in the PCM, the refrigerant condenses and releases the heat to the PCM. This principle makes it possible to transfer a high quantity of heat over large distances through a relatively light and small heat conductor. [Isele, 2014]

In order to determine the system boundaries of the cooling system, investigations have been carried out. The used cooling system corresponds to the geometry of the later system having only a smaller reservoir for the PCM and a smaller support plate for the electronics. For the heat transport three heat pipes with 8 mm diameter and 600 mm length are used. Each heat pipe can dissipate 55 W, according to the manufacturer's instructions. For generating the heat load of 100 W, the heat resistors are mounted on a support plate (copper plate). The heat pipes are plugged with 1/3 of the length inside the support plate. 2/3 of the heat pipes stuck inside the

PCM reservoir. For the experimental setup seven thermocouples are mounted to scan the temperature profiles at the different zones (figure 8, a)). The experiment is carried out in a thermal insulation cabinet, so that the result cannot be influenced by external environmental influences. During the experiment in the thermal insulation cabinet, the PCM reservoir and the heat source are thermally isolated from each other in such way that the heat transport mostly takes place in the Heatpipes. The experiment is carried out with 1.5 L water as PCM.

In Figure 8, b) the results of the study are presented. The curves 1-7 show the temperature profile of each zone until the curve 2 (green) reaches the maximal allowable temperature of 90 °C. The thermocouple 2 sits directly on the heat resistance and measures the hottest place in the system. With 1.5 L of water at an initial temperature of circa -10 °C (pink curve) and a heat load of 100 W, the cooling system holds the temperature below 90 °C for circa 8000 seconds (circa 2.2 hours). Moreover it can be seen that in the first 1000 seconds a temperature peak of 50 °C is reached (green curve). The reason is that the heat pipes need a certain time before the cooling medium evaporates to enable the heat transfer. Between 1000 and 3500 seconds the temperature is relatively constant in a range between 20 °C and 40 °C. During this time the ice absorbs heat and changes its phase from solid to liquid. The phase change takes place without the water temperature rising. After 3500 seconds the phase change is completed and the heat from the heat pipes is dissipated by an increase in temperature of the water. The heat transport is performed only as long as there is a temperature difference between the PCM and the heat source.

Figure 8: Experimental result of the cooling system; experiment with a load of 100 W and 1.5 l H_2O; heat transfer by three heat pipes, each with a diameter of 8 mm

2.5 Camera module

The camera module of GeoKam has a front camera and two side cameras. All three cameras are arranged axially to the probe, because the installation space only allows a maximum diameter of 46 mm. With mirrors a view to the borehole wall for the side cameras is possible. Through the main drive the complete camera module can be rotated, so that the cameras always have a clear view through one of the side windows. The self-rotation of the camera module is being prevented with a worm drive (self-Retaining). With ball bearings and plain bearings a trouble-free operation is ensured even at temperatures above 90 ° C. For each sensor a lens is used in which the focus and aperture can be adjusted. To prevent the miniature drive from damaging the focus and the aperture of the lenses, they are electrically and mechanically stopped. All electrical drives are suitable for an operating temperature of 125 °C. (Figure 9)

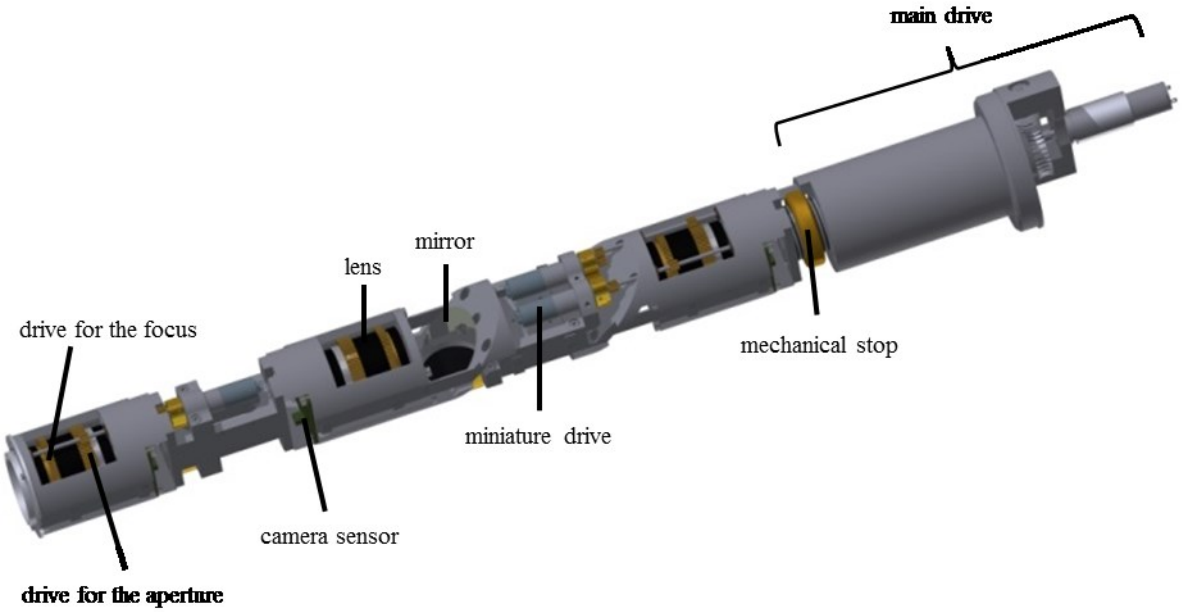

Figure 9: 3D design of the camera module

Each camera is composed of a camera sensor, a lens and two miniature drives. The wide-VGA sensors (video graphics array) have a resolution of 752 x 480 (H x V) pixels. The camera sensors send a digital serial stream in color with up to 60 fps uncompressed to the camera electronics, which then compresses the stream and converts it to a suitable format. The sensors are certified for temperatures up to 105 ° C. Through the effective lens aperture of 21.5 mm (front) and 12 mm (rear), the sensor can be supplied with sufficient light.

The camera electronic of GeoKam is used for a range of computationally intensive tasks. For example, it is used for the three cameras of the camera module, the control of the motors for focus and aperture, the control of the lighting system as well as for the realization of the digital modem for data transmission. For this reason, an FPGA (field-programmable gate array) is used as a central component, since it can be configured universally depending on the application. Other components on the board are a fast SRAM (static random-access memory), an analog-to-digital and digital-to-analog converter and an Ethernet PHY chip. The camera electronic can be operated at temperatures up to 125 ° C without cooling. [Isele 2014]

To ensure a trouble-free operation and an optimum in image quality of the camera module, different investigations were carried out. For example the lighting system, the lens and the electrical drives were examined in a dark room (figure 10). In addition, the mechanics of the lens were tested in a furnace under cyclic thermal load between 20 ° C and 90 ° C. New knowledge was gained through the investigations and the camera unit could be further optimized.

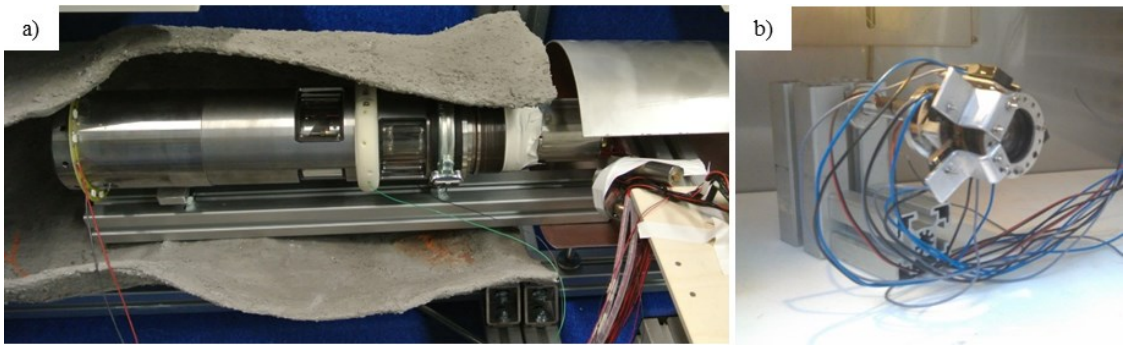

Figure 10: a) test of the camera image at a rough surface and the lighting system; b) thermal stress test at 90 °C of the lens mechanics

Figure 11 shows camera images of the camera unit. The camera images are from a side camera in which the object is 100 mm (Figure 11 a)) and 400 mm (Figure 11 b)) away. The images were carried out in a dark room. To illuminate the object, the lighting system of the camera unit was used.

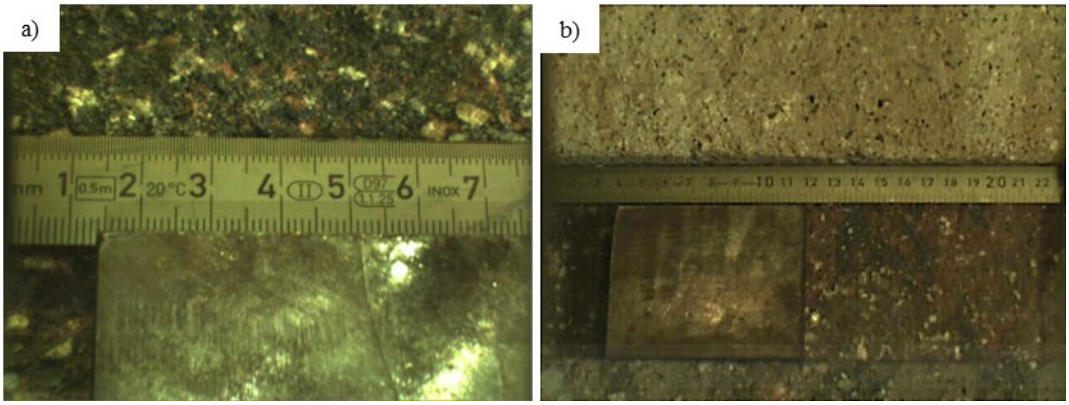

Figure 11: Camera images; a) object with a distance of 100 mm and b) object with a distance of 400 mm

3. CONCLUSION

The results of this paper show that in the future the GeoKam can be used in extreme conditions. It allows by a variety of new developments, the streaming of high-quality images in operation. It has also been shown that the development of an user-friendly handling of the probe was a main priority. Through a high level of flexibility, as for example the lighting system or cooling systems have, the user can adapt the GeoKam excellently to the borehole conditions. Also the reliability of the camera unit was confirmed by investigations on a laboratory scale, which plays an important role for the later application.

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