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Progress Report: GeoKam – A Modularly Designed Real-time Video Inspection System

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Keywords

Deep geothermal energy, instrumentation, quality management, EGS, downhole tools

ABSTRACT

The video inspection tool GeoKam is being developed for the harsh wellbore conditions in deep geothermal boreholes. The main part of the GeoKam components were completed in 2016, and initial tests on laboratory scale were carried out. Some components such as the camera housing, which consists of a metal-ceramic composite, are not yet ready for use and must be further optimized. Therefore, different solutions have been developed, technically implemented and validated. Furthermore, important design standards for downhole logging tools have been established and implemented to increase tool efficiency and thus operating time.

1. Introduction

At Karlsruhe Institute of Technology, Institute for Applied Computer Science (KIT-IAI), a real-time video inspection system (GeoKam) for deep geothermal boreholes is being developed. The ZWERG concept, which stands for a highly flexible platform strategy for fast and low-cost development of different borehole tools, offers the basis for the technical realization of GeoKam, e.g. Isele et al. (2015). The main application of GeoKam will be to detect and locate damages and leaks in casings, to perform general inspections, and to explore the open hole, which is of high interest to geothermal energy production, e.g. Holbein (2015).

Other manufacturers have also recognized the need for a video inspection tool to minimize the well-known risks in geothermal energy. The geothermal well inspection camera developed by Perma Works LLC is designed for temperatures of up to 250 °C and pressures of up to 35 MPa. In two different modes, with or without conical mirror, the camera is able to inspect the wellbore wall radially or in the axial direction. The mirror is mounted before operation, as required. The heat-sensitive camera sensor and lens are protected by a nonpermanent cooling system using CO_2 (dry ice). The generated five MPx images are stored downhole on a memory card (micro

SD). The camera has a diameter of 73 mm and is 5.4 m long, e.g. Normann (2016). Moreover, there is the WellCAM® E-Line inspection camera by Vision iO AS, which is designed for temperatures of up to 125 °C and pressures of up to 103.4 MPa. A wide-angle camera with 5 MPx behind a pressure window (dome) allows a radial and axial view of the wellbore. The generated images can be stored with full resolution downhole and transmitted via wireline to the surface with low bandwidth (control images). The lighting system is inside the housing as well. The camera is 1.85 m long and has a diameter of ca. 57 mm, e.g. Vision iO (2017). Furthermore, there is the “Big Boy” downhole camera provided by Hitwell Deep Well Imaging Inc. for temperatures of up to 204 °C and pressures of up to 69 MPa. With a resolution of 0.46 MPx, the camera is capable to transmit the images via wireline to the surface. The tool has a diameter of 60 mm and is 1.5 m long, e.g. Hitwell (2017).

However, GeoKam is especially dedicated to meeting the requirements of geothermal wells in Central Europe, providing advanced operation possibilities for future handling applications, which are fully remote controlled and visually supported, as e.g. downhole casing repair.

2. Performance of the GeoKam

Through special materials, an ingenious cooling system and insulation, powerful electronics with a real-time capable data transmission via wireline and a modular tool design, ZWERG tools can be flexibly adjusted and applied in different boreholes worldwide. In a first step, an operating temperature of up to 165 °C and pressure of up to 48 MPa will be achieved. In a second step, operating temperature and pressure will be increased to up to 200 °C, respectively 60 MPa. Furthermore, it is an objective to use standard electronic components (automotive standard, <125 °C) ensuring that electronic systems can be implemented in a fast and affordable way and that powerful standard components such as sensors or actuators can be applied without long development times. With an outer diameter of 95 mm and a length of 2.4 m, the tool can be used in boreholes of 8 ½ inches (ca. 215 mm). Due to the high pressure, temperature and corrosive thermal water, the housing of GeoKam consists partly of a nickel-based superalloy (Inconel® 718) and the transparent magnesium spinel (Perlucor®, CeramTec ETEC GmbH). Both high performance materials allow a thin-walled housing design, considering the harsh borehole conditions. For an optimal borehole inspection, one front camera (VGA sensor, 0.36 MPx, 60 fps) and two side cameras with adjustable lenses are installed. The cameras can rotate 360 ° and have large fields of view. Besides the cameras, a lighting system has an important effect on the image quality, too. Through subtle positioning and individually controllable and dimmable lights inside and outside of the housing, important details of a borehole can be made visible. Disturbing reflections in the image, which are caused, e.g. by the floating particles in the borehole or by the casing, can be reduced to a minimum through indirect illumination of the observed object, e.g. Spatafora 2015. To protect the heat-sensitive actuators and sensors from the high operating temperature of about 165 °C, a cooling system and Dewar flasks are used. The cooling system is a nonpermanent cooling system, which includes a PCM (Phase Change Material, water) storage and heat pipes. This type of cooling is compact and flexible. Therefore, tool manufacturers often use PCM as heat sinks, e.g. Normann (2016). To determine the performance of the cooling system of GeoKam/ZWERG, several investigations with promising results were carried out, e.g. Spatafora (2015).

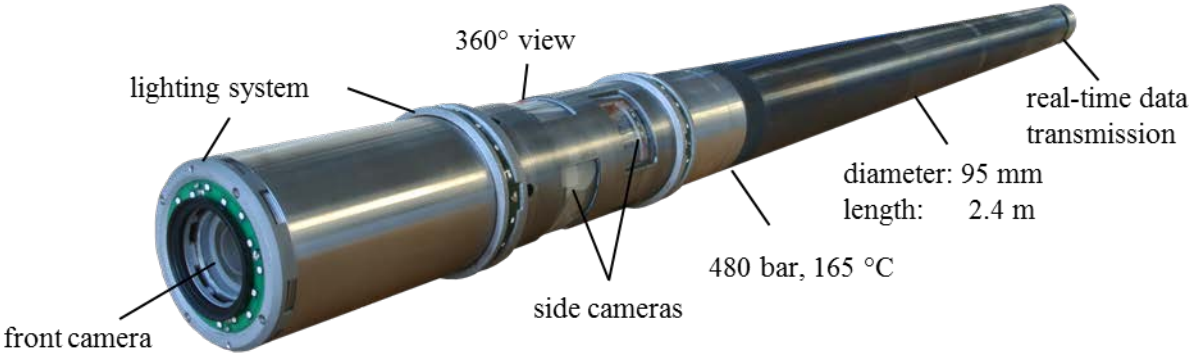

Figure 1: Video inspection system GeoKam, e.g. Spatafora (2016)

3. Design-related Challenges

The modular designs of GeoKam and all other tools based on the ZWERG platform have the advantage that single modules such as the electronic module can be used for different tools universally. Therefore, the single modules must be compatible, which is solved by a definite construction guideline. The design of each module is composed of a cylindrical housing, with an internal cylindrical Dewar flask insulation and sensors and actuators needed for the special tool type. In Figure 2, two different schematic designs of GeoKam are shown. In the upper one, electronic and cooling modules are realized as separate units, which can be mounted mechanically and electrically by special housing connectors. This design version allows a high flexibility of modules, but complicates the manufacturing process of the components, the assembly of the tool and the thermal insulation. Hence, in this case, a high modularity depth leads to a deterioration of the tool properties as well as to longer development time and higher costs. Below, an optimized design, where the electronic and cooling modules are connected is shown. In this way, the cooling system works more efficient, because there is less heat transfer between electronic unit, heat pipes and PCM cartridge. Moreover, the steel Dewar flask consists of one part, thus additional heat inputs at the Dewar interruptions are avoided. Assembly of the tool is simplified too, because actuators and sensors are fixed on the same mounting plate and do not need to be secured against twisting when the housing is closed. The housing of the camera unit is also modified by an additional housing connector for a simplified exchange of LEDs of the lighting system. For GeoKam, the electronic module and the cooling module are combined, but basic constructional standards have been established so that e.g. new housings or Dewar flasks only vary in length. The cooling system and electronics can also be used separately in other tools.

One of the major challenges for the technical realization of GeoKam is the housing of the camera module, which consists of a metal-ceramic composite. In the area of the camera, only transparent materials such as sapphire or magnesium spinel (Perlucor®) are usable. For the camera unit of GeoKam, Inconel® 718 and Perlucor® are used, e.g. Spatafora (2016). In Table 1, the physical, thermal and tensile properties of Perlucor® and Inconel® 718 are shown. The large mismatch between the CTEs of Inconel 718 and Perlucor® and the low bending strength as well as a brittle material behavior of Perlucor® require an adequate joint design. The weak point of the bond is definitely the polycrystalline ceramic Perlucor®, which is sensitive to tensile stress.

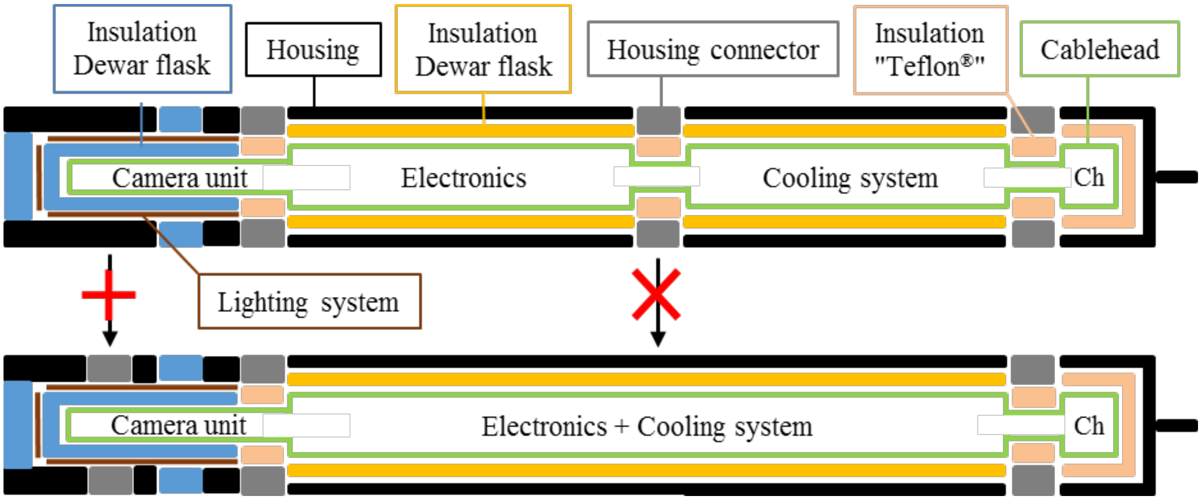

Figure 2: Schematic designs of GeoKam; top: first design with several weak points; bottom: current optimized design

Table 1: Physical, thermal and tensile properties of Perlucor® and Inconel® 718

(20 – 200 °C)		Perlucor®	Inconel® 718
Young´s Modulus	[GPa]	280	190
Coefficient of Thermal Expansion (CTE)	[10^{-6} K^{-1}]	6.5	13.4
Yield Strength (0.2% offset)	[MPa]	-	1.120
Tensile Strength	[MPa]	-	1.370
Bending Strength (FPB)	[MPa]	250	-
Compressive Strength	[MPa]	2.000	-
Poisson´s Ratio		0.22	0.3

The GeoKam design provides one front camera and two side cameras for inspecting the wellbore optimally. For the front camera, a plane ceramic window is used, which is relatively unproblematic. Moreover, it is possible to design the frame of the window in a specific manner so that mainly compressive stress acts on the ceramic, and tensile stress can be kept low. In contrast, the available space for the side windows in the radial direction is limited due to the housing outer diameter (95 mm) and the glass Dewar flask outer diameter (67 mm) (see Figure

2). The height is given by the camera sensor and lens and should be minimum 44 mm. Due to high thermo-mechanical loads in operation, a complex Perlucor® manufacturing process, limited mounting space for the side windows, and a difficult joining process between metal and ceramic, a cylindrical window shape is preferred (Figure 3). Both cylindrical windows are bonded on the front sides with Inconel® 718 mounting threads. An Inconel® 718 frame protects the ceramic cylinders against shocks, bending and tension. Between protection frame and cylinders, a small gap is realized to enable a constant hydrostatic pressure from the thermal water on the outer sleeve of the side windows. Since the compressive strength of Perlucor® is eight times higher than the bending strength, a thin wall thickness of the windows is achieved. Thus, critical tensile stresses are not caused by high hydrostatic pressure in operation, but rather by thermal stresses induced due to different CTEs and the temperature gap in operation or during the joining process.

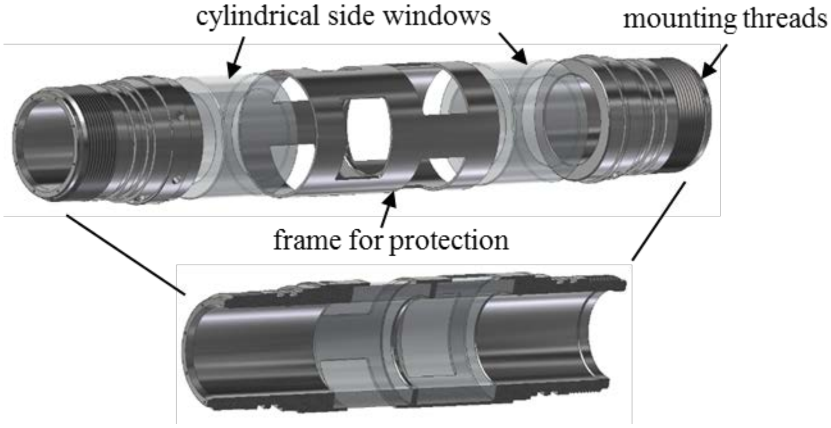

Figure 3: Schematic design of the side windows of GeoKam; top: exploded drawing; bottom: cross section

4. Advancement in the Robust Window Joining Process

The joining process finally decides whether the Inconel® 718-Perlucor® composite is reliable or not. Several joining variants such as high-temperature brazing, shrinking, gluing and sealing with O-ring were examined. Each technology has its own advantages. By high temperature brazing with an active braze, a high strength of the joint and high operating temperatures can be realized, e.g. Spatafora (2014). But the required brazing temperature lies above 700 °C to reduce the surface energy of the ceramic and induces critical thermal stress during the cooling phase of the brazing process when the liquid braze is solidified and the mismatch of the CTEs lets the tensile stress increase continually, e.g. Fernie (2009). With an adequate construction design and brazing process, these critical stresses can be diminished to a minimum and the requirements on the GeoKam housing can be increased. Therefore, the brazing technology is one of the favorite technologies to produce a highly loadable joint for the camera housing. However, due to a large number of design and manufacturing variables, this method requires further development efforts. Hence, other technologies with slightly inferior properties are investigated as temporary solutions.

Gluing, which requires a low joining temperature of less than 220 °C, is another promising adhesive bonding technique. No complex joining facilities, such as vacuum furnaces or mounting devices, are needed. However, due to high temperatures and pressures during tool operation, a special reinforced one-component epoxy glue and a large adhesive surface are required. Despite the low joining temperature compared with brazing, critical stresses due to the mismatch of the CTEs are induced as well, which is made visible by means of a polarized light in Figure 4. After an autoclave test at 60 MPa, the joint shows several damages. Comparing the damages in the center of Figure 4 with the stress flow on the left side in Figure 4, it can be seen that they correspond quite well. Thus, the glue cannot diminish the thermal stresses from the joining process in an acceptable range, e.g. Spatafora (2016). In a simulation study with the FEM software tool Abaqus® CAE, the gluing process was investigated. It was established that critical tensile stresses caused by the joining process are induced on the cylindrical ceramic window and a fracture as shown on the right side in Figure 4 is expected.

Figure 4: Result of a gluing joint between the cylindrical side window and Inconel® 718 housing; left: stresses visualized by polarized light; center: fracture of the side window after an autoclave test; right: removed ceramic side window with fracture after stress test

Both joining techniques induce critical tensile stresses leading to fractures in the ceramic side window. Through an adhesive bond between ceramic and Inconel® 718, the stresses caused by the joining processes can only be diminished through plastic deformation of the Inconel® 718, braze or glue. Due to the high Young´s modulus and yield strength of Inconel® 718 (Table 1), only braze or glue are able to compensate the mismatch between the CTEs, e.g. Ghosh (2011). But the thickness of the brazing foil or glue is very thin (ca. 50 - 200 µm). Therefore, additional ductile materials for the joint are necessary.

A quasi-thermal decoupling of both materials, in which the contact surfaces can slide against each other and thermal stresses are reduced, is achieved by shrinking. The Inconel® 718 frame is heated to approx. 270 °C and subsequently fitted onto the cold cylindrical side windows. By cooling the frame, a joint pressure (frictional connection) is thus created. This type of joining is favorable for the ceramic windows, because the tensile stresses are low and the ceramic is mainly loaded by compression. The tensile stresses on the outer surface of the cylindrical windows, which depend on joint pressure, CTE and surface friction, can be diminished with an adequate design of the Inconel® 718 frame according to, e.g. Kochendörfer (1992). The weak point of this joining technique for a geothermal application is the limited operating temperature, because the height of the joining pressure depends on the operating temperature and at critical temperature, the joint detaches. In the case of GeoKam, an operating temperature of 165 °C may be realized, which is confirmed with a FEM study. On the other hand, the joining process is complex due to the required high fabrication tolerances of Inconel® 718 and Perlucor® as well as a difficult assembly process.

Another possibility for thermal decoupling of both materials is sealing with O-rings. By using special O-ring materials, high operating temperatures and pressures as well as a good chemical resistance against thermal water can be achieved. The O-ring can be positioned axially on the front side of the cylindrical side windows (flange gasket), so that no gap tolerances need to be taken into account and a space-saving design can be realized. Thus, the dimension of the O-ring groove remains constant in operation, and pressures above 60 MPa at 200 °C can be obtained. In a FEM study, with subsequent calculation of the fracture probability of the ceramic side window, according to DIN EN 843-5, a theoretical feasibility was confirmed. In an autoclave test with 60 MPa and 220 °C of a cylindrical side window sealed with EPDM O-rings, these results were confirmed (Figure 5). The positive results and the relatively simple implementation lead to the use of this joining technique for the camera housing of GeoKam.

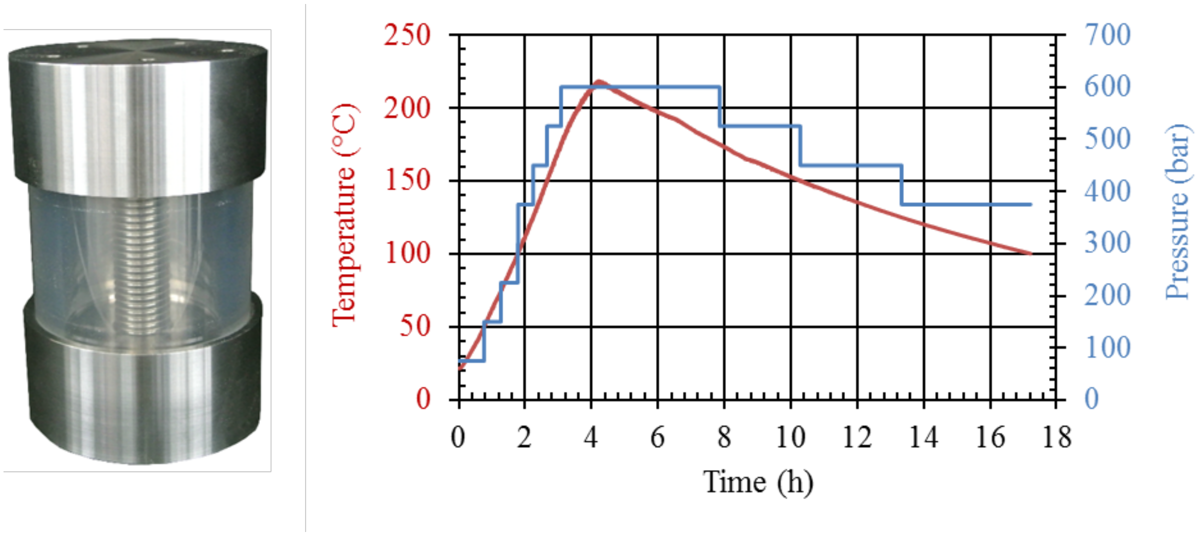

Figure 5: Left: test cylinder consisting of a cylindrical Perlucor® side window, two flanges and two EPDM O-rings for an autoclave test; right: temperature-pressure-time diagram of the autoclave test

5. Conclusion

The GeoKam requirements were accomplished by different design optimizations and a robust joining process for the metal-ceramic composite. The design was developed on the basis of ZWERG, and further important standards such as the connection of the cooling and electronic modules were defined. With the installed cooling system, the operating time can be extended. The demands on the metal-ceramic composite of the camera housing are fulfilled using O-rings and a suitable joining design. The new development results are implemented in the previous prototype. From the mechanical point of view, GeoKam is thus ready for operation. In parallel, the development of the data transfer technology is being finished.

The complete system shall be ready by the end of 2017. It will provide new insights into deep geothermal wells and build the basis for further tool implementations.

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