What is the use of heat flow measurements?

The term ‘geothermal heat flow’ refers to the thermal energy that dissipates constantly from its sources within the earth to the surface, either by convection or conduction.

Geothermal heat is the driving force for a variety of multi-scale geologic processes taking place in the earth’s crust e.g. plate tectonics. It is also driving chemical reactions like the thermal degradation of organic matter, which leads to hydrocarbon (oil and gas) formation. The latter explaining the industrial interest, while the first point is more of scientific interest. The internal temperature of the earth increases with depth. Near the surface, the average geothermal gradient is relatively constant with on average 30 K for every kilometer of depth. However, there are also places where it can be higher e.g. along mid-ocean ridges or mantle plumes.

Even though called heat flow measurements, heat flow itself is not measured directly. But based on the assumption, that heat conduction is the dominant transport process through the earth’s crust, and conductive heat flow occurs in the direction of decreasing temperature, heat flow can be calculated as the product of the vertical thermal gradient and thermal conductivity (Fourier’s law). If however other mechanisms like heat advection are involved (for example fluid flow processes), heat transport may be characterized by non-linear thermal gradients and also occur horizontally.

Therefore, a heat flow measuring system is actually a device to measure in-situ thermal gradients and thermal conductivities of marine sediments, from which heat flow (or the heat flux density) can be determined. Also additional thermal parameters such as the sediments thermal diffusivity and volumetric heat capacity may be derived. All these parameters provide essential information regarding technical and environmental aspects to a number of applications, some of them described in more detail in the following.
Oil and Gas Exploration

In the field of petroleum geology heat flow measurements are essential in the exploration of new oil and gas reservoirs, as they provide critical constraints for sedimentary basin modeling and aid in thermal maturity calculations. In order to determine the probability of oil and gas formation it is decisive to unravel the thermal history of potential source beds, as the generation of hydrocarbons strongly depends on the temperature the sedimentary source rock has experienced since deposition. The degree to which the metamorphism from organic matter to hydrocarbons has progressed can be inferred from thermal maturity of a rock, but only if a valid conceptual model of local geology is available, including the present day heat flow and thermal conductivity distribution.

Cable Route Survey

The booming offshore wind energy market has recently opened a new field of activity for heat flow measurements, as in particular thermal conductivity values provide useful information for estimating the dissipation mechanisms of thermal energy and also the environmental impact of power cables. When electric energy is transported via sub sea cables from the transformation platform to shore, a certain amount gets lost as heat, leading to an increased temperature of the cable and subsequent warming of the surrounding environment. Important factors determining the degree of temperature rise are besides the cable characteristics itself – the thermal characteristics of the surrounding environment, in particular the thermal conductivity, thermal diffusivity and heat capacity of the sediment.
Gas Hydrates

Heat flow measurements also enable stability analysis of gas hydrate deposits. Gas hydrates have been found to occur naturally in large quantities in ocean sediments, deep lake sediments, and permafrost regions. The amount of methane potentially trapped in natural gas hydrate deposits is significant, which makes them of major interest as a potential energy resource for the future. The formation of gas hydrates is an exothermic process, i.e. heat transfer always accompanies the formation, which allows the detection of gas hydrate reservoirs with the help of heat flow measurements.

The figure above shows temperature profiles across a gas hydrate reservoir. The Profiles 'Pen 3' and 'Pen 4' show strong deviations from linear depth dependence indicating enhanced advection processes.
Data

The FIELAX heat flow measuring system records temperature as a function of time. A full measuring cycle starts with the penetration process. The probe is lowered to the ground (A) and penetrates the sediment, causing the temperature to rise due to frictional heating (B). From frictional heat and subsequent decay relative sediment temperatures as a function of depth are derived (C). After a certain period of stability time (~ 12 minutes), a heat pulse (typically 350-400 W) is released and heats up the sensor tube and the surrounding sediment (D). The probe remains in the sediment for another 20 to 30 minutes to record the decay of the injected thermal energy (E). The decay of the heat allows the depth-dependent determination of the sediment’s thermal parameters such as conductivity, diffusivity and capacity of the sediment. The cycle ends with the retrieval of the probe (F).

Instrumentation

The temperature is recorded with thermistors that are placed within a sensorstring. The length of the sensorstring is adjustable to the customer’s requirements, but the maximum number of temperature sensors is limited to 22. The sensors are designed for temperature ranges of -2°C to 60°C, with a resolution better than 1 mK resolution and accuracy within 2 mK. The sensorstring also contains a heating wire with which a distinct amount of energy is released into the sediments. The amount of energy dissipated from the heating wire is determined by precise voltage and current measurements. The data acquisition unit and the power supply unit are build in Grade-5 titanium pressure housings. Online or memory-based data recording with a frequency of 1 Hz is possible, which allows 2000 minutes of continuous recording. When operated in autonomous mode the heat pulse is controlled automatically via defined stability criteria.
Principal of Measurement

**Measuring Procedure**

A  B  C  D  E  F

**Temperature recording**

A  B  C  D  E  F

Temperature vs. Time (°C)
Different instruments are currently available for measuring thermal gradients and thermal conductivities. FIELAX provides full campaign services with all measuring systems:

Thermal measurements taken with the classical HeatFlowProbe have been conducted in a wide range of deep-sea environments, with the device using its own weight and gravity to penetrate the seafloor. The probe can be operated in water depths up to 6000 m. Also, ‘Pogo-Style’ measurements, i.e. where the probe remains lowered at depth during transit, are also possible and minimize deployment time considerably.

The VibroHeat measuring device has been developed specifically for in-situ thermal measurements in shear resistant marine sediments, typical for shallow seas, coastal and continental shelf regions. Therefore the measuring components are combined with a VKG6 type Vibrocorer. The FIELAX VibroHeat device can be operated from small vessels in water depths up to 200 meters. Being time and cost-efficient, it can retrieve sediment cores and acquire thermal conductivity profiles in one go.

In cooperation with Marine Sampling Holland, FIELAX has further developed the system to work with a CPT unit used for in-situ geotechnical measurements (PushHeat), in order to overcome possible liquefaction, which may occur in harsh sediments due to the vibrocoring. So far the sensorstring was adapted to fit into a standard coiled CPT-tube of 6 m length. Currently a combined version i.e. a sensorstring with a cpt cone mounted is also available.

The latest development allows OnshoreHeat measurements using borehole drilling technology of Wiertsema & Partners B.V. (The Netherlands). The system can be brought down the desired depth and measure the thermal parameters up to 5 meters downwards from the bottom of the borehole.
Classical HeatFlowProbe

VibroHeat

PushHeat

OnshoreHeat
Data processing and results

Processing of temperature data includes the calibration of sensors, inversion of in-situ sediment temperatures and temperature gradients, correction for probe tilt during penetration as well as the calculation of thermal conductivities and thermal diffusivities. The depth dependent in-situ temperatures, thermal conductivities and diffusivities are determined by an iterative inversion procedure. Both, thermal conductivity and also thermal diffusivity are derived independently from the temperature data, which also allows determining the volumetric heat capacity. This parameter serves as a valuable control of the measured thermal parameters. Low variation of volumetric thermal capacity with depth is a good indication of a reliable measurement. Advantageous is the comparatively high resolution of data with depth, which allows to track distinct variations in each parameter over several sensors.
Bullard plot: Heat flow steady state and its deviations

The Bullard plot compares what is called ‘integrated thermal resistance’ with temperature. The interpretation of this data allows deciding whether heat flow is in steady state i.e. purely conductive (linear relationship) or if other mechanisms are involved. Deviations from linearity most likely originate from advective processes such as vertical fluid/gas movements or transient processes like bottom water temperature variations. Both processes lead to a 'deformed' temperature distribution in the upper layers which then are not useable for steady state heat flow determinations. Therefore penetration depths of more than three meters are essential for obtaining geothermal gradient estimations independent of seasonally influenced sediment layers. Nonetheless these data yield valuable information and allow the calculation of fluid flow velocities or the reconstruction of seasonal bottom water variations.
Calculating the thermal effect of fluid advection

(A) The convex shaped temperature distribution indicates that the non-linear variations of the temperatures in the upper four meters originate from advective processes such as migrating pore water and/or escaping gas (open symbols). For conductive heat flow determination only the lowermost five sensors (solid symbols) are used. (B) By fitting the temperature data of the upper four meters to a theoretical advective temperature distribution equation assuming a simple homogeneous, conductive half space model, vertical fluid flow velocities can be estimated.
Thermal effect of bottom water temperature variation

From measured sediment temperatures (A) and thermal diffusivities (B) (open symbols) seasonal bottom water temperature variations can be reconstructed by using an inverse model of the temperature disturbance diffusion equation into the sediment. In (C) the reconstructed water temperatures are shown. The variations over the last year are approximated by a sinusoidal wave with an annual mean of 9.8°C, an amplitude of +/- 5.7°C and a phase with minimum temperatures at the end of January (day 27). The solid green line in (A) represents the temperature-depth profile derived from forward modeling with the inversion results received in (C).

![Graphs showing thermal effect of bottom water temperature variation](image_url)
Deployment and Recovery Options

At the aft, using the A-frame and a lifting deployment head

At the aft, using the A-frame with two blocks

Over the side using two cranes

Over the side, using a crane and a rotatable deployment head
FIELAX heat flow survey experience

Publications

Selected references:

- Marine Sampling Holland
- HYUNDAI Heavy Industries Co., Ltd.
- NGU
- NGI
- AWI
- IFM-GEOMAR
- Total
- GARDLINE
- HRT
- GEUS
- JX Nippon Oil & Gas Exploration
- CSIRO
- CICESE
- Total
- Gardline