

# NOVEL CO<sub>2</sub>-HEAT PIPE AS EARTH PROBE FOR HEAT PUMPS WITHOUT AUXILIARY PUMPING ENERGY

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## ABSTRACT

In Germany approximately half of the heat pumps installed are vertical earth coupled devices. The contamination of ground water through substances has been legally classified (1999). Water-glycol mixtures, used in conventional earth coupled heat pumps, are in class 1, which means moderate contamination. Carbon dioxide has been classified as a substance causing no contamination of ground water.

Research work at FKW has been done as well theoretically as also experimentally in order to lead the development of a CO<sub>2</sub>-earth probe to success regarding the performance and especially the capacity limit due to critical heat flux as also regarding the optimum charge.

The paper will present the experimental setups, experimental data from the measurements with the new developed CO<sub>2</sub>-earth heat probe for heat pumps and the verification of the theoretical investigations.

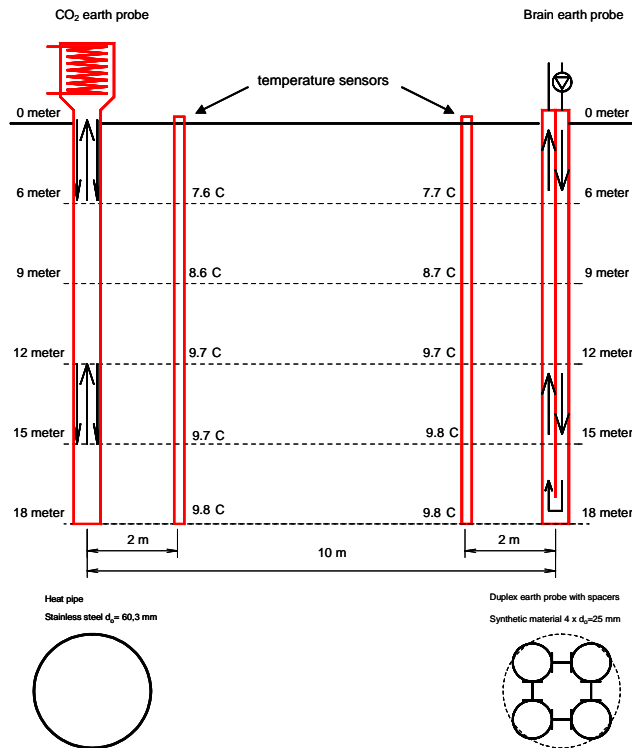
Using this new development it will be possible to build earth coupled heat pumps with this industrially manufactured CO<sub>2</sub>-earth heat tube for effective and environmentally-friendly heat pumps compared with conventional heat pumps using water-glycol mixtures. Cost considerations show the applicability of this new pumpless CO<sub>2</sub>-earth probe instead of the conventional pumping type.

**Key Words:** *CO<sub>2</sub>, earth probe, heat pumps, heat tube, heat flux density*

## 1 INTRODUCTION

In 1998 FKW Hannover applied for a patent regarding the application of carbon dioxide in a heat pipe for earth probes of the earth coupled heat pumps (Kruse 1998). Within a research project of the German Ministry of Economy first feasibility studies were performed in various laboratory tests and field investigations (Fig. 1).

Especially a field test was performed for comparison of the commonly used brine earth probe with the newly developed CO<sub>2</sub>-Heat Pipe, both of a length of 18 m, and each connected to identically heat pumps whereby the evaporator of the one heat pump was built directly on top of the heat pipe working there as carbon dioxide condenser and, on the other hand the evaporator for cooling the glycol was of the plate heat exchanger type serving the poly-ethylene dual type conventional duplex earth probe.



**Fig. 1. Field Test Set Up**

Therefore, FKW decided to develop the CO<sub>2</sub>-Earth Probe together with two other partners, namely on the one hand Aetna GmbH, Wildau, for the adaptation of the heat pipe to the earth and on the other hand Kaeltro OHG, Berlin, for the connection of the heat pipe to the heat pump, whereby FKW had the task to develop the heat pipe itself.

This development project was sponsored since 2003 by the German Environmental Foundation (DBU) and finished in June 2004. The aim of the project was “To develop for the heat pump a CO<sub>2</sub> earth probe working with the thermosyphon principle” which can be applied in similar earth bores as they are drilled for the conventional brine earth probes. Former investigations in Germany show that the heat extraction from the earth by an earth probe depends on the ground properties and can be assumed for a depth down to 100 m between 30 and 70 W/m. In general, for the first layout of the earth probe a heat extraction of 50 W/m is assumed which will be transferred from the ground to the earth probe.

## 2 THEORETICAL CONSIDERATIONS

In case of a heat pipe there is a limitation concerning a critical heat flux at which a flooding of the heat pipe can occur. This means that the vapour flowing out of the lower part of the heat pipe into the upper section is able acting by shear stresses on the down stream fluid film to convert its direction upwards so that no further liquid feeding to the inner side of the pipe can occur meaning that it will dry out due to lack of liquid which is stored at the upper end the heat pipe. This is an important phenomenon for the working limitations of heat pipes and depends besides the fluid properties on the length and diameter of the heat pipe. A lot of investigations on this effect have been done and presented in the literature and are summarized mainly by Faghri (Faghri 1995). Important correlations of the critical heat flux where flooding takes place derived from experimental investigations were presented by Wallis (Wallis 1969) and Kutateladze (Kutateladze 1972) whereby Wallis considered the equilibrium of the inertial and the hydrostatic forces evaluating his experiments with open pipes and gas and liquid water as

Because of better energetic results of the heat pipe earth probe in comparison to the conventional one due to the smaller temperature differences between on the one hand earth and CO<sub>2</sub> as well as on the other hand CO<sub>2</sub> and refrigerant as compared to the brine system and because no electrical pump energy is needed due to the automatic thermosyphon principle it was concluded that such a system offers special advantages in competition to the commonly used brine system.

Besides the energetic advantage especially the legal situation in Germany concerning the environmental protection of the ground water is an important argument for using carbon dioxide as an earth probe fluid. In Germany a regulation of 1999 regarding the ground water protection classifies various fluids in classes like class 1 for salt or glycol brines, hydro fluorocarbons etc., and on the other hand hydrocarbons and carbon dioxide etc. as not ground water effecting fluids.

fluid pairs whereby the surface tension of the liquid was not taken into consideration. Kutateladze considered the two phase equilibrium criteria depending on the inertial-, the buoyant- and the surface forces but not taking into consideration the effect of the diameter which can be important at smaller diameters. Further authors like Tien and Chung (Tien and Chung 1978), Imura (Imura 1983) and Faghri (Faghri 1989) have improved these correlations and included the effects of the diameter, the surface tension and the other fluid properties. A recent publication was presented by Zapke and Kröger (Zapke and Kröger 1996).

The theoretical critical heat fluxes according to these former investigations are shown (Fig. 2) depending on the pipe diameter and maximum length of the liquid film meaning that a longer pipe can not be wetted by the liquid film because of the limit of the specific heat flux into the pipe as caused by an average heat flux from the earth of 50 W/m depth. For example, for one heat pipe in an earth probe a film length of 80 meter needs a tube of 36 mm inner diameter or 2 tubes in parallel of 26 mm or 4 tubes in parallel of 18 mm at the heat flux limit. In order to reach a depth of one hundred meter which is the limit of the legal heat pump applications because without special governmental license deeper earth bores are not allowed for this purpose, a pipe diameter of 40 mm, 38 mm and 20 mm, respectively, is necessary.

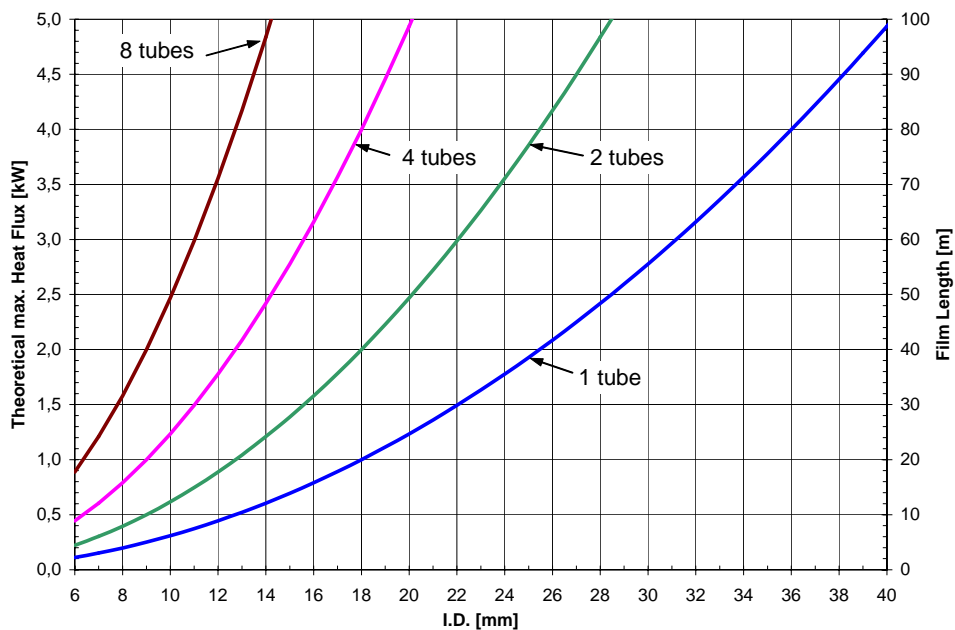


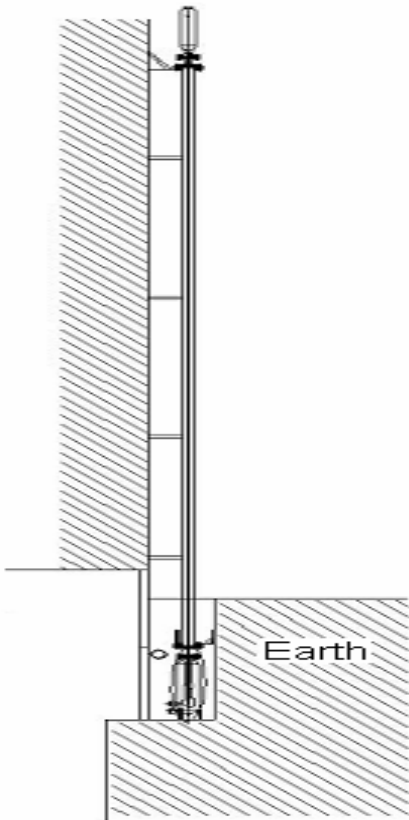
Fig. 2. Maximum Heat Flux and Film length at Flooding Limit

### 3 EXPERIMENTAL INVESTIGATIONS

In order to measure further the performance of CO<sub>2</sub> heat pipes, additionally to the laboratory and the field test setup as shown in Fig. 1 a special heat pipe test stand was built at the vertical rear wall of the FKW building allowing a total height of around 10 m with a netto heat pipe test length of around 7 m (Fig. 3).

The test setup consisted of a water filled insulated plastic pipe of a diameter of 60 mm filled with water which is pumped around through a thermostat in order to achieve a constant water temperature. This water is cooled or heated respectively to a temperature of around 10°C which represents the earth temperature under depth below 10 m to 100 m. Into this water filled tube the test heat pipe can be inserted to be heated by the water bath. On the inner side of the heat pipe which is filled with carbon dioxide

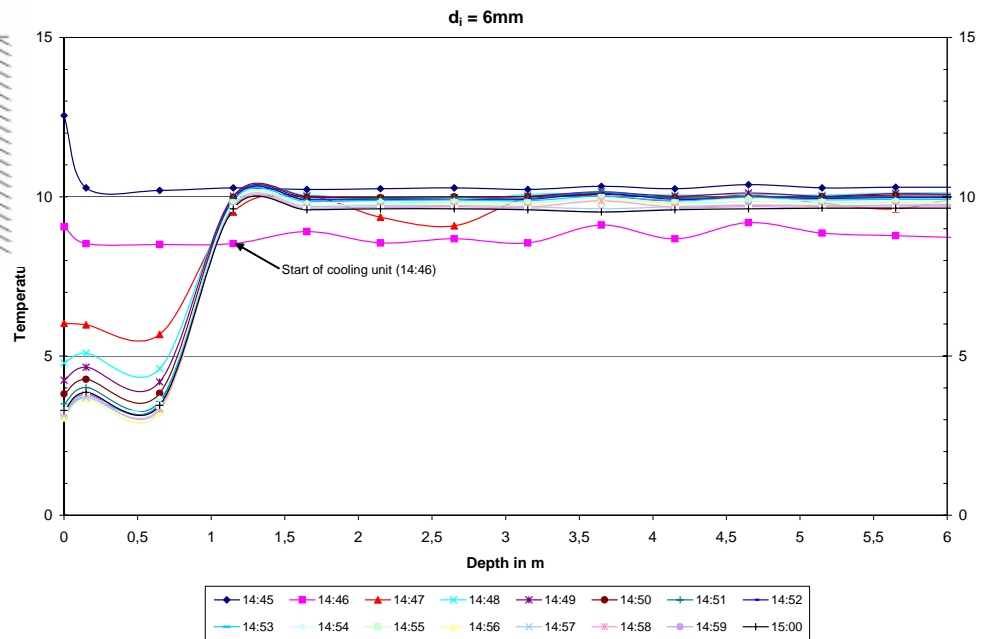
depending on the evaporation temperature of the liquid at the wall various heat fluxes through the wall can be generated in order to simulate the influence at different earth heat fluxes. So, for instance heat pipes from 6 mm to 25 mm inner diameter were used as heat pipes in order to investigate the heat pipe performance at different heat fluxes. This concerns as well the optimal CO<sub>2</sub> filling of the heat pipe depending of the heat flux and also the critical heat flux at which flooding occurs and the CO<sub>2</sub> film despite sufficient charge can not cover the whole inner surface of the heat pipe. In order to determine the dry out region the outer surface of the heat pipe was provided with 15 thermocouples at a distance of 0,5 m each which gives a temperature signal if at the inner surface evaporation takes place or not.



**Fig. 3. Laboratory Test Set Up**

### 3.1 Heat Pipe with 6 mm Inner Diameter

For instance test results of a heat pipe of 6 mm inner diameter are shown in Fig. 4 where the outer surface temperatures of the heat pipe are drawn connecting the 15 different points along the pipe.



**Fig. 4. Surface Temperatures along the Heat Pipe**

The different curves as parameter show the history of the tests for a quarter of an hour every minute beginning with 14:45 and ending at 15:00. It can be seen that at the beginning of the test a constant surface temperature of the heat pipe of around 10°C can be stated over the full length of the measured section of the pipe of 6 m. Only the first temperature point at the upper end of the heat pipe is higher and influenced by the ambient temperature. After 1 minute by starting the heat pump the CO<sub>2</sub> temperature is decreased and so cooling the CO<sub>2</sub> inside the pipe by the operation of the heat pipe evaporator. Two minutes later at 14:47 already the next curve shows a step in the temperature curve of the heat pipe outer surface indicating an evaporation inside at the upper 0,5 m. In the following minutes this step stabilises at around 3-4°C showing that evaporation takes here place obviously inside the tube. A temperature increase between 0,5 m to around 1,3 m depth indicates obviously the end of the closed film evaporation of carbon dioxide at the inner surface of the heat pipe followed by a certain broken film. This behaviour happens

although a sufficient charge was provided in order to generate a closed film at the inner side of the pipe. This means that stabilized stable conditions reached after a quarter of an hour when starting the heat pump a flooding of the heat pipe occurred, leading to the effect that the liquid film only covers the upper half a meter inside the pipe. As can be seen the temperature difference between the evaporation and the dry out region is around 8 K indicating that the temperature difference between the carbon dioxide film evaporation and the outside water temperature is at least this value or even more. The evaluation of the measurements showed that this test result can be related to a specific heat flux of around 150 W/m whereby it could be concluded from that for a normal stationary earth specific heat flux of 50 W/m a film length of around 1,5 m as fully the inner surface covering film theory can be concluded. This value can be also taken from the theoretical calculations in Fig. 2 showing that for 1 pipe of 6 mm inner diameter a film length of around 2 m at the specific heat flux of 50 W/m can be achieved. By inserting in parallel 2 pipes of each 6 mm inner diameter into the test setup a total film length of 4 m and hence a heat flux of 0,2 kW can be achieved with this configuration. 4 or even 8 pipes in parallel lead to only behaviour 0,5 or 1 kW heat flux at maximum films length of 8 or 18 m, respectively. This means that the test setup with seven meters is not sufficient to evaluate these two configurations concerning flooding.

### **3.2 Heat Pipe with 25 mm Diameter**

Further investigation therefore were performed with heat pipes of 25 mm inner diameter by which according to Fig. 2 a total film length of 44 m could be reached and, with 2 pipes in parallel of around 78 m. These configurations could be applied in a real earth probe and were also investigated furtheron in the test setup in order to evaluate the performance at different heat fluxes. During these tests it could not be expected that due to the maximum length of the test setup of 7 m and with a normal specific heat flux of 50 W/m the critical heat flux of the heat pipe could be reached so that various tests have been performed in order first to evaluate the minimum CO<sub>2</sub> charge of the heat pipe for a heat flux of 50 W/m and then by filling with enough additional charge to be able to reach the heat pipe flooding behaviour when increasing the heat flux.

#### **3.2.1 Minimum Charge**

At first a test with the heat flux of 50 W/m was performed in order to determine the minimum charge for these conditions at a pipe diameter of 25 mm. This was done in the way that at first a sufficient charge of CO<sub>2</sub> was filled into the pipe so that in a sight glass at the lower end of the heat pipe still a liquid level could be stated. By applying a steady specific heat flux of 50 W/m meaning for 7 m length of the pipe supplying 350 W from the water bath to the heat pipe, a stepwise decrease of the charge by blowing carbon dioxide out of the pipe it could be stated when at the lower end of the pipe it showed a tendency to higher temperatures than the rest of the heat pipe. At this condition this was an indication that at the lower end there was no more an evaporation and no liquid level was in the sight glass.

Therefore, from the beginning of this “dryout” the minimum charge could be derived for a specific heat flux of 50 W/m and a pipe of 25 mm diameter and 7 m length. Decreasing furtheron the charge shows an increasing of the dry out region at the lower end of the heat pipe as shown in Fig. 5 over a time period of a quarter of an hour from 15:30 to 15:45 with stepwise blowing off the charge. This dry out at the lower end of the tube shows that no more a sufficient charge exist inside the pipe and a full fluid film can only be generated down to around 5,5 m with possibly a broken film at already 6 m.

The charge being sufficient to generate a film which fully covers the inner surface of the pipe is defined as the minimum charge for a heat pipe of this special configuration with 7 m length, and inner diameter of 25 mm and a specific heat flux of 50 W/m length. In order to run the heat pipe with a higher heat flux than with this value a higher charge has to be provided for sufficient film generation over the full length of the tube.

### 3.2.2 Critical Heat Flux

In so far as with the specific heat flux of 50 W/m only and the given test setup with a maximum heat pipe length of 7 m the flooding of the 25 mm heat pipe could not be stated the following tests were devoted to generate higher heat fluxes. For this purpose according to Fig. 6 the heat flux was increased by decreasing the CO<sub>2</sub> temperature of the evaporating film achieved by a decreasing evaporation temperature of the heat pump. By this the temperature at the outer surface of the heat pipe was decreased from around 13°C down to around 5-7°C. Not really a dry out could be stated but greater variations of the temperature along the heat pipe downwards.

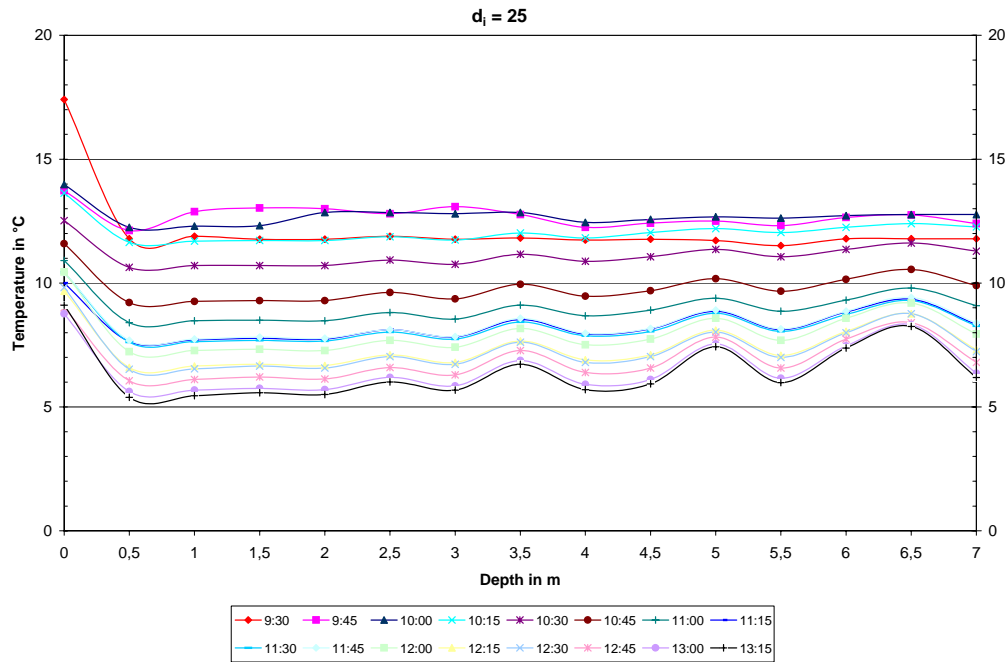


Fig. 5. Surface Temperatures along the Heat Pipe

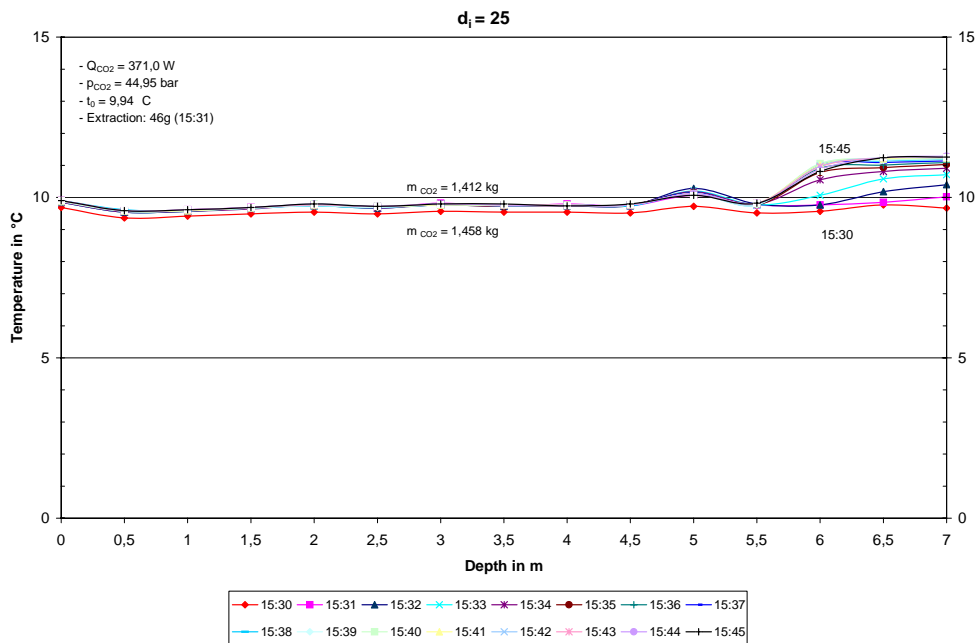
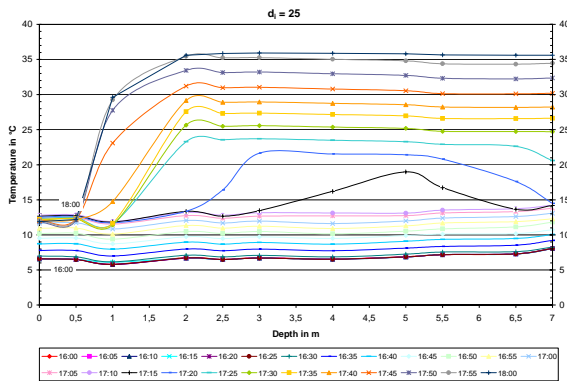


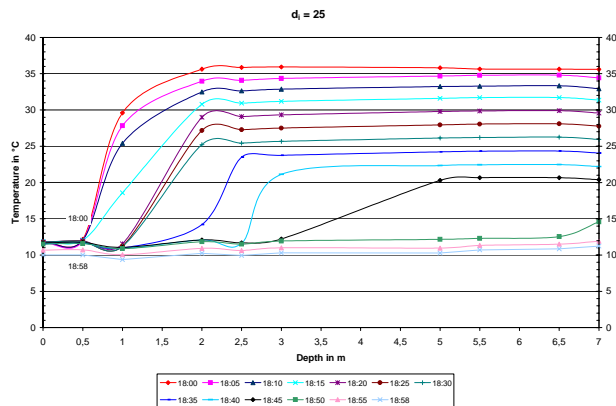
Fig. 6. Surface Temperatures along the Heat Pipe (CO<sub>2</sub> Cooling Test)

This can be explained by a broken film configuration on the inner side of the heat pipe which at increasing heat fluxes generates uneven flow conditions obviously for the liquid film and the evaporated gas, leading to uneven evaporation conditions on the inner surface on the pipe possibly by entrainment of liquid into the gasflow.

Since the refrigerating capacity of the heat pump was not sufficient to generate flooding conditions at this given heat pipe setup with 7 m length and 25 mm tube diameter the following test was devoted to reach the critical heat flux conditions by increasing the water bath temperature around the pipe, using direct electrical heating power. Figure 7 shows that following the former tests immediately by increasing the outer surface temperature of the heat pipe via the water temperature during the next 2 hours to +35°C obviously again a stepwise temperature distribution was generated along the pipe. A dry out region of around 6,5 m can be stated leaving only the upper half a meter as a full fluid film inside the tube. This happened at around a heat flux of 2000 W which was transferred from the water bath to the CO<sub>2</sub> heat pipe. A following decrease of the water temperature according to Fig. 8 led again to an increasing film inside the pipe.



**Fig. 7. Surface Temperatures along the Heat Pipe (Water Cooling Test)**



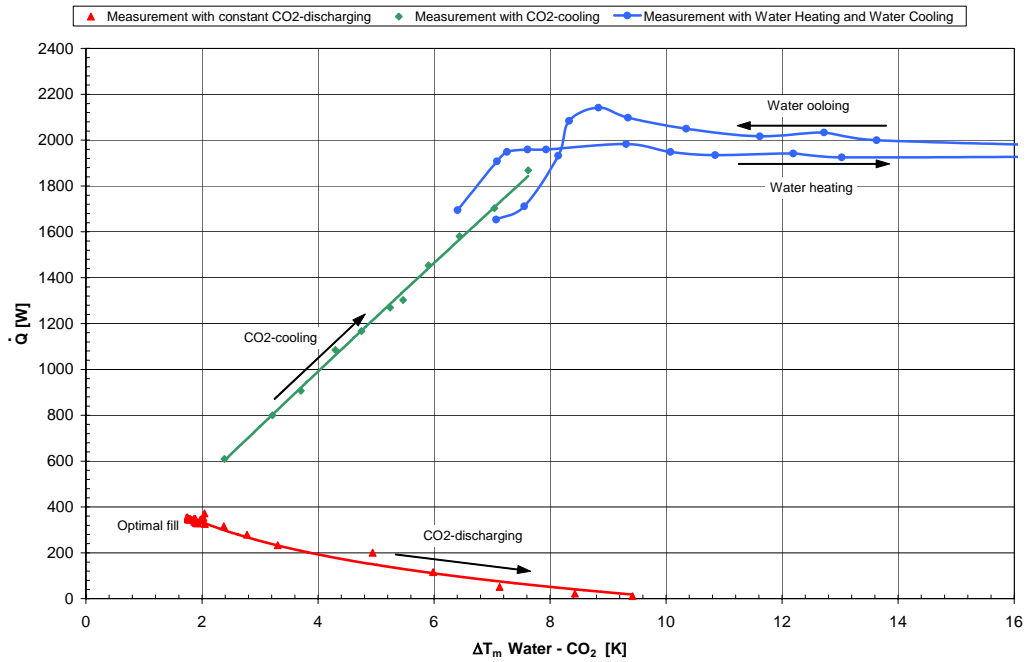
**Fig. 8. Surface Temperatures along the Heat Pipe (Water Recooling Test)**

### 3.2.3 Conclusion

Summarising these results in Fig. 9 which shows the heat flux depending on the temperature difference at the three different tests performed it can be seen that for the normal test conditions of 50 W/m, namely 350 W for the 7 m long heat pipe and, at a temperature differences of 2 K the normal performance of the heat pipe can be stated.

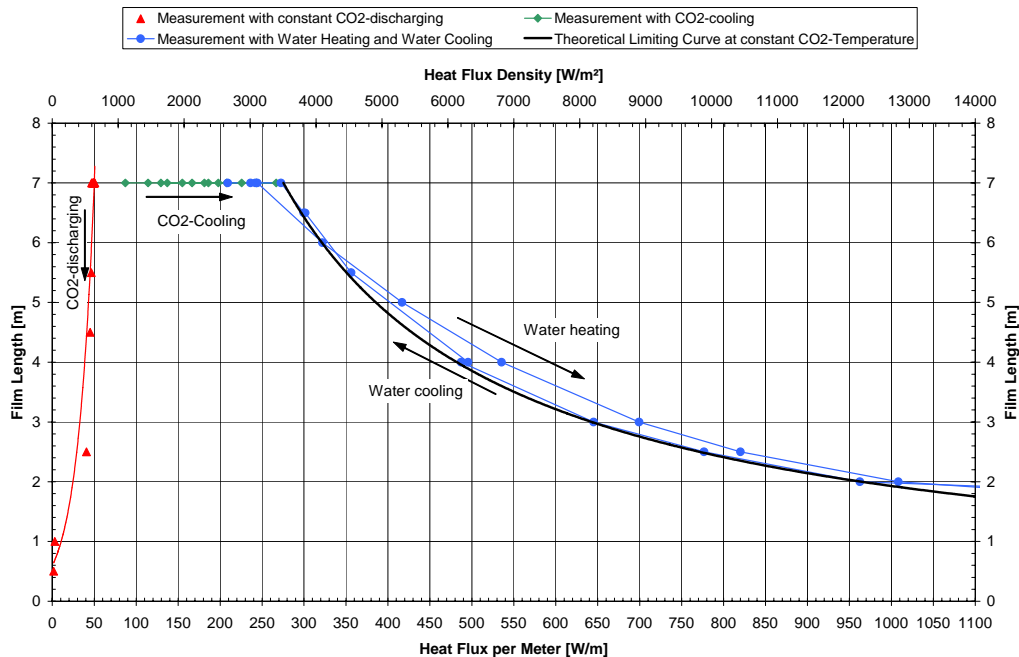
First, decreasing the charge through blowing off stepwise carbon dioxide from the pipe represented by the lower downward line in Fig. 9 a decreased heat flux at a higher temperature difference can be transferred only until at nearly no charge and 10 K the heat flux is almost zero. The minimum filling of the heat pipe is determined at 2 K temperature difference and 350 W for a pipe for 7 m length and a diameter of 25 mm.

By increasing the temperature difference and the heat flux using lower evaporation temperatures of the heat pump represented in Fig. 9 by the middle upward line it was not possible to reach the critical heat flux at flooding behaviour due to a capacity limit of the heat pump.



**Fig. 9. Heat Flux versus Temperature Difference (Filling-, Cooling-, Heating and Recooling Test)**

This occurred only after electrical heating of the water bath increasing the temperature difference to around 8 K, and more, further on at a constant heat flux of 2000 W represented in Fig. 9 by the upper horizontal lines. In this region higher temperature differences led to a reduced film length at the critical heat flux for flooding conditions as can be seen from Fig. 10 where the film length is plotted against the specific heat flux per meter film length or as upper scale as specific heat flux per square meter heat transfer area to the film..



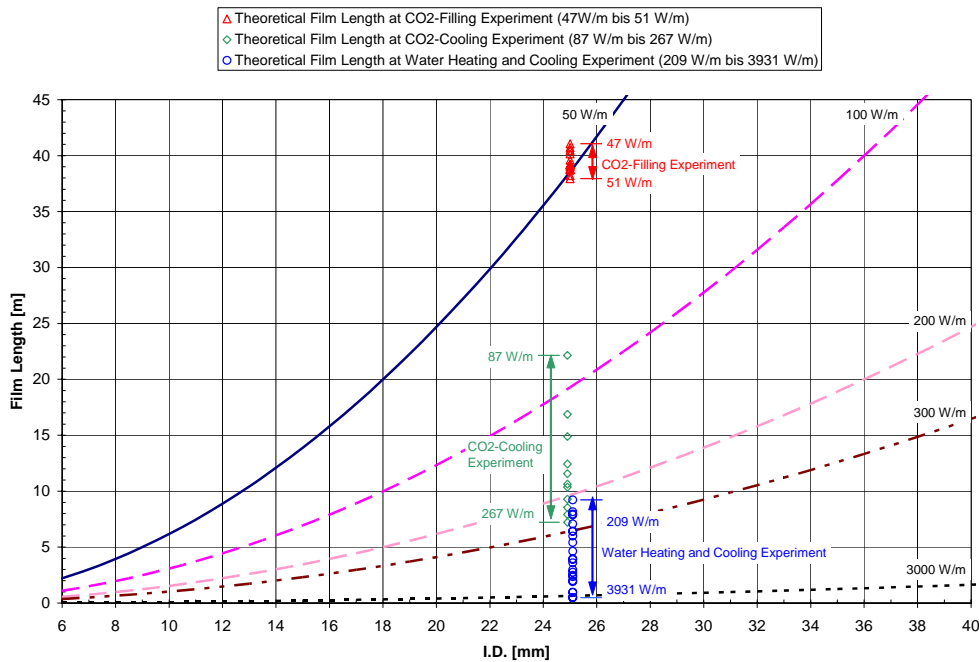
**Fig. 10. Film length versus Specific Heat Flux [ $\text{W}/\text{m}$  and  $\text{W}/\text{m}^2$ ]**

It can be seen that at 50 W/m or 600 W/m<sup>2</sup> the liquid film of CO<sub>2</sub> extends just over the whole pipe length of 7 m meaning that this is the minimum filling and no pool exist below. With an additional filling of around double the value the cooling test was performed represented by the next upper line up to 270 W/m or 3400 W/m<sup>2</sup>, respectively. Furtheron increasing the heat flux by heating the water bath leads to the upper line with a decreasing film length until only 2 m and a heat flux of 1000 W/m or 12800 W/m<sup>2</sup>. Further on decreasing the heat flux by cooling back the water bath shows a recovery of the film until the former length of the whole tube at 7 m is reached again.

So the critical heat flux of this investigated heat pipe with a diameter of 25 mm and a tube length of 7 m shows a critical heat flux of 3400 W/m<sup>2</sup> or 270 W/m respectively. This means that 5 to 6 times the normal heat flux of 50 W/m can be produced in this given heat pipe by evaporating carbon dioxide at a lower temperature, so leading to a higher temperature difference of around 8 K at the critical heat flux.

#### 4 COMPARISON OF THE THEORETICAL AND EXPERIMENTAL INVESTIGATIONS

In order to compare the former theoretical critical heat flux investigations concerning the film length at the critical heat flux as given in Fig. 2 the test results were plotted into a similar diagram (Fig. 11) which also contains besides the normal heat flux of 50 W/m as parameter also lines for 100, 200, 300 and 3000 W/m. Into this diagram the test results for the filling tests, the cooling test and the heating and recooling test were plotted by different points, respectively.



**Fig. 11. Film length Specific Heat Fluxes at Flooding Limit**

It can be seen that for the heat pipe diameter of 25 mm the filling test points for 47 until 51 W/m confirm very accurately with the theoretical film length as calculated with 50 W/m. The same holds also for the cooling tests with points between 87 and 267 W/m which are assembled in the region of the theoretical 100 W/m and 200 W/m lines so that they also confirm the theoretical results as well as also the points between 209 until 3301 W/m which represent very well the region between 200 and 300 W/m until 3000 W/m, where flooding occurred. Also, considering the first test with a pipe diameter of 6 mm and the film length as given by the test results of around 0,5 m then it can be seen that also the 2 curves for a heat flux of 100 and 200 W/m respectively include the test results for 150 W/m. In summary it can be stated that as

well the theoretical as also the experimental investigations confirm the critical heat flux as calculated from the former investigation of other authors for tubes with a very much smaller  $l/d$  ratio also now for very long heat pipes with relative smaller diameter and hence a very much higher  $l/d$  ratio.

## 5 CONCLUSION

The theoretical and experimental investigations of the CO<sub>2</sub> heat pipe show that for extracting the required heat flux from the earth which can be estimated in average to around 50 W/m depth in the stationary case then the critical heat flux concerning the flooding behaviour of the heat pipe is important. This critical heat flux determines the length of the liquid film at the inner wall of the tube because only this film can transfer the heat from the earth by evaporation and generate vapour which causes a vapour flow upwards by its lower density. At the higher critical heat flux the evaporated liquid mass leads to an also higher vapour velocity which in the upper layer of the liquid film generates shears stresses sufficient to prevent the film from flowing downwards further on. The diameter of the heat pipe therefore, must be chosen according to the depths of the earth probes and must be sized according to the film length and heat extraction from the earth.

## 6 DESIGN OF THE HEAT PIPE

The design of the heat pipe must consider first the thermodynamic data of the working fluid. Especially important is the fluid pressure as generated by the temperature in the two phase liquid charge which is prescribed by the earth temperature of around 10°C to 13°C. Here, for carbon dioxide a pressure of around 50 bar exists and has to be the basis for the selection of the heat pipe material. Because of this high pressure, and also because of the high diffusion of carbon dioxide through plastic materials the normally used polyethylene tubes for earth probes can not be applied for a CO<sub>2</sub> heat pipe. Therefore, it seems to be necessary to use metallic materials like stainless steel as been selected in the experimental investigations.

On the other hand it would be favourable to use the same handling for bringing the heat pipe into the bore like it is conventionally done with the PE-earth probes which are flexible plastic tubes. A choice could be to use PE-coated copper pipes as they are used normally for direct expansion horizontal earth collectors from a coil which are available on the market up to outer diameters of 16 x 1 mm ( $d_i = 14$  mm) and with 500 m length. This is a possibility which is used in Austria whereby four heat pipes in parallel are inserted into one bore.

According to Fig. 2 in the case of four pipes of 14 mm inner diameter a maximum film length of 48 m and a heating power of 2,4 kW can be achieved if the heat extraction is 50 W/m depth. For higher heat extraction and film lengths up to 100 meter 8 pipes per bore in parallel have to be provided which on the one hand can be difficult to insert into one conventional bore and which requests a higher mass of copper material and hence a higher price of the earth probe. Another solution would be to drill a second bore of 50 m but this solution requires additional drilling costs of a second bore and an additional heat exchanger on top of the second earth probe.

Another consideration by using PE-coated copper pipes is the question if this material has enough protection against corrosion when it is inserted into a long vertical bore where an eventual corrosion can take place later if the PE-coating is damaged by sharp rocks or stones in the bore during inserting the heat pipe into the earth without a later control possibility as with collectors in the still open embeddings. Field investigations have been performed over two years by Sanner and Knoblich (Sanner and Knoblich 1991) with 12 tube sections and 5 different materials for earth probes in depths from of 30 m to 40 m. The results were that PE-coated copper pipes showed a material loss of around 2% as compared to non coated copper pipes with 3 or 4 % but that stainless steel showed no indication of corrosion at all (Table 1).

**Table 1. Corrosion Results (Sanner and Knoblich 1991)**

*Table 2: Mass of Samples for In-situ Corrosion Test, Before and After Exposure.*

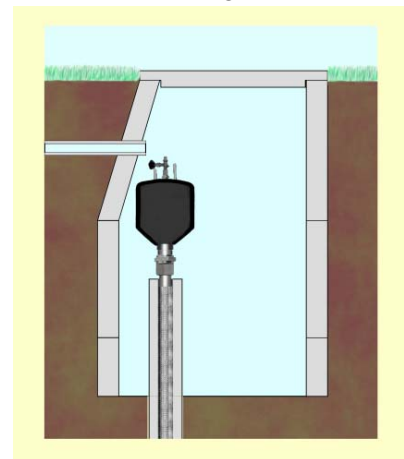
Sample	Mass before exposure (grms)	Mass after exposure (grms)	Mass loss (absolute) (grms)	Mass loss (specific) (%)
Iron, test body	17.94	17.18	0.76	4.24
Iron, test body	17.83	17.02	0.81	4.54
Steel, tube 1 3/4"	126.77	121.41	5.36	4.23
Steel, tube 1 3/4"	127.47	119.89	7.58	5.95
Steel, tube 1 3/4"	124.76	121.41	3.36	2.69
Inox, corrug. tube 2"	28.06	28.06	0.0	0.0
Inox, corrug. tube 2"	28.37	28.37	0.0	0.0
Copper, tube 1"	27.26	26.38	0.88	3.23
Copper, tube 1"	27.02	26.02	1.00	3.70
Cu, corrug. tube 2", PE	51.30	50.31	0.99	1.93
Cu, corrug. tube 2", PE	51.15	50.18	0.97	1.90
Cu, corrug. tube 2", PE	52.76	51.72	1.04	1.97



**Fig. 12. FKW Heat Pipe**

Therefore, for the development of the FKW heat pipe stainless steel as tube material was the basis of the further design. Flexible stainless steel tubes from a coil are also on the market but only normally up to outer diameters of 12,7 mm, and only in larger dimension upon special request. Therefore, the solution FKW has chosen covered by a German patent application is flexible steel pipes of larger diameters. These types of stainless steel tubes can be inserted into the earth bore so that after refilling of the bore they are embedded concentrically into the earth. On the other hand a lot of diameters can be selected concerning the generation of an adequate liquid film inside the tube.

In order to achieve a smooth film at the inner tube wall a special CO<sub>2</sub> condenser working also as refrigerant evaporator of the heat pump has been designed for an optimal working condition together with the developed heat pipe. Both components form a unit like shown in Fig. 12 and can easily be inserted into a conventional earth bore. Steel tube prices have been compared to PE-coated copper pipes of 4 tubes in parallel for 50 m lengths which leads the same material costs. Lower material prices for greater depths down to 100 m can be achieved with steel pipes up to 40 mm as half the material price compared to the PE-copper tubes with up to 8 parallel pipes of 14 mm. So, the developed CO<sub>2</sub> heat pipe as earth probe together with the newly developed evaporator-condenser as connecting heat exchanger to the heat pump leads to a favourable solution for earth coupled heat pumps (Fig. 13) since it saves a special evaporator at the heat pump itself. By using the CO<sub>2</sub> earth probe and connecting the evaporator including a thermostatic expansion valve only by a liquid and a suction line to the heat pump a very simple configuration can be offered to the market: As a heat pump only a condensing unit from the market is necessary which can be chosen from a lot of manufacturers in a broad range of capacities so that the manufacturing of the heat pump consists only of adding an adequate housing and control system.



**Fig. 13. Built in FKW-Heat Pipe System**

Therefore, by developing this earth coupled CO<sub>2</sub> heat pipe together with the connected evaporator-condenser and coupled with a condensing unit gives the opportunity of low costs earth coupled heat pumps to be offered on the market. The developed FKW CO<sub>2</sub>-Heat Pipe as earth probe has been covered additionally to (Kruse 1998) by further patent applications in the last years since 1998 at the German Patent Office.

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