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EXPERIMENTAL INVESTIGATIONS ON SODIUM-FILLED HEAT PIPES

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16. Abstract

The possibilities of producing heat pipes and, especially, the necessary capillary structures are discussed. Several types of heat pipes are made from stainless steel and tested at temperatures between 400 and 1055°C. The thermal power was determined by a calorimeter. Bubble-free evaporation of sodium from rectangular open channels is possible with a heat flux of more than 1,940 W/cm^2 at 1055°C. The temperature drop along the tube could be measured only at low temperatures. A subdivided heat pipe worked against the gravitational field. A heat pipe with a capillary structure made of a rolled screen supported by rings and bars operated at 250 W/cm^2 heat flux in the evaporating region. (tr-auth).

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Dorner; Reiss; Schretzmann

Summary

The possibilities of producing heat pipes and, especially, the necessary capillary structures are discussed. Several types of heat pipes are made from stainless steel and tested at temperatures between 400°C and 1055°C. The thermal power was determined by a calorimeter. Bubble-free evaporation of sodium from rectangular open channels is possible with a heat flux of more than 1,940 W/cm^2 at 1055°C. The temperature drop along the tube could be measured only at low temperatures. A subdivided heat pipe worked against the gravitational field. A heat pipe with a capillary structure made of a rolled screen supported by rings and bars operated at 250 W/cm^2 heat flux in the evaporating region.

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1. INTRODUCTION

Recently, a specific device for heat transport at higher temperatures has become known under the designation "heat pipe". This device exhibits several interesting technical and physical properties [1, 2, 3]. Heat pipes are closed tubes filled with small quantities of vaporizable materials. These materials can transport heat in latent form from places to which heat is flowing (evaporation region) to places where heat is to be given off (condensation region) by forming a vapor-liquid circuit. The liquid flows in a capillary structure from the condensation region back to the vaporizer, according to the suggestion of Gaugler [4] from the year 1942. This idea was not taken up again until 1964 in connection with work on thermionic converters and nuclear reactors for applications in space flight [3, 5, 6]. Even in the first experimental investigations it was determined that the heat transport capacity of heat pipes is very high in comparison to the heat conduction capacity of solid substances. The temperature drop belonging to a certain heat flow in the direction of heat transport is extremely low. This is because relatively large amounts of heat per mass unit can be absorbed or given off in latent form during vaporization and condensation without a change in temperature. In addition, the relatively low temperature drop can also be attributed to the fact that a certain pressure drop is associated with only a relatively low temperature drop. This pressure drop necessarily occurs in the direction of vapor flow because of the great dependence of vapor pressure on temperature. Calculations and tests on the vapor, liquid, and heat flow [2, 6, 7, 8, 9] and on the best dimensions have been performed elsewhere. The calculations are related to the case when vaporizer and capacitor are connected by a pipe with vapor and liquid flowing through without heat transfer. In many experimental investigations, specifically for those described in this paper, heat is transferred by radiation to the entire surface. Because of the continuous covering of the wall with sinks for vapor, the mathematical treatment of the mode of operation is more difficult since the known equations of flow (Hagen-Poisseuille Law) always presume that the divergence of the mass flow disappears at the edges of the flow path or is different from zero only at individual points.

Since heat pipes of large heat efficiency have a relatively low weight, they are of particular interest for space vehicles and satellites. In this regard it has been suggested to obtain the heat for heat pipes from isotope heat sources [3, 5], or from the core of nuclear reactors [6, 3] and to lead it to equipment for direct conversion into electrical energy or other heat consumers. Even the transport of waste heat from the energy converters to the radiators was foreseen by means of heat pipes [3, 6, 8]. There are several theoretical and experimental investigations on this [10, 11, 12].

Moreover, it has been suggested to transfer the heat of fission from stationary high efficiency and high temperature reactor cores via heat pipes to the actual, liquid, or gaseous coolant. Here, the heat transfer to the coolant could occur at a smaller heat efficiency than for direct cooling, without resulting in a large temperature drop. In addition, greater cross-sections for coolant flow could be used. Both measures would make possible a reduction of pump performance for the circulation of coolant [13].

The vaporizers used in the heat pipes have capillary structures and can be stressed with a very much greater heat-flow density than all other vaporizer surfaces before the known crossing from surface vaporization to bubble and film boil and attendant, sudden, burn-out occurs. Now with regard to this interesting property, experimental work on heat pipes has begun. First, the task was to prepare heat pipes with the desired capillary structures. We now report on this and on the tests and results obtained with them.

2. SURVEY ON THE POSSIBILITIES FOR PRODUCING CAPILLARY STRUCTURES

The capillary structures can be rigidly connected to the interior wall of the heat pipe vessel or be placed loosely into it.

Capillary structures rigidly connected to the interior wall can be produced by stressed or non-stressed deformation of the wall and by insertion of solid material. Drawn pipes of tantalum, niobium and niobium-1%-zirconium have been prepared industrially with different longitudinal grooves*. Tests to introduce longitudinal grooves into

*W. C. Hergeus GmbH., Hanau

pipes by broaching have been successful. Likewise, tests to prepare pipes with longitudinal grooves by filing flat plate and subsequent rolling and welding have been successful. Suitable capillary structures should also be possible by electro-erosion. The application of electro-erosion for fine-finishing grooves which is done coarsely by other procedures, would be especially interesting. Rigidly-connected capillary structures (to the wall) can be obtained without deformation by removing the material above suitable cores by electrolytic means from aqueous solutions by salt melts or by thermal decomposition from the gas phase [14]. Under some circumstances, material can be applied to the inside of hollow bodies after appropriate masking, so that the steps form the capillary structure. Finally, electro-erosion material transfer can be used. Capillary structures situated loosely against the wall can be prepared by inserting wire screen [1], by inserting capillary support bodies [6], by inserting sinter mateials [8] and by flame-polishing porous coatings. They can also be formed from powder coatings held by suitable wire mesh.

In the experiments which are reported here, capillary structures were first prepared in inserted wire screen because of the simple procedure. After we succeeded in building suitable broaching tools, pipes were provided with longitudinal grooves. As a third version, heat pipes with wire mesh supported by rigid cages were built - these are an improvement over the first design. In the fourth design, the interior space was subdivided. Here again, the capillary structure consisted of simple wire mesh.

3. HEAT PIPE DESIGN

3.1 Heat Pipes with Wire Mesh

For these heat pipes, two layers of non-rusting steel wire screen of 150 μm Ø with a 250 μm strand separation (60 mesh) wound on a suitable spindle and inserted into the encasing pipe. The encasing pipes consisted of different types of stainless steel and of Vacon 70 with outside diameters between 10 and 20 cm and wall thicknesses between 0.16 mm and 1.5 mm. The lengths were up to 1 meter. Related to the corresponding interior diameter, the wire mesh had a significant spring force which causes a pressing of the mesh to the wall, at least before the first annealing.

X-ray photographs of such pipes showed (see, for example, Figure 1) that folds and bulges form in the network with the result that there is no contact with the wall at these points.

3.2 Heat Pipes with Grooves

Contrary to wire screens, axis-parallel inside grooves in heat pipe tubes provide a defined and high-efficiency capillary structure whose properties can be varied by changing the dimensions. For the intended tests, the pipes should have longitudinal grooves along their entire interior surfaces. Therefore, rolling and welding of flat plate was not considered. Filing, sawing, or chiseling of the one-tenth millimeter-wide and -deep grooves to lengths of 0.5 to 1 meter needed here was not possible. Thus, the pipes had to be broached.

The manufacture of a broaching spindle with the negative of the capillary structure as a cutting profile brings up problems of hardness since the bars broaching the rills are inclined to have a hardness at the bar base which could cause a rupture. This problem was surmounted by a dismountable broaching tool into which preshaped, hardened cutting edges can be inserted into the non-hardened handle of the broaching tool.

Thus, in grooves in seamless precision tubes made of high-heat resistant, stainless steel - X 15 CrNiSi 2520 - of 20 mm outside diameter, a 0.8 mm wall thickness and 20 μm diameter tolerance can be prepared. In a single procedure, 36 grooves of 0.2 mm width and 0.4 mm depth were made. Figure 2 shows a cross-section of a tube through which the tool has been pulled several times. There resulted from this about 91 grooves.

The residual filings in the grooves could not be removed by brushes or similar means because of the low groove width. The tubes were cleaned in a hot nitric-hydrofluoric acid mixture by ultrasonic means.

3.3 Heat Pipes with Rolled Screen Support Cages

Deverill and Kemme [5] tried to eliminate release of the wire mesh from the wall by additional pressing of the wire by an inserted tension spring made of tungsten wire. But the release of the wire can only be prevented by a shaped, rigid cage placed against the wire, since the spring effect of all materials is reduced quickly with increasing temperature. Figure 3 shows a part of a designed cage. It is made of bars and rings into which outside, axial slits are filed. Rings and bars are connected by spot welds. The cages are [illegible] so that they can be shaken together with the wound layer(s) or wire into the outside tube. The wire mesh was examined optically after the joggling.

3.4 Subdivided Heat Pipes

Many articles discuss the difficulty of operating heat pipes against external forces over extended periods of time. This difficulty can be avoided by subdividing the heat pipe perpendicular to the heat transport direction. These subdivisions are at most no larger than the height of rise of the working liquid in the capillary structure. In the separating walls between the individual sections (which also have capillary structure) one section then heats all others which lie in the direction of heat flow. Thus, there results a temperature jump between the sections due to the finite heat conductance of the separating wall.

A heat pipe according to the above was constructed of 4 individual components from stainless steel. Figure 4 shows an X-ray photograph of this. The capillary structre was obtained by inserting wire mesh of stainless steel 200 mesh (50 µ wire thickness, 75 µ mesh). The total interior space including the heat transfer surfaces was covered with two layers of wire mesh and this was attached to the wall by spot welding. The assembly occurred by welding the first section at the base. Then an appropriate quantity of sodium was introduced through the open end and a seal with pump support was placed on top and the pipe was operated briefly under vacuum and then welded shut by using high-frequency. Now, the outside of the heat transfer surface had wire mesh wrapped around, the sheath of the second stage - also provided with wire mesh - was placed on top and welded to the first with an argon arc. Filling the second stage and the further construction then proceeded.

3.5 Filling with Sodium

Sodium is filled into many heat pipes in solid form, in others it is in liquid form.

To fill with liquid sodium, a funnel of stainless steel was welded onto the fill supports of the pipe. A frit was pressed into its exit. First, the sodium was melted into the funnel under a vacuum by inductive heating and finally pressed through the frit by inert gas. The oxides and hydroxides in the sodium were kept back by the frit. Filling with solid sodium is simpler. This occurs in a box protected by inert gas. Here, the sodium only need be purified carefully. The cover is not set onto the filled tube and the tube is introduced into a vessel which is evacuated directly thereafter.

Upon operation, no differences appeared betweeen the heat pipes with with liquid sodium fill and those with solid sodium fill.

3.6 Gas Removal

In the literature [1, 3, 8, 15] the importance of good evacuation of gases from the pipes and the propellant is indicated. In the project described, only in a few cases was cleanliness a factor and was evacuation done exactly. In the less carefully-prepared heat pipes, in individual cases gas cushions at the cold ends appeared initially. However, for the materials used by us, during operation at red heat, this gas disappeared regularly in the course of the first hours of operation and gave rise to the expected isothermal condition over the entire length. It is supposed that the gases - provided they are not vaporized by getter - diffuse through the walls into the vacuum surrouding the heat pipes. In order to reduce the time until the ideal operating level is reached, it proved to be useful to operate the still-open heat pipe under a vacuum in the inside space and to weld it shut when it operated isothermically as far as the fill supports.

3.7 Sealing the Heat Pipes

In the first tests, the fill and pump supports made of nickel were welded shut after evacuation. Besides the low mechanical resistance of the cold weld, this process is inadequate because only a few materials can be cold-welded and because wetting the parts to be welded prohibits a thick weld - at least for sodium or cesium. The often-mentioned closing by electron beam welding would be laborious for reasons of internal operation. The heat pipes were thus welded shut under a vacuum by heating the fill support with high-frequency radiation. This can occur in the same evacuated quartz tube in which the heat pipe was previously filled and evacuated, and in which later, it will be operated. The procedure is simple and provides reproducible results. For details, see [16].

4. RESULTS OF THE EXPERIMENTAL INVESTIGATIONS

4.1 General Test Assembly

The heat pipes were usually heated inductively by high-frequency radiation. For this, a single- or multi-wound coil was placed around the pipes. This coil was powered by a 15 kW generator operating at frequencies of 330-500 KHz.

Of the generator power output, only a small fraction is input to the heat pipes as heat since the cleft between the heat pipe and coil had to be large because of the quartz or glass tube situated in between. This resulted in a poor coupling efficiency. After introduction of high-frequency energy into the vacuum, the cleft between coil and heat pipe can be kept very small. The vacuum-heat pipe arrangement used had such a high self-induction that the total power input into the heat pipe was smaller still.

In inductive high-frequency heating one obtains a very high heat power density in the wall material of the heat pipe. The production of heat is greatest at the points lying closest to the coil (in the plane of the coil) and decreases down to both sides. Figure 5 shows the course of heat efficiency per pipe length unit N' as a function of the distance z from the coil plane for typical pipe and coil dimensions. The ordinate is standardized with respect to the efficiency and thus has the dimensions cm^{-1}. The ring-shaped pipe seciton with height dz, produced heat power of the amount

$$dQ = Q_o \cdot N'(z) \cdot dz ,$$

where Q_o is the total power. We see that of the three coils, coil Sp 1 can attain the sharpest spatial concentration of heat output and thus the highest power density at total constant power.

In many cases, two concentric glass tubes were used as sheating of the heat pipes. The interspaces were filled with circulating coolant water. Thus, we assumed that the heat pipes were located in an environment of constant, known temperature. By measuring the current density and the temperature increase of the coolant water, the heat radiated from the heat pipe could be determined. The thickness of the water layer of somewhat more than 1 mm was sufficient for absorption by the calorimeter of the heat radiated by the heat pipe.

The temperature of the heat pipes was determined initially with pyrometers. The temperature values obtained could not be calculated accurately because of the unknown radiation constants and the gradual re-vaporization of the quartz or glass tube from the read-off values. Therefore, thermo-elements of nickel-chrome wire of 0.2 mm Ø were welded to the heat pipes.

4.2 Heat Pipes with Wire Screen

Heat pipes with capillary wire mesh were operated without difficulty. But operation over longer periods of time was not possible without the formation of hot spots. Because of the low heat capacity of the wall, the movement and level of sodium as well as the spread of sodium vapor in the tube was very easy to see by variations in brightness in thin-wall pipes.

4.3 Heat Pipes with Interior Grooves

With the heat pipes equipped with interior grooves, no hot-spots appeared at high temperatures and detailed measurements have been performed on them as regards the relationship of temperature and heat power. These measurements are shown in Figure 6 and relate to a pipe of 48 cm length. We see that in stationary operation with the various coils, temperatures between 600°C and 1055°C at power outputs from 500 to 3050 W result. The greatest power - 3050 W - was attained with the twice-wound coil Sp 2. With a single-wound coil Sp 1, a power of only 2080 W could be put into the pipe by the generator. But there resulted a power output per length unit of 1400 W/cm at the point of greatest power density. That is the greatest power per length unit achieved in these experiments in the stationary state. Related to the interior surface, this corresponds to a power density of 233 W/cm^2.

At the points of high heat flow density there exists a large heat flow density in a single direction in the wall. Thus a temperature difference of up to 80°C occurs between the outside and the inside of the wall. A more accurate calculation of this difference is given in [17]. Since the heat pipes are nearly isothermic in the inside, their outside is hotter by this temperature difference than in the unheated regions at the points of greatest heat power density.

At large heat flow density, we see quite clearly that the temperature on the outisde of the heat pipe has different values for different azimuths at points of the heated zone located the same distance from the mid-plane. We see bright and dark strips running parallel to the axis. The temperature differences are so low that they cannot be detected by a pyrometer. The number of bright or dark strips corresponds to the number of grooves in the tube. The aximuthal temperature variation originates due to the different heat power densities between the bars and the points where the grooves are cut into the wall and where the electric current lines have to compress together. Or, they are caused by the fact that the vapor cooling in the interior of the pipe does not act everywhere, but only on the bars or the grooves. The first reason cannot be of primary importance to the observed effect. If the heating coil is heated slowly during the operation, the vapor cooling is interrupted suddenly as soon as the distance of the coil from the lower edge of the heat pipe exceeds the height of rise of the sodium in the capillaries (ca. 6 cm). At this moment, the bright and dark strips disappear. This state of operation may exist only briefly for full transmitter power since the steel pipe will melt. For a satisfactory observation of this phenomenon, the time span is sufficient. From this follows that the vapor cooling in the interior of the pipe does not act everywhere. It seems that if the vaporation does not occur everywhere, it then appears in the grooves. This confirms the observation that the heat pipe's lower part acts against the force of gravity as far as the height of rise of sodium in the grooves. Here the liquid in the lower part of the pipe must flow from bottom to top. It can only flow in the grooves. There, the dark strips would correspond to the grooves. Since with increasing height, the strips do not change brightness, the dark strips also represent the grooves even in the upper part of the heat zone.

From this it follows that the entire heat conductance to the inside is limited to the groove surface. The total width of all 36 grooves is 7.2 mm. If the heat flow density is related to this surface, then we see that the greatest, stationary power density (ML) (with coil 1) is attained at 930°C and is 1945 W/cm^2. Here, the vaporization zone is not yet inclined to dry out. Also, film boiling which would have been discernable for higher over-temperatures (ca. 230°C) did not appear. The heat flow density in stationary operation calculated with coil SP 1 in the midplane is shown in Figure 7 plotted against the temperature as curve ML.

Since the vaporizer does not dry out at these heat flow densities, the maximum possible power density (MML) must be even greater. We proceeded as follows in getting a more exact determination of this value.

The transmitter was adjusted to a certain power stage and then switched on intermittantly. On and off times were between 0.1 and 2 seconds. The ratio of off-times to heating-times was always selected so that no hot spots occurred. The temperature increased constantly and was recorded. The on-times had to be constantly increased compared to the off-times. The 100% on-time was noted on the chart paper. Since the total power at this point is known, a pair of values of temperature and maximum possible power (or heat flow density) was obtained. We proceeded accordingly with the other power stages.

The values so obtained are entered in Figure 7 as curves MML. They begin at 530°C at 160 W/cm^2. The MML of 1940 W/cm^2 is attained at 815°C and we see that the value of the MML at the same temperaure is about twice as great as the values of the ML which occurred in stationary operation.

Detailed tests were performed to measure the temperature drop in the longitudinal direction. However, for various reasons, safe values for the true temperature drop could not be obtained.

The thermo-elementts provide different temperature values even when they are placed along the same circumference. Thick weld beads reprepsent a large heat resistance against the passage of heat through the bead where it is radiated off at the surface. This resistance reduces the total heat flow at this point to a very small cross-section. Hereby the temperature drop at this point decreases in the pipe wall from the inside as far as the actual thermoelectric effective surface. A second reason why the location of thermoelements on the same circumference can lead to different temperature readings is the different vaporization of the surrounding glass or quartz tube. If the glass or quartz tube is somewhat vaporized at one point and the heat reflected, the heat flow density at this spot is again lower than at other spots. This in turn results in a smaller temperature drop in the wall. The temperature drop in the heat pipe wall is on the order of magnitude of 4°C. A reduction in the heat flow by reflection of about 1/10 causes a temperature change in the readings of the thermoelements by about 0.4°C. Similarly, small changes in the emission capacity have the same effect. Furthermore, the experimental determination of the temperature drop is significantly impeded because the voltage supply of the high-frequency generator could not be stabilized. With a varying voltage supply, the heat power to the pipe and thus its temperature, change.

According to the test results it can only be guessed that the temperature drop at an operating temperature of around 950°C, a heat flow on the order of 2.5 kW and the average transport length of 25 cm (radiation cooling on the entire surface) lies between 1/100 and 1/10°C.

A heat conductor of tantalum wire was wound on a heat pipe and insulated and attached with flame-welded Al_2O_3. With this arrangement temperatures of only up to about 600°C could be attained because of the large heat resistance between the heat conductor and pipe. Larger temperature gradients appeared along the pipe. Corresponding profiles were taken by four thermo-elements. These profiles are shown for stationary operation in Figure 8. Below 400°C, the temperature drop was 50°C or more; it decreases quickly with increasing temperature. At 474°C initial temperature, it is only 1°C, for instance. We should mention that the pipes used had no gas cushion.

4.4 Heat Pipes with Support Cage

These pipes were operated under stationary conditions up to heat power densities of 250 W/cm^2 based on the inside mesh surface, without any difficulty. Higher powers could not be attained with the available generator. During operation in the temperature range around 960°C, the rings of the cage formed bright azimuthal zones at the outside pipe wall. It is supposed that this is caused by additional production of heat in the massive support rings (ring wall thickness 0.8 mm, penetration depth of the heat pipe field 0.7 mm). The height of rise of the sodium in the 200-mesh wire support was 22 cm. It was only 16 cm in a non-attached mesh cover of the same mesh width.

4.5 Subdivided Heat Pipes

The heat pipe consisting of four subdivided stages operated satisfactorily. In a perpendicular position it was started up from room temperature without preheating of the individual compartments, at a constant power of ca 250 W. The heat coil was placed either at the level of the lowest compartment (operation with gravity) or at the level of the top compartment (operation against gravity). When operating against gravity, the pipe operated satisfactorily along its entire length. Here, the greatest distance between the coil mid-plane and the end of the lowest compartment was 40 cm. The height of rise of the sodium in the mesh used was determined as 16 cm on a control heat pipe with the same heating unit, by the disappearance of the isotherm during slow heating by the coil to high temperatures. The greatest power at which the pipe could be operated without the appearance of hot spots was 530 W. The heated section assumed a temperature of 690°C. A power density of 48 W/cm^2 resulted at the intermediate bottoms. The temperature jumps measured by thermo-elements between the individual compartments were 1.5 to 50 times greater than would correspond to pure heat conductance. These high factors appeared after overloading the heat transfer surfaces and they were cured completely by allowing the sodium to flow back.

5. CONCLUSION

The experiments performed have shown that heat pipes are heat transfer devices which are easy to construct, and reliable in operation. Moreover, they have shown that it is possible during the vaporization of metals from capillary structures - especially from open grooves - to conduct heat flows to a level not heretofore attained. Thus, the use of heat pipes or similar devices appears likely even in larger, technical plants for heat transport. More accurate details on this will be available after the conclusion of additional investigations.

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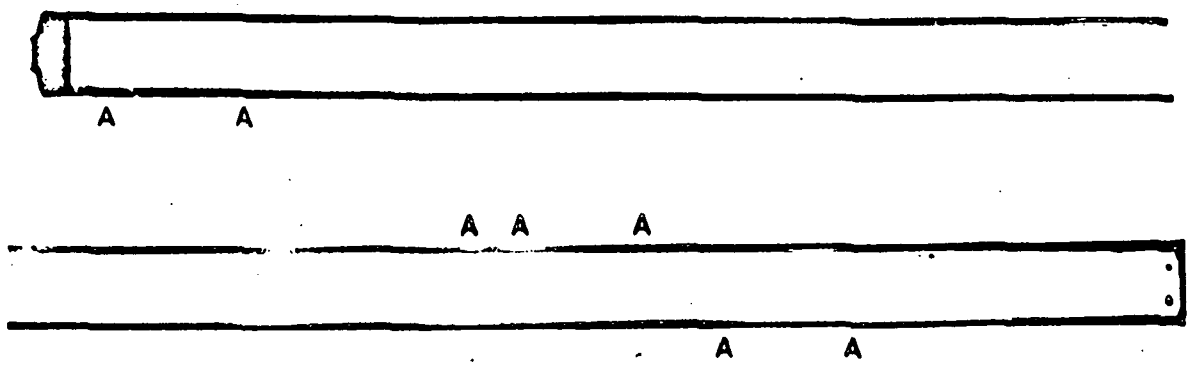

Figure 1: X-ray photograph of a heat pipe with wire mesh. Pipe diameter: 19 mm, mesh width, 250 μm, wire thickness, 150 μm. The wire is not in contact with the pipe wall at point A.

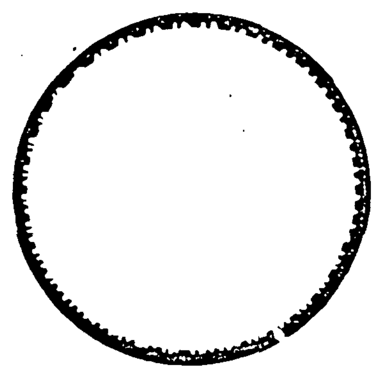

Figure 2: Cross-section through a heat-pipe with interior grooves. Pipe diameter: 20.5 mm, groove width, 0.2 mm, depth, 0.4 mm.

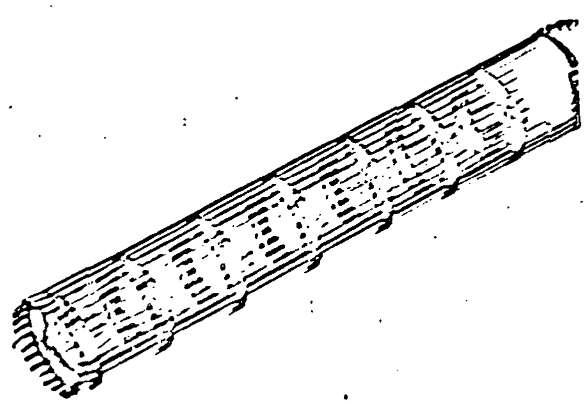

Figure 3: Support cage made of rings and rods. Outside diameter: 19 mm.

Figure 4: X-ray photograph of a subdivided heat pipe with four chambers; Total length, 42 cm.

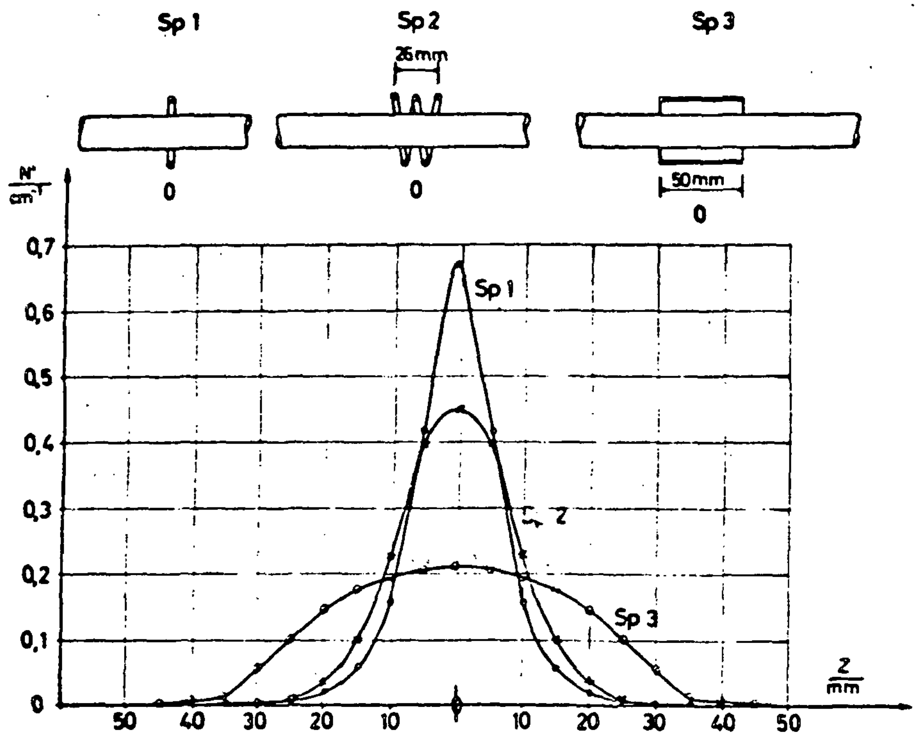

Figure 5: Standardized heat efficiency per length unit N' in inductively heated pipes with three different coils as functions of the distance z from the coil plane. Pipe diameter: 20.5 mm, wall thickness, 0.8 mm, Material: stainless steel X 15 CrNiTi 2520.

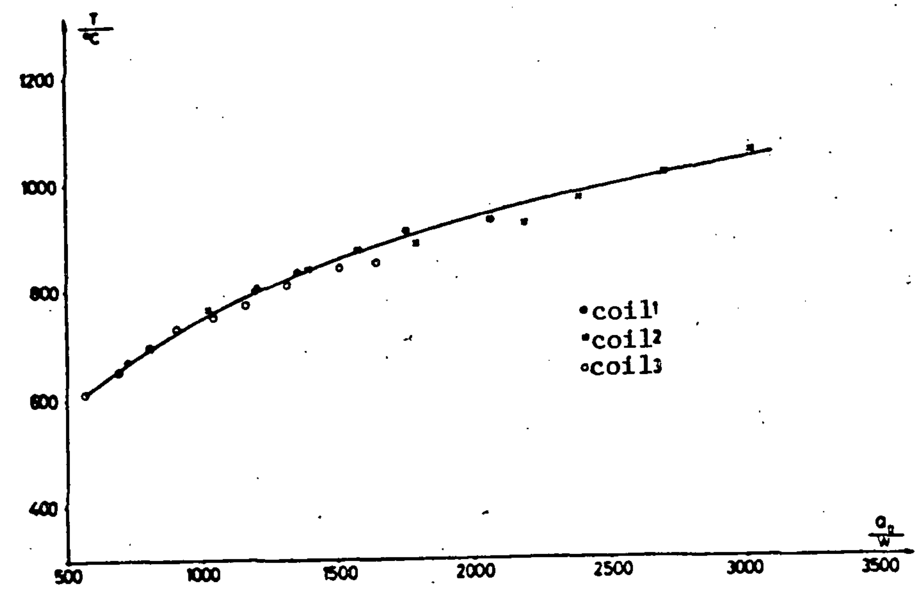

Figure 6: Temperature and heat efficiency of a groove-heat pipe operating in a vacuum. Heat output from radiation over the entire surface. Pipe diameter: 20.5 mm. Pipe length; 48 cm.

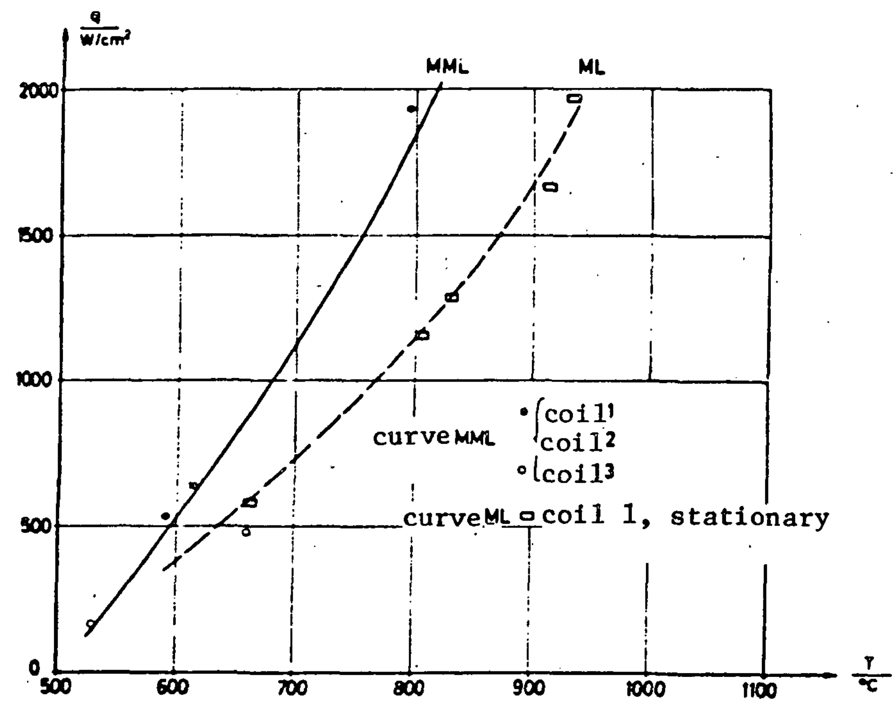

Figure 7: Maximum possible power density for non-stationary operation (MML) of the capillaries of the heat pipe in Figure 6 as functions of the temperature, as well as the power density in the mid-plane of the coil (ML).

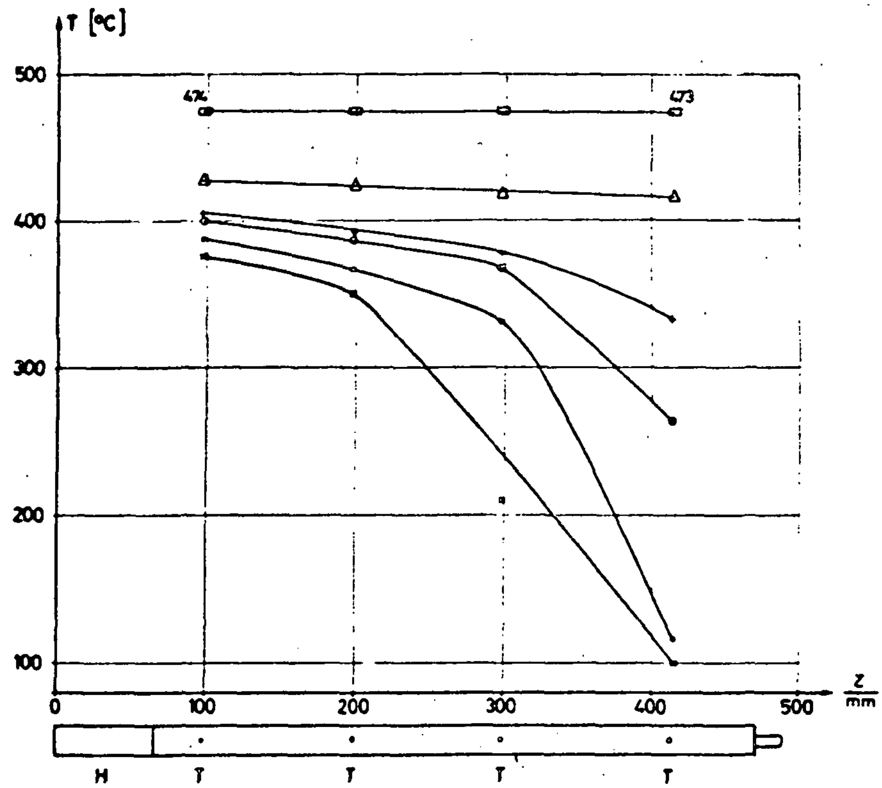

Figure 8: Temperature profiles of a heat pipe at low operating temperatures. Dimensions of the pipes as in Figure 6. H = heating point, T = thermo-element.