SOME EXPERIMENTS ON THE REGELATION OF ICE

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## Abstract

This classical experiment with a wire cutting through a
block of ice was performed with variations in wire mate-
rial, wire size and effective bearing pressure. As ma-
terial, copper and "Perlon" were used with diameters
ranging from 0.125 to 1 mm. Pressures of 5, 8 and 10 bar
were applied. In order to investigate surface effects
two different metallic materials, copper, and stainless
steel (V2A), of markedly different thermal conductiv-
ity  were coated with silver and insulating varnish. The
experimental results presented in terms of speed of the
wire cutting through the ice show good agreement with
results predicted by a model theory based on heat con-
duction.

Experimental setup

The classical experiment for the regelation- or refreez-
ing-    phenomenon is performed with a wire cutting
through a block of ice and nevertheless leaving the
block undivided.

It was the object of our experiments to learn about the
governing mechanism of this phenomenon.

For this reason different wires were used to penetrate
through a block of ice 40 cm long and 12 cm in square.
A sketch of the experimental set up is given in figure 1.
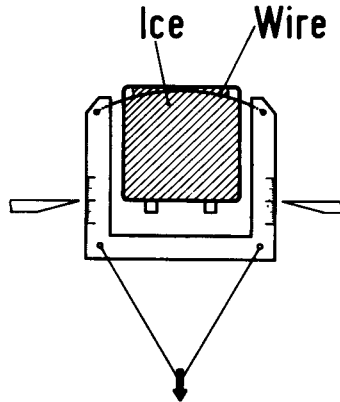Three wires of different diameters were used at a time

Fig.1   Experimental set up

in one run. Each wire was held in a rigid wooden frame
which was loaded with such a weight that the bearing
pressure was the same for each wire.

This pressure was calculated from the weight, the dia-
meter and the bearing length of the wire. Since the ex-
periments were performed in a room with a rather con-
stant temperature of $22^{\circ}C$, heat was conducted along the
wire into the ice by the so-called fin-effect. The wire
length influenced by this effect could be calculated as
well as measured. Since the surplus heat from the room
prevented the refreezing of the water above the wire,
a wedge-shaped mark showed the influenced length on ei-
ther side of the block. This influenced, heated  length
was not considered as bearing.

The penetrating wires were  always placed some distance
away from the ends of the block, so that influences by
edge effects or structural differences in the ice are
kept small.

The descent of the wires within certain time intervals
was observed from a millimeter scale on the frames and
from this the penetration speed was calculated.

Preparation of ice

The first experiments had shown that the penetration
speed is quite sensitive to impurities in the ice, espe-
cially to air.So it had to be a main object to produce
constant quality ice. Clear transparent blocks were ob-
tained from distilled water which had been kept boiling
for at least 30 minutes in order to drive out the air.
The freezing of the water took about 8 hours in a

rectangular shaped container which floated in a cold
bath. One long  side of the container was open and the
water was stirred continuously.Several times the liquid
part with the remaining impurities and reabsorbed air
was exchanged for fresh treated water.

Still remaining impurities collected in the upper part,
in the section which froze last.

In figure 2 two blocks of ice are shown, one with air
and the other treated as described.

In the test runs the blocks were turned upside down, so
that the contaminated section formed the bottom part
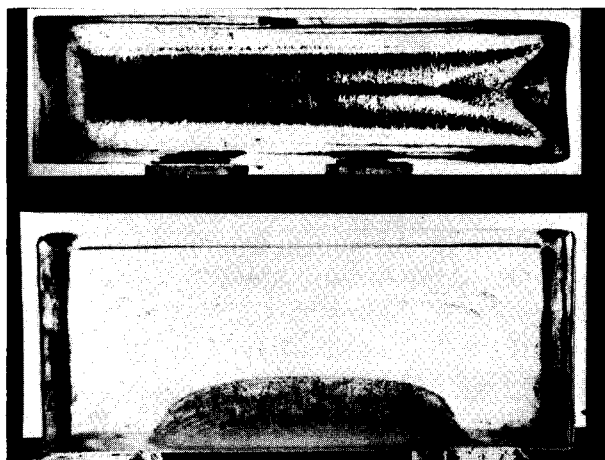and could not affect the experiment.



Fig.2   Ice blocks

## Experiments

In the experiments different wire diameters, different
bearing pressures and different materials were applied.

The materials were selected with respect to their ther-
mal conductivity, copper, with a thermal conductivity
k = 370 W/m·deg, spring steel with k = 30 W/m·deg and
Perlon with k = 0.3 W/m·deg were used.

The results of the experiments are presented in figure 3.
The penetration speed is given as a function of wire di-
ameter, with the mean pressure as parameter. There is a
distinct difference in the behaviour of the two materi-
als. The Perlon string is moving considerably slower
than the copper wire. For both materials an increase in
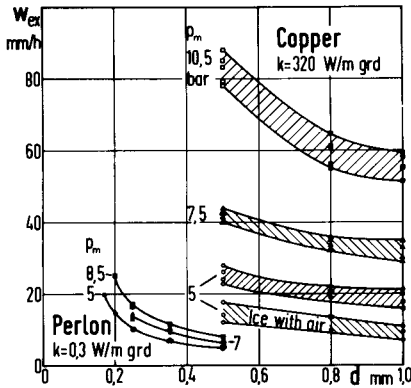diameter causes a decrease in penetration speed, while

Fig.3   Penetration speed of copper   and Perlon wires

an increase in pressure also increases the speed. There
is a striking difference in the scatter of the results.
The reproducibility of Perlon tests is much better than
that of copper. Reasons for this will be discussed.

The plot also shows some results for ice with air inclu-
sions. The penetration speed in this case is always be-
low that for air-free ice.

In order to learn about possible surface effects /1/ cop-
per wires and spring steel wires were either silver plat-
ed or coated with insulating varnish. Again these coat-
ing  materials were chosen for their great difference in
thermal conductivity. The results of these tests are
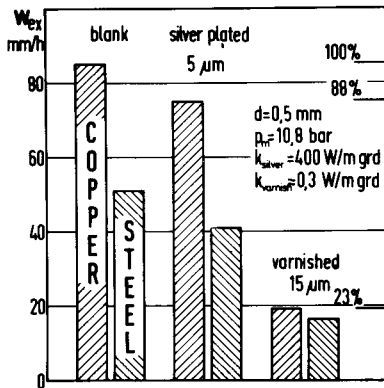presented in figure 4.



Fig.4   Penetration speed of silver-plated and
        varnished wires

The penetration speed is shown for blank, silver-plated
and varnished wires. In all runs the diameter of the wires
was constant 0.5 mm, and the applied bearing pressure
10.8 bar. The silver-plating was 10 μm thick, the
varnish coating 15 μm.

The difference in speed between the two different mate-
rials is maintained even though the surfaces of the
probes were the same: silver or insulating varnish.

The plot shows that silver plating causes a reduction in
speed of about 12%, if the blank copper is taken as the
100% reference. The varnish layer decreases the speed
by about 77%.

## Observations in the experiments

Some observations made in the experiments might be worth
mentioning. The scatter in the results for copper wires
induced a number of variations in the performance of the
experiments. It turned out that the best possible repro-
ducibility was achieved by using the copper wires only
once. Multiple use brings about uncontrollable deposits
on the surface.

The main reason for the scatter of the experimental re-
sults was found in the appearance of bubbles along the
wire. These bubbles were formed on the wire and were
left behind in the ice while the wire moved downwards.
About 15 minutes after their appearance, these bubbles
vanished again in most cases. The occurence of bubbles
was always connected with a decrease in wire speed.

In figure 5 these bubbles are shown in a block of ice.
The decrease in speed is also recorded in this picture.
If the wire remains longer in one place, more heat is
conducted from the surroundings along the wire into the
ice. This means that the incisions from both sides are
deeper when bubbles appear. In the picture the deeper
cuts indicate this bubble appearance.

In general the largest bubbles were observed on the
thickest wire of 1 mm diameter, the most frequent appear-
ance occurred on the 0.8 mm wire. Frequently used wires
showed a greater tendency for bubble creation than new
ones. Only little bubble formation was observed on sil-
ver-plated and varnished wires. So far no special inve-
stigation was performed on the nature and the causes
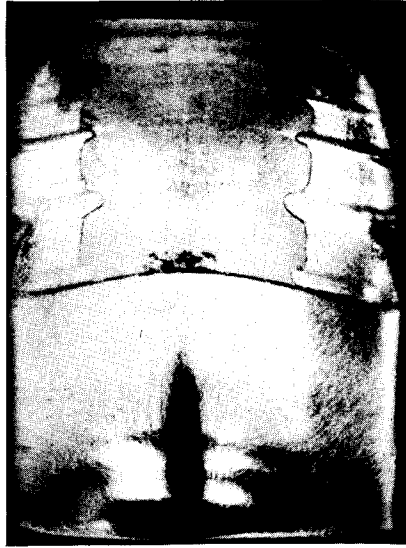of these bubbles.

Fig.5   Bubbles on the wire

## Theoretical considerations

The strong depencence of the penetration speed on the
thermal conductivity of the wire led to the considera-
tion that heat conduction is the significant parameter.

Two different models, for high and low thermal conduc-
tivity specimen were assumed and are presented in fi-
gure 6. Only steady state conditions will be considered,
as far as heat conduction is concerned. In either case,
the specimen is assumed to be surrounded by a very thin
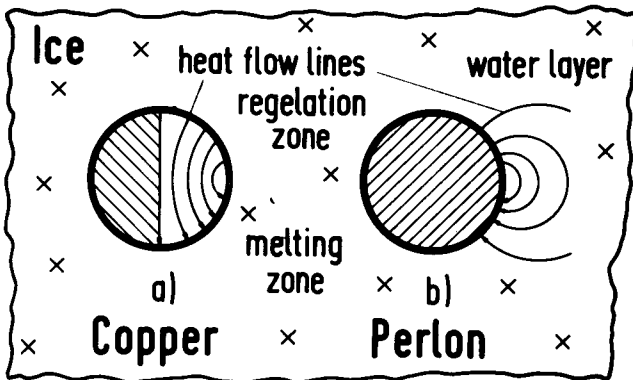layer of liquid water.



Fig.6   Heat conduction model

This originates from the melting of the ice below the wire, is pressed around the wire and freezes again above it. In freezing, the latent heat of melting is set free above the wire, while below the wire it is needed to melt the ice.

So it is assumed that heat will flow from the upper freezing section to the lower melting section. The paths which it takes depend on the thermal resistance or the thermal conductivity of the layers passed.

With copper of a high thermal conductivity and consequently a low resistance, the flow lines are assumed to go through the water layers and the wire as shown in a) of figure 6.

Perlon on the contrary has a low thermal conductivity, so the string represents a high resistance and the flow lines are assumed to go around the wire through the ice, which has a thermal conductivity greater by an order of magnitude than that of Perlon.

For these model cases, the Laplace equation was solved analytically. Using Fourier's equation and the Clausius-Clapeyron relation a heat balance was established from which the penetration speed could be determined as given in the following equations.*

For model fig.6a:

$$\underline{w}_a = \pi T\,(\underline{v}_s - \underline{v}_l)P\;/\;4\;\rho_I\;l^2(d/\lambda_{Cu} + 2\delta/\lambda_{H2O}) \quad (1)$$

and for model fig.6b:

$$\underline{w}_b = \pi T\,(\underline{v}_s - \underline{v}_l)P\,\lambda_I\;/\;4d\;\rho_I\;l^2 \quad (2)$$

where $w$ is the penetration speed, $T$ the melting temperature, $\overline{v}$ the specific volume of solid (s) and liquid (l), p the bearing pressure, $\rho_I$ the density of ice, l the latent heat of melting, d the wire diameter, $\delta$ the water layer thickness and $\lambda$ the thermal conductivity of copper (Cu), water ($H_2O$) and ice (I).

In figure 7, comparison is presented between the theoretical and the experimental results. The ratio of the theoretical speed to the experimental speed is plotted against the bearing pressure.

Full agreement between theory and experiment would result in data on the horizontal line 1. As an explanation for the deviations it should be considered that the

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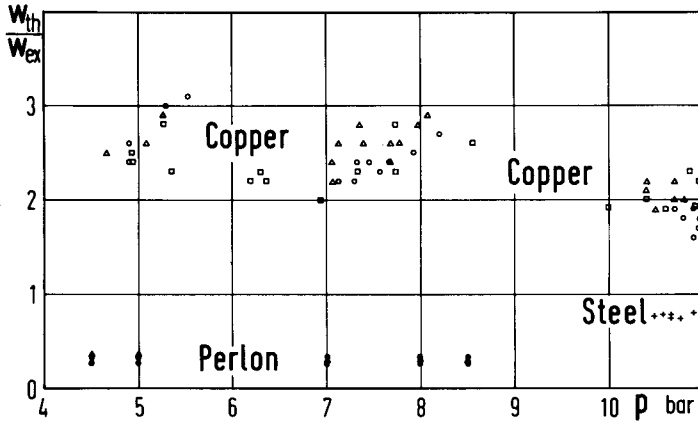*The detailed calculation procedure will be published later.

Fig.7   Comparison between theory and experiment

theoretical speed in the copper model requires an assump-
tion for the waterlayer thickness. For the sake of sim-
plicity a value of 1 µm was chosen. An increase to
2.3 µm, however, would bring the data points well around
the full agreement line.

For the Perlon model it has to be realised that the ra-
tio of the thermal conductivities of ice and Perlon on-
ly amounts to 7 while this ratio for copper and ice is
about 170.

This means that the model a) for copper seems appropri-
ate while the model b) for Perlon needs corrections for
that part of the latent heat which passes through the
Perlon string. Such a correction based on the thermal
conductivities and the heat path lengths brings the da-
ta also closer to the full agreement line. The correction
however, again depends on assumptions. For the spring
steel data also it has to be considered that heat will
flow through the wire and around it, so that none of the
mentioned models applies exclusively.

The theoretical consideration of the silver-plated wires
predicts a decrease in speed of about 1% due to the ad-
ditional silver layer. The experiments, however, give a
decrease of 12% for copper and 18% for steel. Since the
heat path lines should not be changed very much by the
silver layer, the model a) should still be valid and the
extra decrease in speed might indicate an additional
effect.

The small difference in penetration speed with the var-
nished wires might be explained by the drastic change,

from the model a) to the model b) heat flow pattern,
where the wire material is of no influence.

Concluding it might be stated that heat conduction seems
to play the dominant part in regelation.
The deviations of the silver-plated wires from theory
indicate, that additional effects such as surface inter-
actions might be present.

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˙After submitting this paper, the authors learned that
work on regelation had been carried out by Dr.J.F.Nye,
Professor F.C.Frank and others at H.H.Wills Physics
Laboratory, University of Bristol.