Enhancement of Heat Transfer between Two Horizontal Liquid Layers by Gas Injection at the Bottom

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KfK 3223

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Summary

In connection with   investigations concerning the core melt -
concrete interaction the enhancement of heat transfer between two
horizontal liquid layers by gas injection has been studied using
two systems - oil over water and oil over Wood metal - with very
different density ratios. For the largest gas injection rate
(superficial gas velocity 0.63 cm/s) the heat transfer coefficient
is increased by nearly a factor 400 for oil over water and by about
a factor of ten for oil over Wood metal. In the core melt - concrete
interaction the superficial gas velocities might be even higher,
therefore the gas - induced enhancement of interfacial heat transfer
should be taken into account.

Erhöhung des Wärmeübergangs zwischen zwei horizontalen Flüssigkeitsschichten durch Gasinjektion am Boden

Zusammenfassung

In Zusammenhang mit Untersuchungen zur Kernschmelze-Beton-Wechsel-
wirkung wurde die durch Gasinjektion hervorgerufene Erhöhung des
Wärmeübergangs zwischen zwei horizontalen Flüssigkeitsschichten an
zwei Systemen - Öl über Wasser und Öl ober Wood-Metall - mit sehr
unterschiedlichen Dichteverhältnissen untersucht.
Bei der größten Gasinjektionsrate (" superficial gas velocity "0.63 cm/s)
erhöht sich der Wärmeübergangskoeffizient bei Öl über Wasser um fast
den Faktor 400 und bei Öl über Wood-Metall um zehn. Bei der Kernschmelze-
Beton-Wechselwirkung können noch höhere Gasinjektionsraten auftreten.
Deshalb sollte die dadurch hervorgerufene Erhöhung des Wärmeübergangs
über die Grenzfläche berücksichtigt werden.

INTRODUCTION

Experimental investigations of molten core debris- concrete interactions
show that contact between melt and concrete is marked by vigorous gas
evolution /1/. Pool behaviour and heat transfer is then governed
mainly by the stirring action of the percolating gases and natural
convection plays only a minor role.
A pool of molten core debris normally will consist of two liquid
phases, an oxydic and a metallic. For an estimation of the growth
rate of the pool into the concrete, heat transfer at the pool
boundaries and in addition, heat transfer between the two liquid
phases has to be known. Heat transfer at the pool boundaries has
been studied with simulant materials either by injection of gases
at the boundaries of convection cells /2-4/ or by observing the
penetration of a liquid pool into decomposing, gas evoluting solids
/5,6/. These experiments show that the gas will vigorously mix the
pool and compared to pure natural convection this leads to

- a flattening of the temperature distribution and a decrease of the
  temperature difference between the pool and the boundaries and to

- remarkable changes of the heat transfer rates at the pool boundaries.

The aim of the present study was to investigate the influence of gas
injection on the heat transfer between two horizontal immiscible
liquid layers. The results may be used in integral codes like
WECHSL /6/ or CORCON / 7/ to describe the complex melt-concrete
interaction.

In the experiments the lower, higher density layer is heated. Therefore
the experiments simulate the initial (oxide is more dense and has a
higher power density than metal) or the final phase (because of
dilution with concrete oxide is less dense and has a lower power
density than metal) of the melt-concrete interaction. Bottom heating
is used, but it is expected that the local distribution of the heat
sources will not strongly influence interfacial heat transfer.

Two systems - silicone oil (density 0.91 g/cm^3) over water and silicone oil over Wood metal (density 9.5 g/cm^3) - were investigated to study in addition the influence of the density ratio.

EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic diagram of the apparatus is shown in Fig. 1. The double-layer, liquid system is contained is a cylindrical cell. The bottom consists of an electrically heated, porous plate. At the surface a helical heat exchanger tube is immersed in the liquid. The boundaries are essentially adiabatic. The volumetric gas flow rate V is measured with a flow meter. The electical power P_{el} is determined with a wattmeter and the thermal power P_{th} of the heat exchanger (HX) by the rate (flow meter) and the temperature rise (thermocouples TC) of the cooling water. To determine the vertical temperature distribution T(z) a series of thermocouples (Type J, sheath diameter 1mm) were located inside the liquid system equally spaced (10mm) near the axis of the cell.

For the system oil over water the cell consisted of a glass vessel (inner diameter 13cm, wall thickness 3mm). The bottom (area 133cm^2) consisted of a 14mm thick layer of glass balls (4mm diameter) on top of a porous glass plate. In this layer a helical heating coil was inserted. Air was used in this case. Details of the experimental arrangement are shown in Fig. 2.

For the system oil over Wood metal the glass vessel was replaced by a plexiglass vessel (inner diameter 14cm, wall thickness 10mm) to reduce the heat losses (Fig. 6). In addition the bottom used previously was replaced by an electrically heated copper plate (area 154 cm^2) in which a square pattern (distance 10mm) of 1mm diameter holes were drilled for gas injection. Nitrogen was used to avoid oxydation of the hot Wood metal. Details of the two slightly different arrangements used are shown in Fig.3.

The experiments were performed such that in one run the heat flux
was kept constant and the gas injection rate was varied parametrically
(oil over water) or vice versa (oil over Wood metal). After reaching
equilibrium the vertical temperature distribution T(z) was registered,
which is than used to infere the difference between the bulk tem-
peratures of the two layers ΔT as a function of the heat flux $j = P_{el} | A$
and of the superficial gas velocity $v = V/A$ (A is the bottom area).
For the systen oil over water the temperature at the heat exchanger
inlet was $10^\circ C$. For the system oil over Wood metal this temperature
had to be raised with increasing gas flow to avoid solidification
of the Wood metal.

The Wood metal (type CR35; 50Bi-25Pb-12.5Sn-12.5Cd)[*] has a density
of 9.5 g/cm^3 and a melting point between 69 and $71^\circ C$.
Material properties for the silicone oil Ak5[**] used are given in
Tab. 1.

RESULTS

In explanatoring experiments, the influence of the gas bubble diameter
has been investigated by using different porous bottoms. The results
for oil over water shown in Fig. 4 demonstrate,that variations of
the bubble diameter between about 1 and 4mm do not markedly influence
the interfacial temperature difference ΔT.
In Fig. 5 the electrically P_{el} and thermally P_{th} measured powers are
compared.(The different data sets are identified by numbers to facilitate
cross-correlation with the original data). For the system oil over
water P_{th} is generally by about 7% lower than P_{el} and this is attributed
to the heat losses at the boundaries and to heat-up of injected gas
($\leq$ 5W). Although the heat losses are certainly much lower for the system
oil over Wood metal, contained within thick plexiglass walls, P_{th}
is generally much lower than P_{el} (about 30%). This large discrepancy

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[*]   DODUCO, Pforzheim, W. Germany
[**]   Wacker-Chemie, München, W. Germany

is mainly attributed to systematic errors in P_{th} (about $\pm$ 25W) due
to the small temperature rise of the heat exchanger cooling water
(only 4°C for the maximum power level). The electically measured
power is assumed to be more reliable - the error is estimated
to be below 5% - and therefore P_{el} is used for evaluation.

In the case oil over water gas bubbles with diameters between 1 and
about 4mm were released more or less informly distributed over the
bottom area. The gas bubbles cause an irragular, wavy movement of
the interface and the surface and in addition, a complex mass
transfer across the interface. Already at moderate values of the
superficial gas velocity, small water droplets are carried along with
the bubbles into the oil layer. They coalesce within or at the
surface of the oil layer and descend as large droplets to the
interface. Here they stay for some time before they recombine with
the water layer. Both the movement of the interface and the deposition
of water droplets there cause the development of a mixing layer which
increases in thickness with increasing v. Above v=0.4cm/s, also
transport of oil into the water layer is observed and the layered
system changes to a more or less homogeneous mixture.

For the system oil over Wood metal the behaviour is quite different
(Fig. 6): Although the quite large bubbles (* 10mm diameter) cause
again an irregular, wavy movement of the interface and the surface,
even at the highest gas velocities (v=0.63 cm/s) no mixing between
the two layers is observed. Although nitrogen was used after some
time the Wood metal was partly oxydized. The oxydation products
tend to block the gas injection channels, leading to nonuniform gas
injection in some cases.

The measured vertical temperature distribution T(z) is shown in Fig.7.
With increasing gas velocity v the temperature distribution flattens
until for the highest values of v, at least for the system oil over
water, the liquid system is nearly isothermal. As has been mentioned,
for oil over water the inlet temperature at the heat exchanger was
always 10°C. For oil over Wood metal the heat exchanger inlet

temperature had to be raised with increasing gas velocity to keep the Wood metal molten (melting point 70°C). This is reflected in the temperature distributions.

Except for Wood metal the bulk of the liquid layers is very nearly isothermal. For the system oil over water the interfacial temperature difference $\Delta T = T_{high} - T_{low}$ was determined by taking for T_{low} the average of thermocouples 5 and 6 and for T_{high} thermocouple 2 (Fig. 7). For the system oil over Wood metal T_{low} was calculated from the average of thermocouples 4,5 and 6. To determine T_{high}, because of the remarkable temperature gradient in the Wood metal layer, the values of thermocouples 1 and 2 have been extrapolated for the position of the interface. The residual systematic error in ΔT after calibration of the thermocouples is estimated to be ± 0.2°C. This is the main contribution to the error in the evaluated heat transfer coefficients (Fig. 9).

EVALUATION

For a single liquid layer heated at the bottom and cooled at the top, the heat flux is according to /9/

$$j_{single} = h^*_{single} \text{ (material properties)} \cdot \Delta T^{4/3}_{single} \qquad (1)$$

where ΔT_{single} is the temperature difference between the boundaries. Applying this result to a double layer by assuming that in each layer the temperature profile is symetrical one gets for the interfacial heat flux

$$j = h^* \cdot \Delta T^{4/3} \qquad (2)$$

where ΔT is now the difference between the bulk temperatures of the two layers and h^* depends on the material properties of both layers.

Following this relation the experimental data were correlated by

$$j = h(v) \cdot h^* \cdot \Delta T^{4/3} \qquad (3)$$

assuming that the gas injection increases the heat flux by a factor
h(v), depending only on the superficial gas velocity v.

The results are summarized in Tab. 2 and 3. The data corresponding
to a certain value of v (and different values of j) are grouped to-
gether in main columns. Each main column contains three subcolumns.
The first gives the interfacial temperature difference ΔT, the
second the quantity $j/\Delta T^{4/3} = h(v) h^*$. The values of this subcolumn
are averaged to determine $(h(v)h^*)_{av}$ given in the second line from below.
The third column contains the quantity $j/(h(v)h^*)_{av}$ which is used
to check if the evaluation procedure is appropriate. If this is the
case all values $j/(h(v)h^*)_{av}$ should fall on a line corresponding
to $\Delta T^{4/3}$. The values $(h(v)h^*)_{av}$ of the second line from below are
finally normalized to the value for v=0 which gives the $h(v)_{av}$-
values shown in the last line.

In Fig.8 the normalized heat fluxes $j/(h(v)h^*)_{av}$ are shown as a
function of the interfacial temperature difference ΔT. The experimental
data are quite well fitted by the line corresponding to $\Delta T^{4/3}$
demonstrating that the relation (3) is an appropriate description
of the experimental data.

In Fig.9 finally the heat transfer coefficient $h_{av}(v)$ (last line
of Tab.3 and 4) is shown as a function of the superficial gas velocity.
To determine this quantity the individual values corresponding
to different heat fluxes but to the same superficial gas velocity
have been averaged. The heat transfer coefficient $h_{av}(v)$ corresponds
to the relative interfacial heat flux normalized to that for pure
thermal convection.

For the system oil over water the heat flux increases initially quite
steeply, with increasing v, it then flattens to increase again steeply
at about v=0.4 cm/s. This second steep increase is attributed to the
beginning of a strong mixing process. The influence of gas injection
is very strong leading to a heat flux which is for v=0.63 cm nearly

a factor 4oo higher than the pure thermal convection value.
(In a previous evaluation of the oil over water data /10/, especially
for large v, somewhat higher $h_{av}(v)$ - values, up to a factor of
1.7 for v= 0.63 cm/s, have been obtained. The difference comes from
the fact that in this reevaluation the results of a calibration
of the thermocouples have been taken into account). For the system
oil over Wood the influence of gas injection is, as expected, due
to the larger density difference, much less than for oil over water.
Nevertheless the heat transfer increases steadily with v up to a
factor of about ten for v= 0.63 cm/s. The results of the two data
sets (78/12/7) and (79/1/26) are shown separately to get an additional
idea of the accuracy of the data.

Reimann and Stiefel /11/ have fitted the measured heat transfer coeffi-
cients by

$$h_{av}(v) = 1 + 608 \; (\frac{v}{u}) \; (\frac{\rho_h - \rho_l}{\rho_l})^{-0.43} \tag{4}$$

where u is the rising velocity of the gas bubbles and ρ_h and ρ_l the
density of the heavier and the highter liquid respectively. Fig.9 shows
that this relation describes the data well as long as there is a distinct
interface between the two layers (no strong mixing).

CONCLUSIONS

Gas injection at the lower boundary increases the interfacial
heat flux between two(immiscible) liquid layers drastically. The
influence is especially pronounced if the density difference is
small. But even for quite large density differences (8.6 g/cm^3
for oil over Wood metal), the heat flux is increased by about a
factor of ten for quite moderate superficial gas velocities (0.63 cm/s).
During the interaction of a core melt with concrete the superficial
gas velocities might be appreciable higher (some 1o cm/s).
Therefore the effect of enhanced interfacial heat transfer by gas
injection has to be taken into account.

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Table 1: Material properties of silicone oil AK5 /8/

Density (g/cm^3)	0.91 (25°C)
Coeff. vol. expansion (1/$^\circ$C)	1.05-3* (0 - 150°C)
Kinematic viscosity (cm^2/s)	.069 (10°C)
	.046 (30°C)
	.033 (50°C)
Thermal conductivity (W/cm$^\circ$C)	1.17-3
Specific heat (J/g$^\circ$C)	1.42
Surface tension (dyn/cm)	19.7
	.21 - 22 (own measurement)
Interfacial tension	38 (own measurement)
(demineralized water)	

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* 1.05-3 means $1.05 \cdot 10^{-3}$

j (W/cm²)	.0			.042			.084			.17			.31			.47			.63		
	(1) ΔT (°C)	(2) $j/\Delta T^{4/3}$ (W/cm²°C$^{4/3}$)	(3) $j(h(v)\,h^*)_{av}$ (°C$^{4/3}$)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
.16	13.0	5.28-3	23.5	3.5	3.02-2	5.5	1.6	8.52-2	2.29												
.38	22.8	5.94-3	55.9	6.5	3.15-2	13.1	4.2	5.63-2	5.44	2.2	.133	3.22									
.75	35.3	6.55-3	110	12.3	2.66-2	25.6	5.6	7.59-2	10.7	4.5	.101	6.36									
1.17	44.5	7.51-3	172	18.7	2.38-2	40.2	8.5	6.79-2	16.8	5.3	.127	9.92									
1.50	47.6	8.81-3	221	17.4	3.36-2	51.5	10.8	6.33-2	21.5	7.2	.109	12.7	5.4	.159	9.43	1.3	1.06	1.42	.7	2.41	.62
$(j/\Delta T^{4/3})_{av} = (h(v)\,h^*)_{av}$	6.8-3			2.91-2			6.98-2			.118			.159			1.06			2.41		
$(j/\Delta T^{4/3})_{av} / (j/\Delta T^{4/3})_{av,\,v=0} = h_{av}(v)$	1.0			4.3			10.3			17.3			23			156			354		

Tab. 2   Oil over water (78/6), Air flow
Experimental set-up Fig.2
T_{low} average of TC 5,6 ; T_{high} from TC2

Date	j (W/cm²)	v (cm/s) → .0 (1) ΔT (°C)	(2) $j/\Delta T^{4/3}$ (W/cm² °C$^{4/3}$)	(3) $j/(h(v)h^*)_{av}$ (°C$^{4/3}$)	.09 (1)	(2)	(3)	.18 (1)	(2)	(3)	.36 (1)	(2)	(3)	.63 (1)	(2)	(3)
78/12 7	.32	13.6	9.94-3	33.0	8.0	2.01-2	19.3	7.1	2.36-2	12.7	4.8	3.97-2	7.44	3.1	7.11-2	5.29
	.65	24.1	9.44-3	67.1	18.8	1.31-2	39.2	11.0	2.68-2	25.8	7.3	4.62-2	15.1	6.9	4.98-2	10.7
1) $(j/\Delta T^{4/3})_{av}=(h(v)\,h^*)_{av}$		9.69-3			1.66-2			2.52-2			4.30-2			6.05-2		
2) $(j/\Delta T^{4/3})_{av}/(j/\Delta T^{4/3})_{av,\,v=0}$ $=h_{av}(v)$		1.00			1.71			2.60			4.43			6.24		
79/1/26	.32	17.2	7.28-3	48.7	16.4	7.75-3	32.6	9.3	1.65-2	18.2	3.0	7.42-2	7.26	2.5	9.46-2	4.63
	.65	29.7	7.15-3	98.9	23.7	9.65-3	66.3	18.4	1.35-2	36.9	8.4	3.83-2	14.7	5.7	6.42-2	9.41
	.97	46.1	5.94-3	143	31.9	9.70-3	98.9	19.2	1.91-2	55.1	12.7	3.30-2	22.0	8.1	6.00-2	14.0
	1.30	57.8	5.90-3	198	33-6	1.21-2	133	22.2	2.11-2	73.9	16-7	3.07-2	29.5	10.4	5.77-2	18.8
(1)		6.57-3			9.81-3			1.76-2			4.41-2			6.91-2		
(2)		1.00			1.49			2.67			6.70			10.5		

Table 3: Oil over Wood metal (78/12/7, 79/1/26), Nitrogen flow

Experimental set-up Fig.3

T_{low} average of TC 4,5,6 ; T_{high} extrapolated from TC 1,2 for position of interface
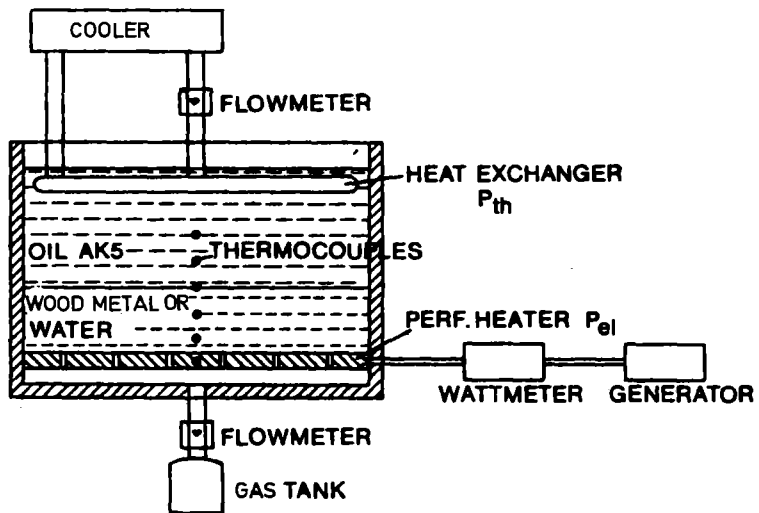
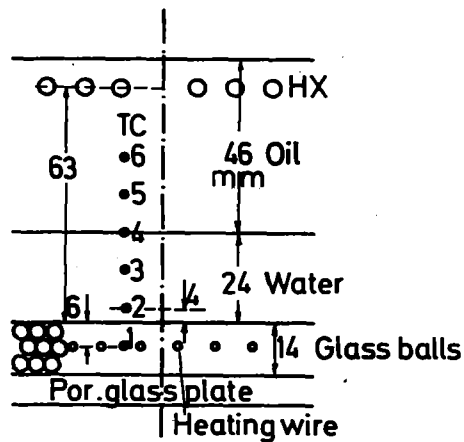Fig. 1 EXPERIMENTAL APPARATUS (Schematic)
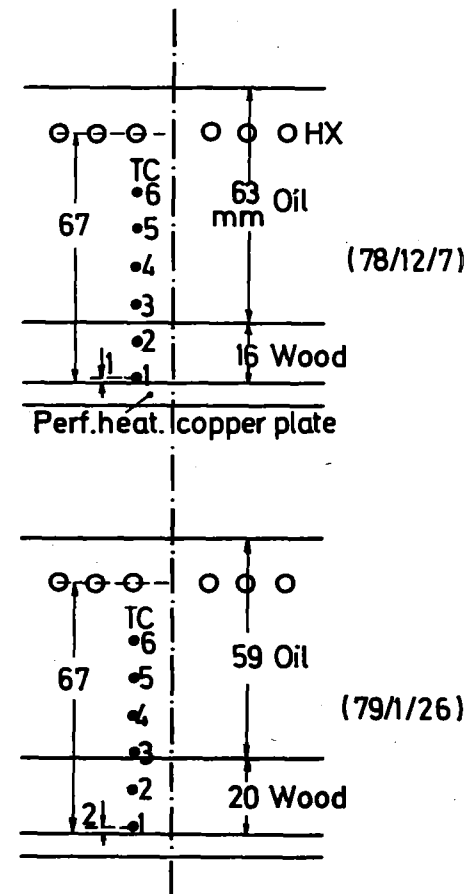

Fig. 2 ARRANGEMENT FOR
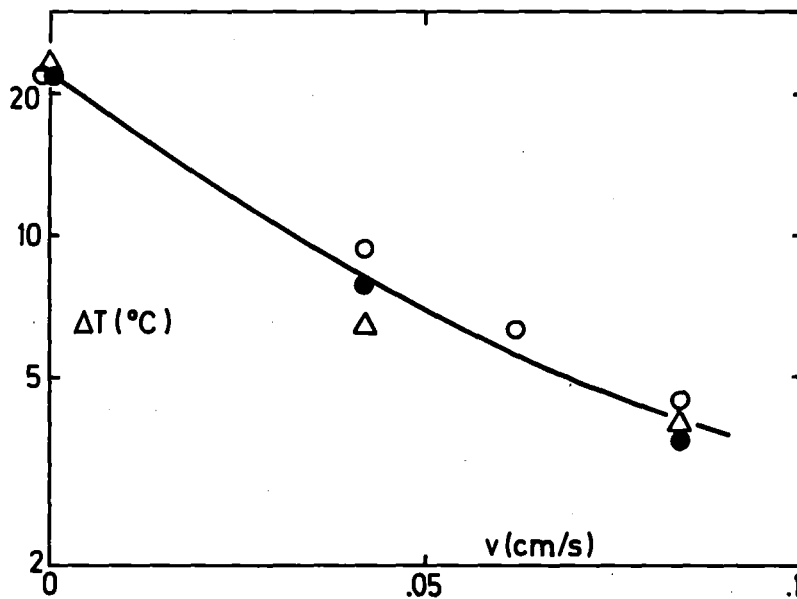OIL OVER WATER

Fig. 3 ARRANGEMENT FOR OIL OVER WOOD METAL

-13-

O   Porous glas plate, bubble diameter 1 mm

●   10 mm thick layer of 3 mm diameter steel spheres above
    porous glass plate, bubble diameter 4 mm

△   10 mm thick layer of 4 mm diameter glass balls above
    porous glass plate, bubble diameter 1 - 4 mm

Fig. 4 DEPENDANCE OF INTERFACIAL TEMPERATURE DIFFERENCE
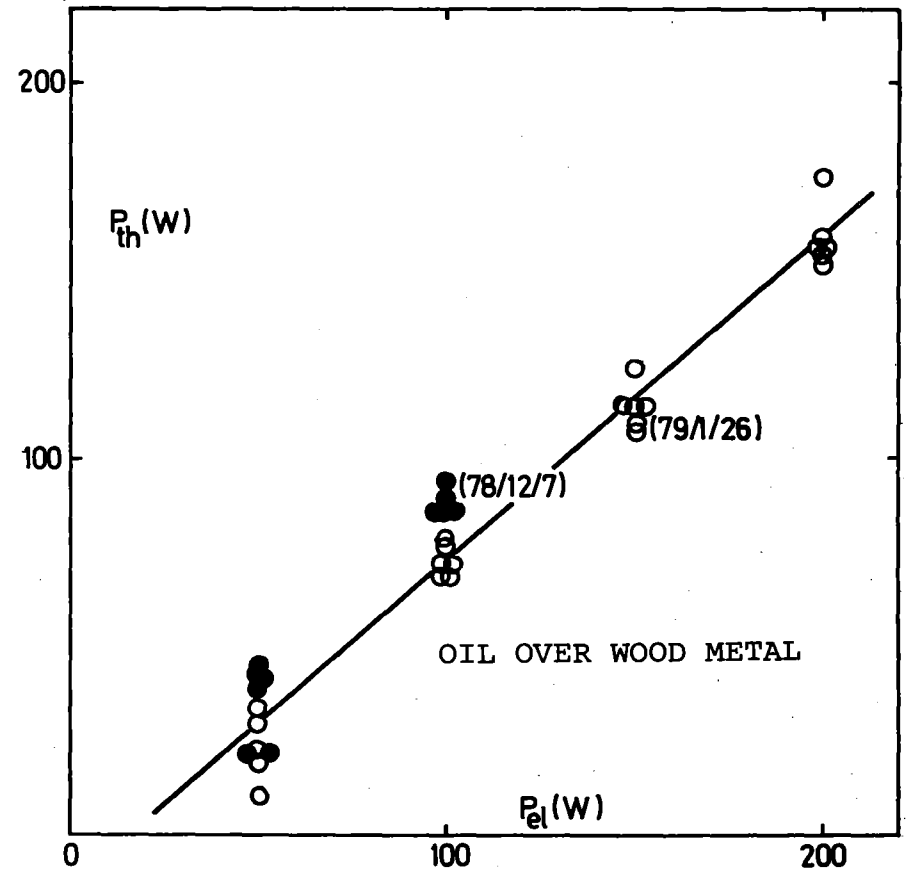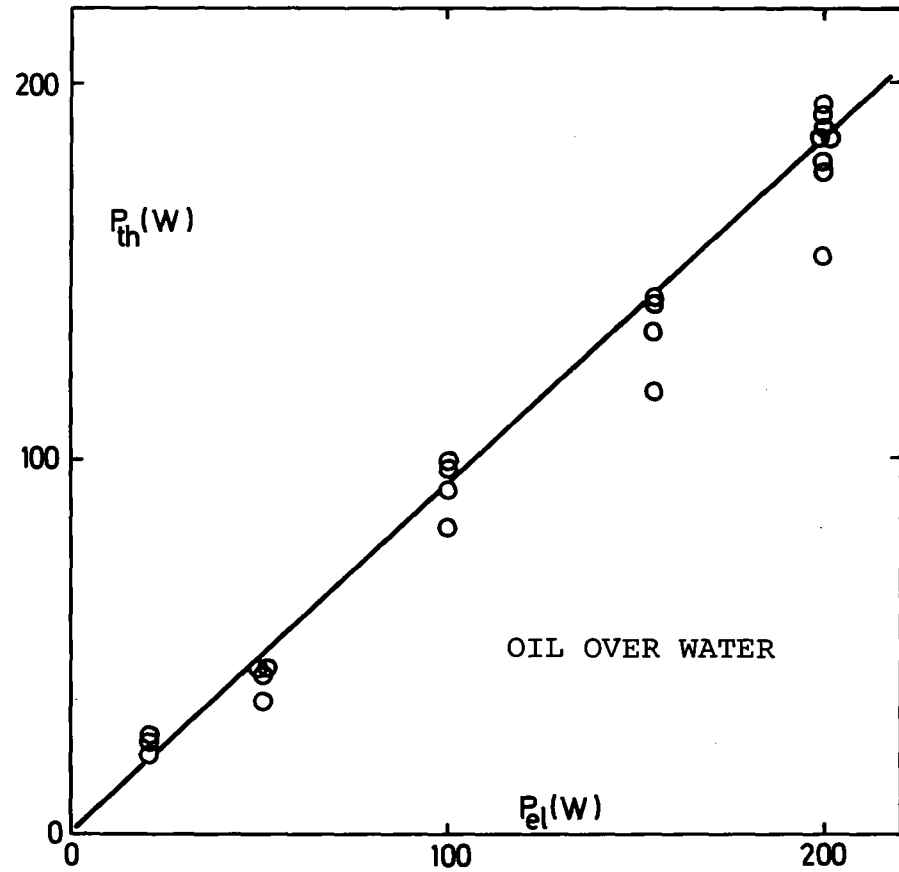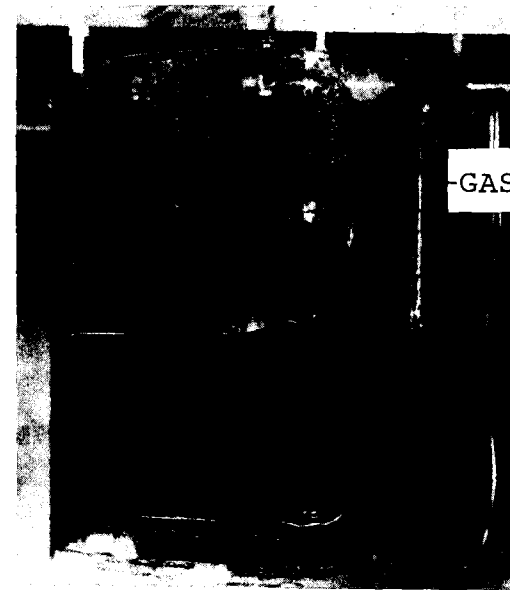
ON BUBBLE DIAMETER FOR OIL OVER WATER (j = 0.38 W/cm^2)

Fig. 5 COMPARISON OF ELECTRICIAL AND THERMAL POWER

HEAT EXCHANGER

OIL

THERMOCOMPLES

WOOD METAL

OXYDIZED WOOD METAL

PERF. HEATING PLATE

v = 0

GAS INLET

v = 0.09 cm/s

v = 0.63 cm/s
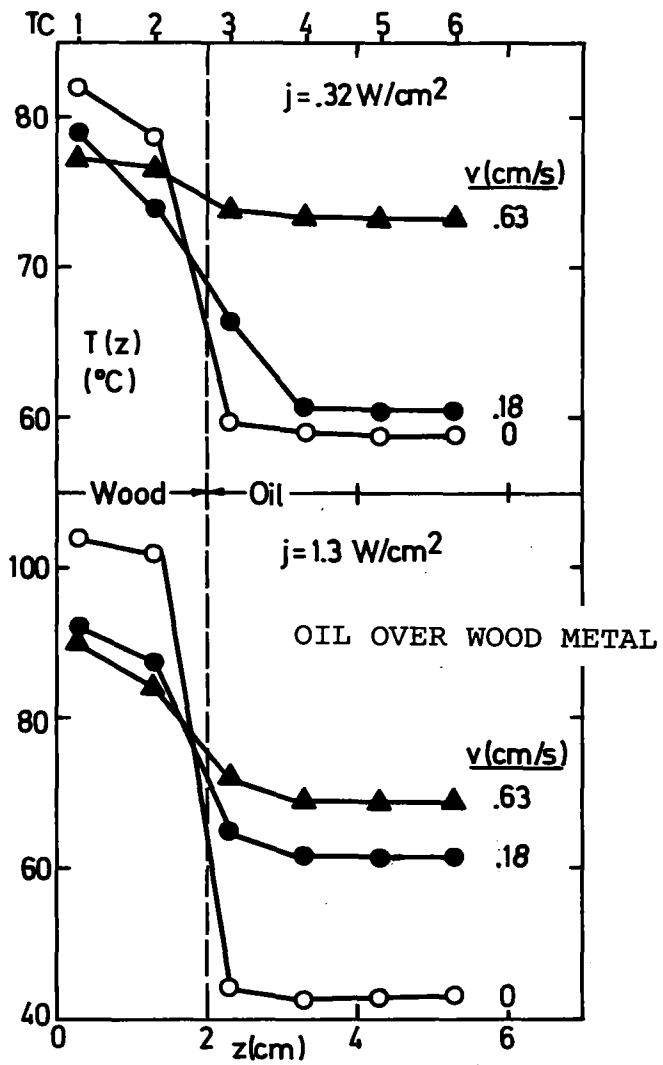
Kernforschungszentrum
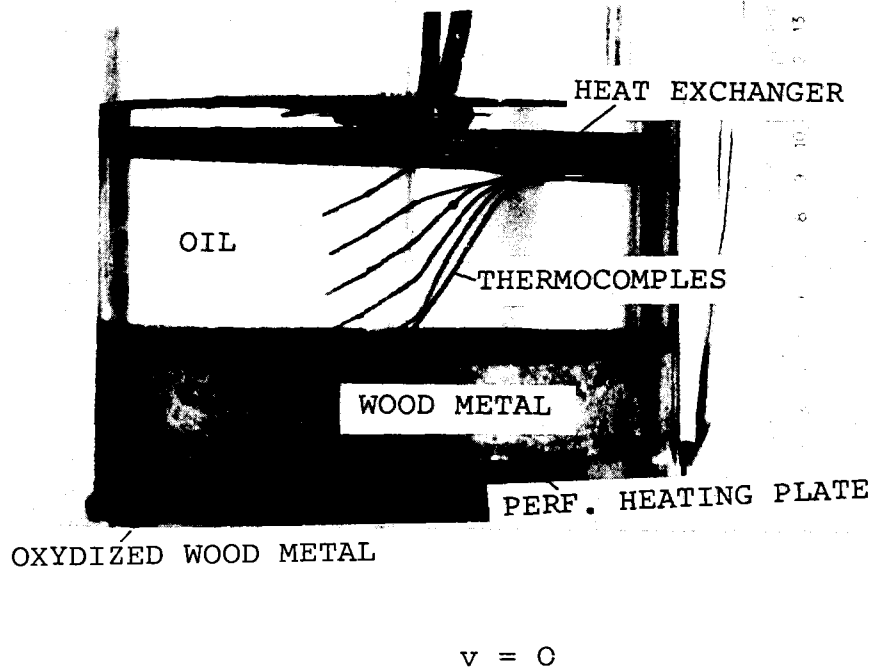
Fig. 6 OIL OVER WOOD METAL
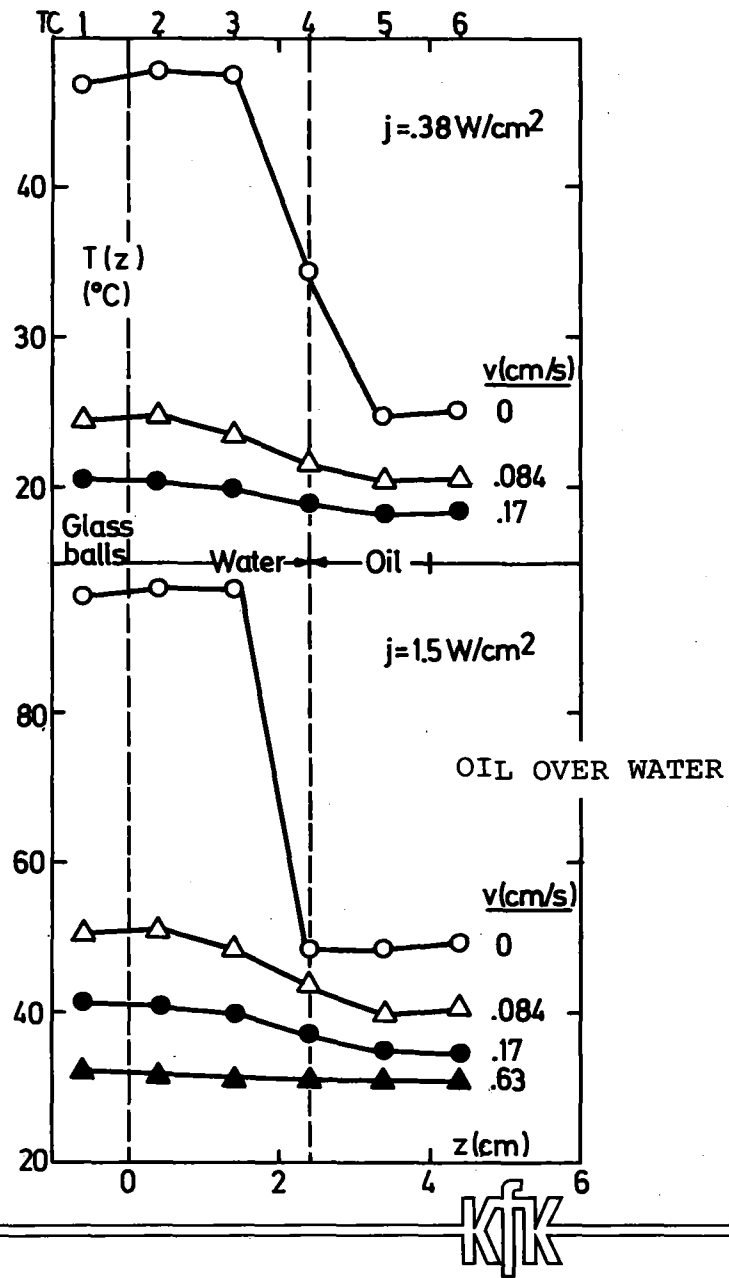
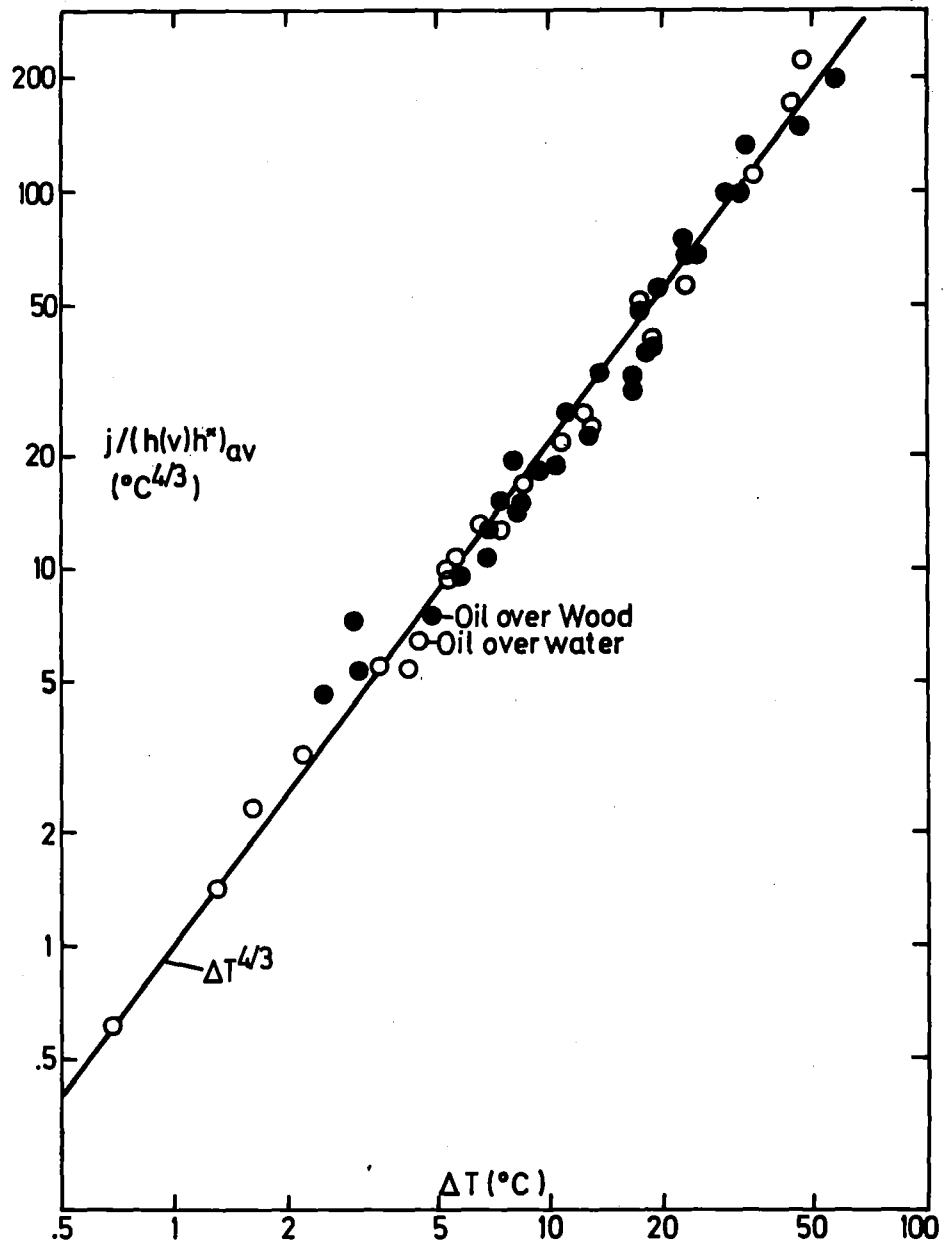Fig. 7 AXIAL TEMPERATURE DISTRIBUTION

-18-

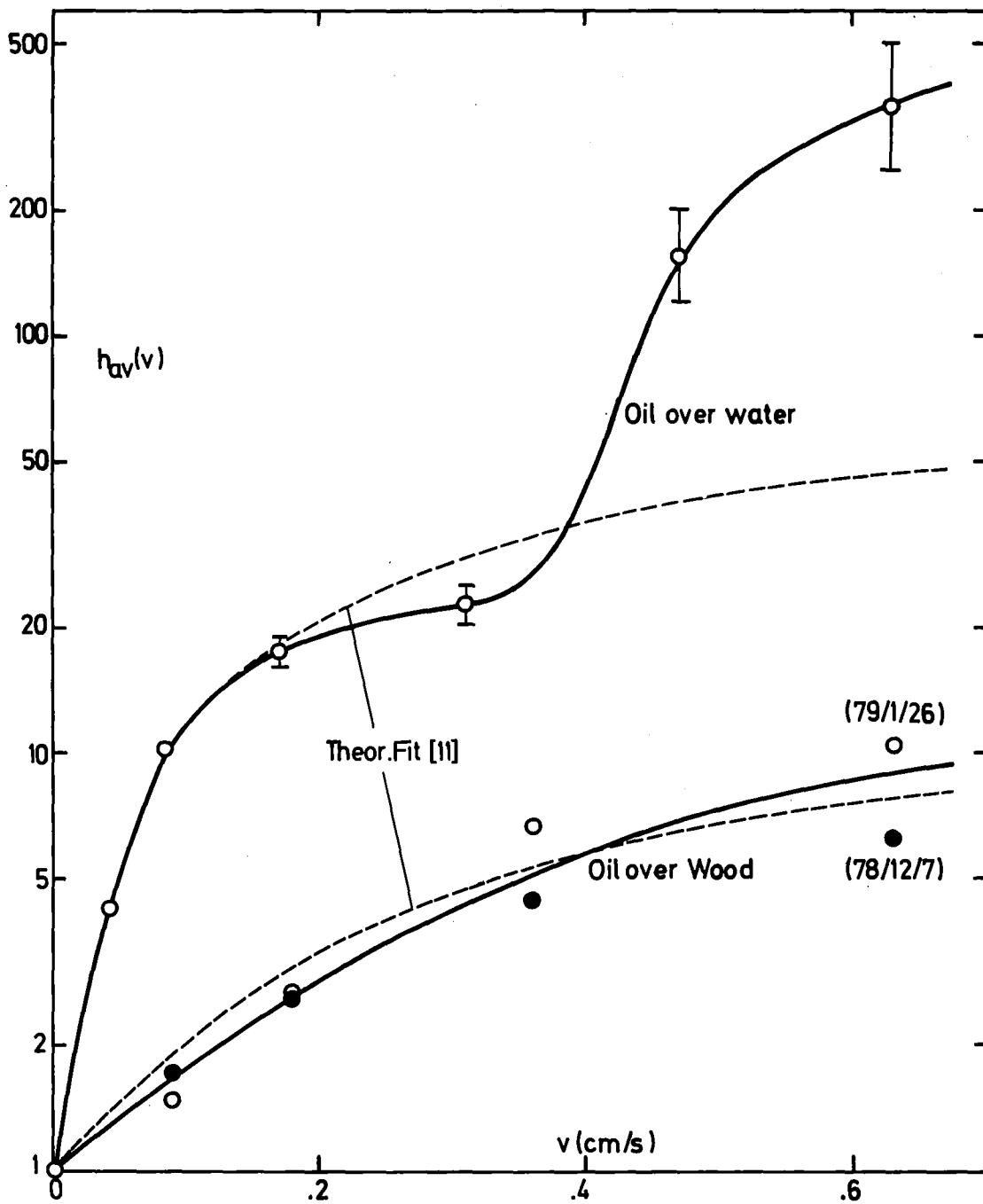Fig. 8 DEPENDENCE OF NORMALIZED HEAT FLUX ON TEMPERATURE

DIFFERENCE

Fig. 9 HEAT TRANSFER COEFFICIENT AS A FUNCTION OF
SUPERFICIAL GAS VELOCITY