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Institut für Neutronenphysik und Reaktortechnik
Projekt Schneller Brüter

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Abstract:

The installation of thermocouples within the cladding of an electrically heated BR-2 rod might cause local variations of heat flux. In order to detect a resulting temperature variation at the outer surface, experiments with a single electrically heated rod with heat fluxes up to 30.80 W/cm^2 and heat transfer coefficients up to 1000 W/m^2K by forced convection in air were conducted. The surface temperatures were measured with an optical pyrometer. The experiment showed about 0.6% variation in the surface temperature. An analyis with the TAC2D-code shows that local variation in the heat flux under these conditions is less than 1.2%.

Experimentelle Bestimmung örtlicher Wärmeflußschwankungen in einem elektrisch beheizten BR-2 Brennelementhüllrohr

Zusammenfassung:

Durch den integralen Einbau von Thermoelementen in die Hüllrohre von BR-2 Brennelementen besteht die Möglichkeit eine örtliche Variation der Wärmeleistung in den direkt beheizten Hüllrohren zu verursachen. Um eine daraus resultierende Temperaturänderung an der Oberfläche des Heizrohres im Bereich der Thermoelementposition zu entdecken, wurden Versuche an einem Einzelstab mit Wärmeflüssen bis zu 30,80 W/cm^2 und Wärmeübergangskoeffizienten bis zu 1000 W/m^2K mit konvektiver Luftkühlung durchgeführt. Die mit einem optischen Pyrometer gemessenen axialen Temperaturverläufe ergaben Temperaturveränderungen an den Thermoelementpositionen von etwa 0,6%. Eine Analyse mit dem Rechencode TAC2D ergab unter diesen Bedingungen eine Variation des Wärmeflusses kleiner 1,2%.

Nomenclature:

α	W/m^2K	heat transfer coefficient
c_p	J/kgK	specific heat at constant pressure
C_s	W/m^2K^4	emission of black body
ε	-	emittance factor
d_R	m	diameter of heater rod
D_i	m	inner diameter of glass tube
I	A	electric current
L	m	length of heater rod
Q	W	electric power
q	W/cm^2	total heat flux
q_R	W/cm^2	heat transmitted by radiation
T_B	K	gas bulk temperature
T_E	K	gas bulk temperature at test section entrance
T_R	K	room temperature
T_W	K	wall temperature of heater rod
ΔT_s	K	temperature variation
U	V	voltage

Subscript

x	at axial position x

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1. Introduction

Heat transfer calibration tests on 12-rod bundles have recently been performed in the high pressure helium loop of the Heat Tranfer Laboratory of the Institute of Neutron Physics and Reactor Engineering /1,5/. The purpose of these tests was to obtain information relevant to the thermohydraulic design of the 12-rod bundle fuel element to be irradiated in the Belgian Reactor BR2 /2/. The rod bundle test section consisted of 12 tubes of heat resistant steel (German denomination number 1.4981) with a diameter of 0.8 mm o.d. and a wall thickness of 0.64 mm and a roughened heated length of L = 59 cm. The roughness geometry was cut into the outer surface of the rods with a trapezoidal shape. The roughness ribs had a height of 0.112 mm and a pitch of 1.214 mm. The tubes were directly heated by direct current. The wall temperatures were measured by means of Ni - NiCr thermocouples which were installed in the wall of the tubes (Fig.1). Since the diameter of the sheathed thermocouples (0.5 mm) and the thickness of the tube wall are not very different from each other, the question was raised, what heat flux variation will result due to the higher electrical resistance at the thermocouple location and therby what temperature measurement error. In order to verify the magnitude of the local heat flux variation two sets of experiments were performed, with a single electrically heated rod.

2. Experiment with Natural Convection

2.1 Experimental Arragement

A single heater rod (No.121, in /5/) was mounted in a horizontal position so that it could be uniformly cooled by natural convection (Fig.2). The unheated portions at the ends of the rod were insulated to minimize axial conduction, but for the electrical connections short portions had to be left uninsulated. The rod was heated by alternating current (app.1.5 V). The temperature signals of five thermocouples (No.3 defective) were continously registered on a Polycomp (Fig.3).
The surface temperature of the rod was measured with an infrared optical pyrometer (Braun) with a temperature range from 100°C to 250°C, which could be moved parallel to the rod. The surface of the rod was sprayed with a graphite dispersion in order to get a uniform emission factor. Since the emittance of the surface was not exactly known, it was calibrated against one of the thermocouples.
The sensitivity and accuracy of reading of the pyrometer was $< 0.5\,^{\circ}C$. The circumferential position of the thermocouples and the oval measuring spot (1 mm in axial by 3 mm in circumferential direction) coincided.

2.2 Testing Procedure and Results

In Fig.4 the results of two runs are shown. The temperatures of the thermocouples were registered together with the pyrometer reading at this position. In order to take account of the temporal variation of the voltage and thereby the heat production thermocouple No.6 was used as reference. The temperature reading of this thermocouple was registered at the time of the respective pyrometer measurement and is shown at

this position in the diagramm.
Besides these temporal variations no local variation of temperature and thereby heat flux were detected.

2.3 Conclusion

In this experiment the heat transfer coefficient by natural convection in air was approximatly 8.5 W/m^2K. For this small heat transfer coefficient, any variation of the heat flux will be damped out due to axial conduction. An analysis with a two-dimensional heat transfer code conducted by Baxi /3/ showed that the heat transfer coefficient should be much higher in order to detect any local heat flux variation by measuring the surface temperature along the rod surface. These high heat transfer coefficient can be reached by forced convection only, therefore a second experiment was performed.

3. Experiment with Forced Convection in Air

3.1 Experimental Arrangement

The test rig is shown in Fig.5. A single rod (No.60 in /5/) was mounted vertically concentrically within a glass tube with an inner diameter of D_i = 16.7 mm and a wall thickness of 2.0 mm. The rod was heated electrically by passing alternating current through the cladding and cooled by air flowing downward into the open. The heated length of the rod was 680 mm with 90 mm smooth and 590 mm rough surface. The rough surface of the rod was sprayed with a graphite dispersion in order to get a uniform emission factor. The outer glass tube

was fastened in a watercooled flange at its upper end.
The heater rod was instrumented with six Ni-NiCr thermocouples of which No.6 failed at the beginning of the test runs.
The axial temperature distribution on the rod surface was measured by an optical pyrometer (IRCON Series 300T) with a temperature range of 60 - 280°C, which could be moved parallel to the rod. The distance between rod and pyrometer lens was 100 mm which resulted in a circular measuring spot with a diameter of 0.52 mm. The heater rod was positioned in such a way, that the temperature was measured at the side of the rod where the thermocouples were placed.

3.2 Testing Procedure

The surface temperature along the test rod was measured with four different heat fluxes and air mass flow rates. The air mass flow rate was measured by means of a standard orifice plate. The electrical power was determined by the measurement of current and voltage. The inlet temperature of the air was measured with a thermocouple.
The temperature signal of thermocouple No.5 was taken as reference, and was held constant by adjusting the electric power. By the calibration of the pyrometer against this thermocouple, the emittance was set to $\varepsilon = 0.64$ which proved to be valid for all temperatures. In the vicinity of the two sets of three thermocouples the distance between the pyrometer readings was 1.0 mm, in the central portion of the rod every 4.0 mm measurements were taken.

3.3 Analysis and Results

The important parameter for the magnitude of local temperature variations due to local heat flux pertubations are the heat tranfer coefficient α and the heat flux q. They were evaluated as follows:

Total electric power $$Q = I \cdot U \qquad (1)$$

Heat flux $$q = Q/F \qquad (2)$$

with $$F = d \cdot \pi \cdot L$$

Heat flux by radiation $$q_R = \varepsilon \cdot C_S \left[\left(\frac{T_W}{100} \right)^4 - \left(\frac{T_R}{100} \right)^4 \right] \qquad (3)$$

Bulk temperature at position x $$T_{Bx} = T_E + \frac{(q - q_R) \cdot x}{m \cdot c_p} \qquad (4)$$

Convective heat tranfer coefficient $$\alpha = \frac{q}{(T_W - T_B)} \qquad (5)$$

In table 1 all measured and calculated data are given. As additional data the Nusselt and the Reynolds-numbers are given as well.

The heat transfer coefficients and temperature variations were evaluated for the position of thermocouple No.5 at the axial length 326 mm from the start of heating. The temperature variations ΔT_s were taken from Fig.6. Since there is a steep axial temperature gradient, systematic temperature variations due to pertubation by the thermocouples are difficult to detect, and even more by the fact that there are

also stochastic temperature variations of the same magnitude. So the given temperature variations are only approximate and represent the maximum variations due to the installed thermocouples for this set of parameters. The highest temperature variation of about $\pm 2K$ was measured with the highest heat flux of 30.80 W/cm^2 and a wall temperature of 417°C. The last two rows in table 1 show that the temperature variations seem to depend more on the magnitude of the heat flux than on the heat tranfer coefficient. To clarify this dependence experimentally more experiments with a systematic study with the parameters q and α would be neccessary.
These experiments showed that for heat fluxes up to 30.80 W/cm^2 and heat transfer coefficients up to $\sim$ 1000 W/m^2K the surface temperature perturbation $\Delta T_s/(T_w-T_B)$ is less than 1% for heater rods of the BR-2 type.

3.4 Discussion

The experiments were initiated by the fear that a heat flux variation as high as 20% of the average flux would exist in the vicinity of the thermocouples. An analytical study with a two-dimensional computer code TAC2D was undertaken by Baxi /4/, to evaluate the heat flux variations from the experimental data. The model shown in Fig.7 was employed.
It can easily be understood that for a certain heat flux difference in zone 2 in respect to the rest of the heated rod (zone 1), the temperature difference at the surfaces of the zones will be higher for higher heat transfer coefficients or higher Biot-numbers. On the other hand a heat flux variation can be evaluated for a certain heat transfer coefficient and an observed temperature difference at the surfaces.

In his analysis Baxi used a heat transfer coefficient of α = 1000 W/m^2K and a bulk to surface temperature difference of approximately 300 K. For the local heat flux in zone 2 higher than in zone 1 by q% the persentage in surface temperature perturbation $T_S/(T_W-T_B)$ was obtained. The results are shown in figure 9. The calculation was performed for four different axial lengths of perturbation zones. The diameter of the thermocouples in a BR-2 rod is only 0.5 mm and they are embedded in the tube thickness for a length of about 4 mm along the circumference (see Fig. 1), but even if they were mounted in an exactly circumferential position, the region where the electric flux and thereby the heat generation is altered, is certainly larger than 0.5 mm. Since the electric current behaves like a potential flow the flow characteristics look as shown in Fig. 8. The region where the heat flux varies is probably best approximated by an axial length of 0.4 mm (same as the disturbed circumferential length). Thus with a measured temperature perturbation of 0.6% the local heat flux perturbation will be about 1.2%. For a three-dimensional calculation this value would be smaller.

3.5 Conclusion

Experiment and analysis showed thet the local heat flux pertubation due to installed thermocouples in the cladding of electrically heated BR-2 rods is less than initially assumed and possible errors in the wall temperature measurement are within the experimental uncertainty.

Acknowledgment

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Nr.	U [V]	I [A]	Q [W]	q [W/cm^2]	q_{st} [W/cm^2]	T_{Wx} [°C]	T_{Bx} °C	$(T_W-T_B)_x$ [K]	α [W/m^2K]	Nu	Re_B	T_E [°C]	T_A [°C]	ΔT_s [K]	$\Delta T/(T_W-T_B)$ %	$q/\Delta T_s$	$\alpha/\Delta T_s$
1	10.63	213.2	2266.4	13.26	0.167	206	55.3	150.7	868.6	266.1	$1.0 \cdot 10^5$	28.2	84.8	±1.0	0.67	13.2	868
2	14.44	275.6	3981.8	23.30	0.387	306	71.4	234.6	976.5	287.5	$1.21 \cdot 10^5$	32.4	112.9	±1.5	0.64	15.5	650
3	17.02	309.2	5263.2	30.80	0.810	417	83.8	333.2	900.0	257.2	$1.16 \cdot 10^5$	32.2	139.8	±2.0	0.60	15.4	450
4	9.22	184.6	1703.1	9.97	0.167	206	53.4	152.6	653.3	201.6	$0.73 \cdot 10^5$	24.9	84.4	±0.75	0.5	13.3	870

TABLE 1 Result of experiments with forced convection cooling

Geometrical data of experiment

d_R = 8.0 mm
L_H = 680 mm
D_i = 16.7 mm

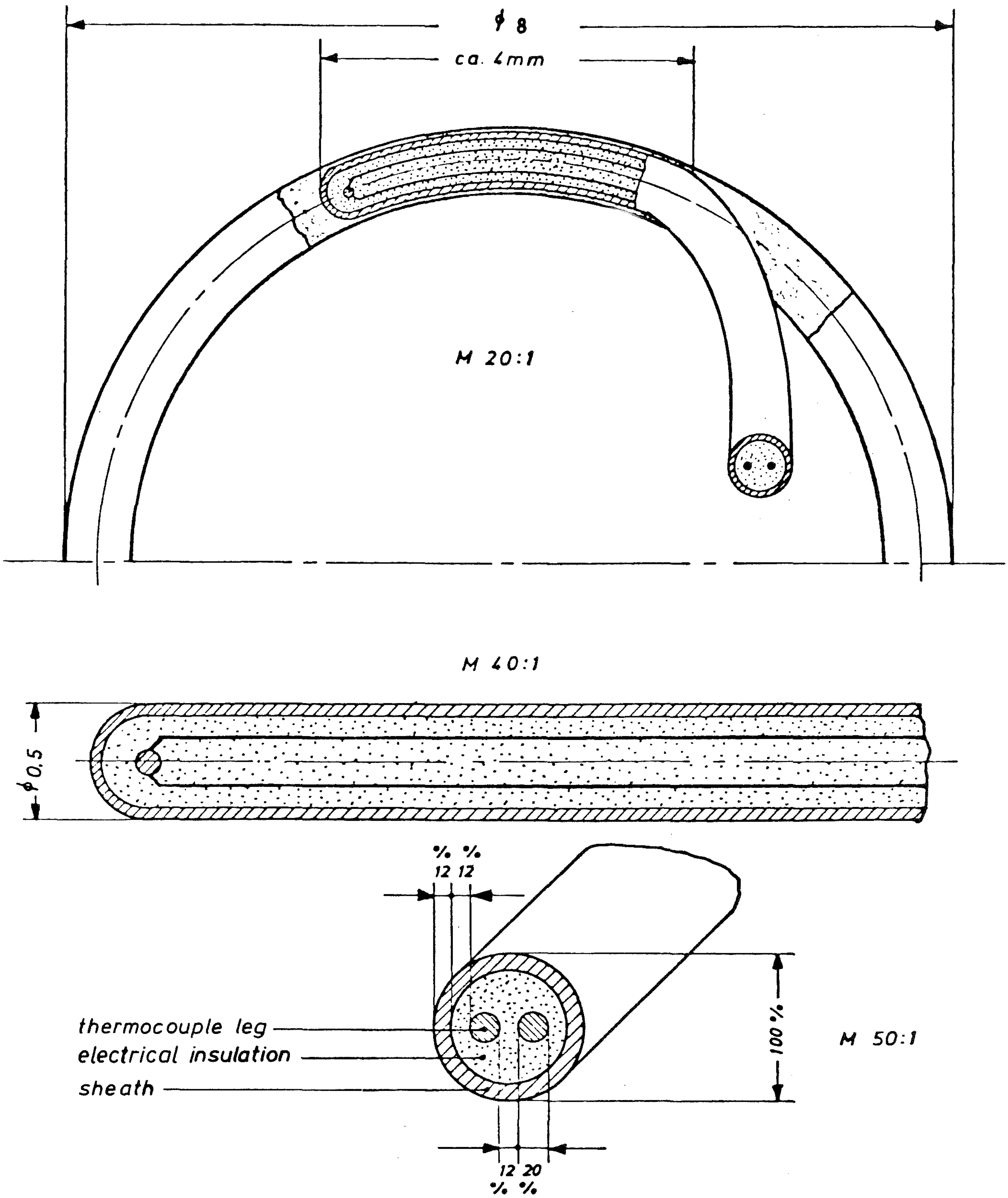

Fig. 1: Thermocouple installation in a BR-2 heater rod

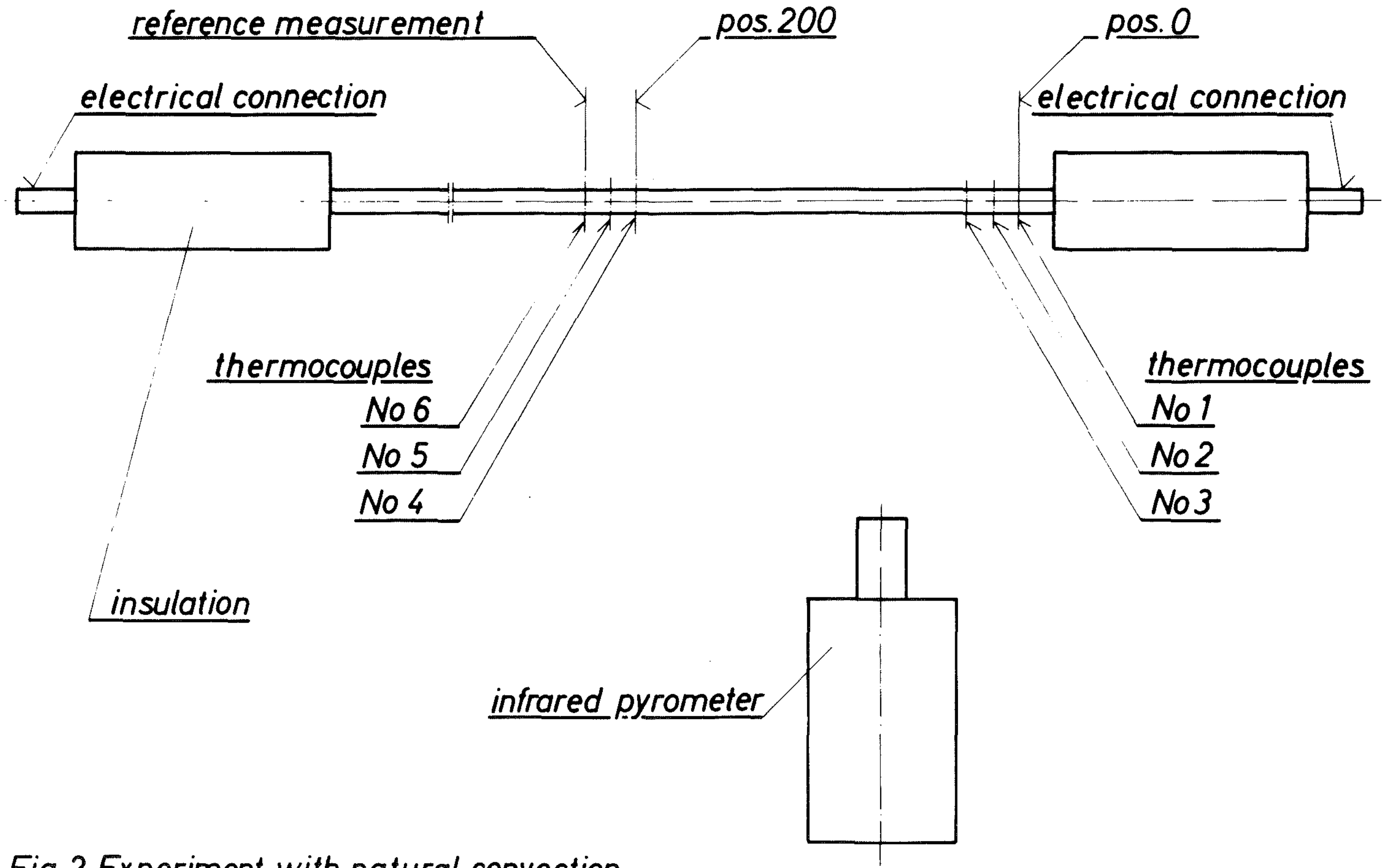

Fig. 2 Experiment with natural convection

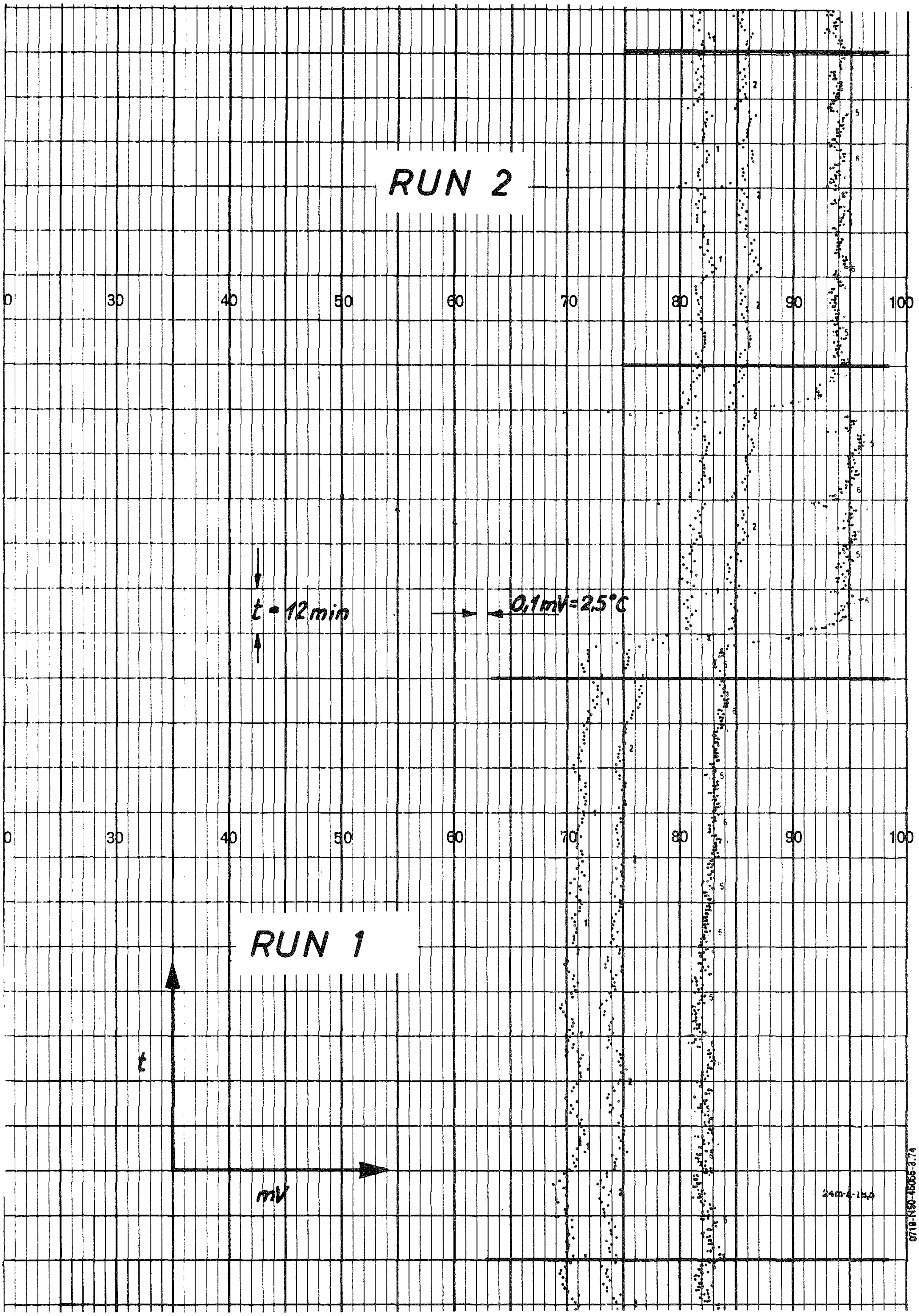

Fig. 3: Thermocouple reading during experiment

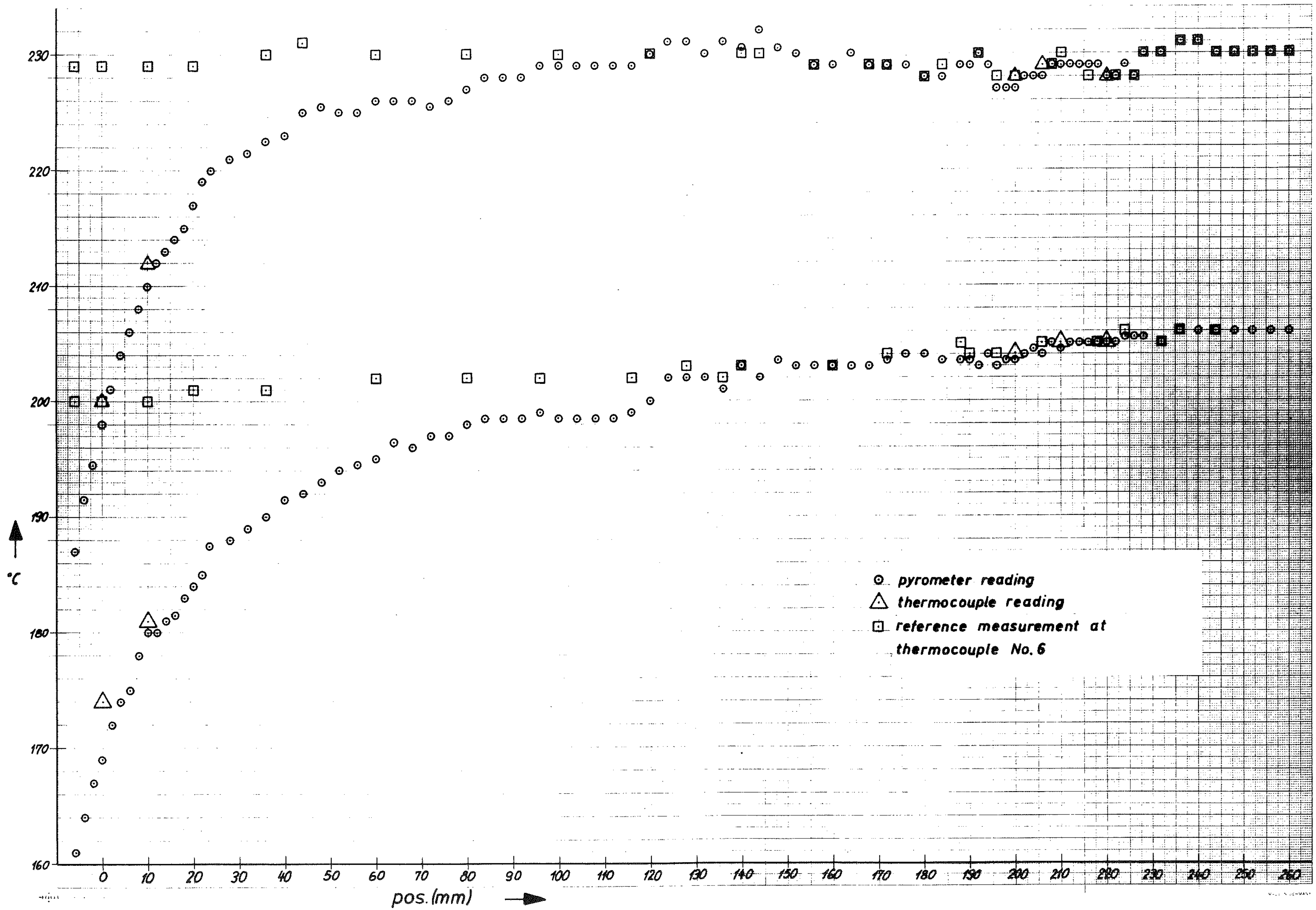

Fig. 4: Pyrometer readings for two runs with natural convection cooling

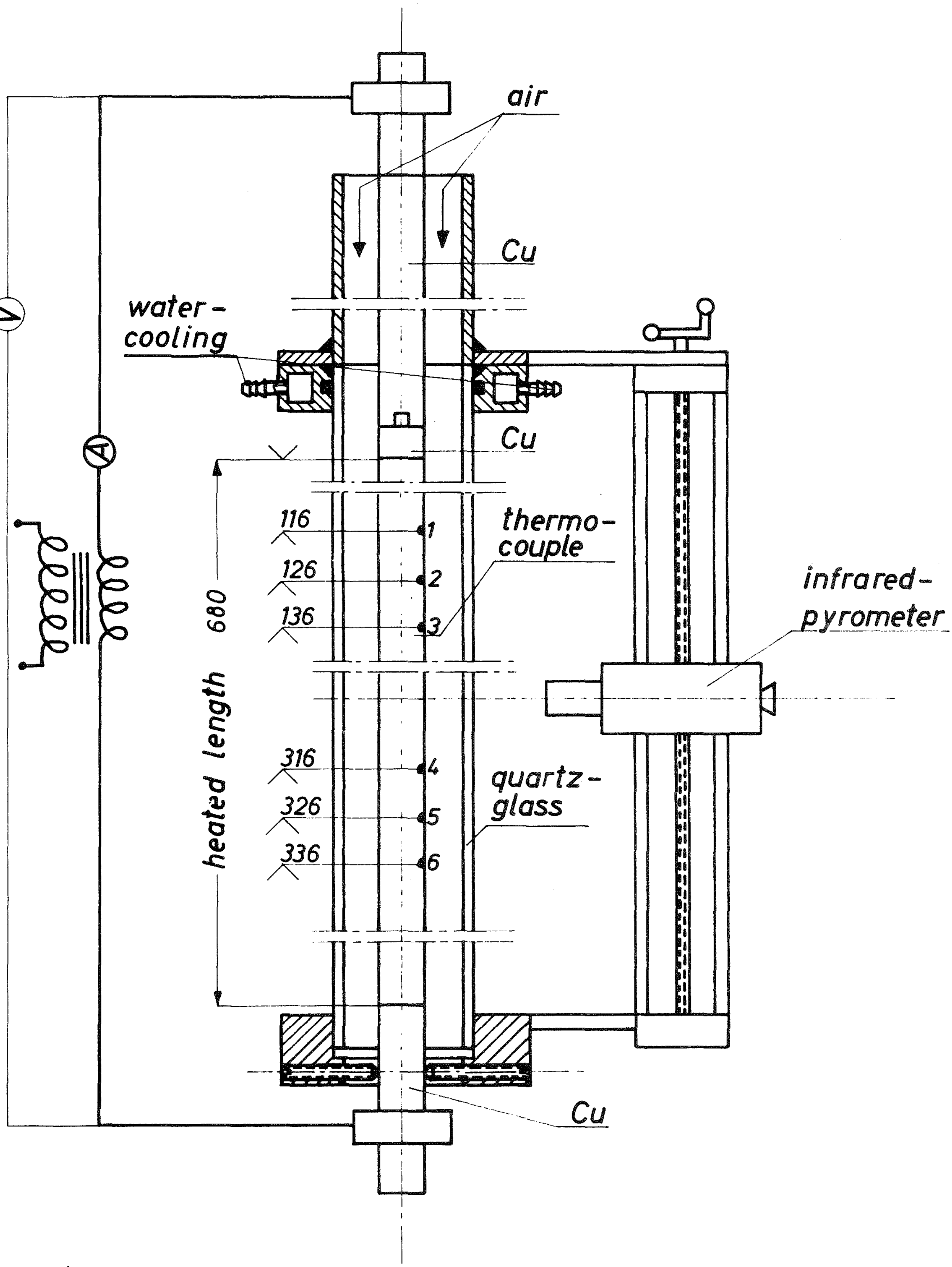

Fig. 5: Test rig for experiment with forced convection cooling

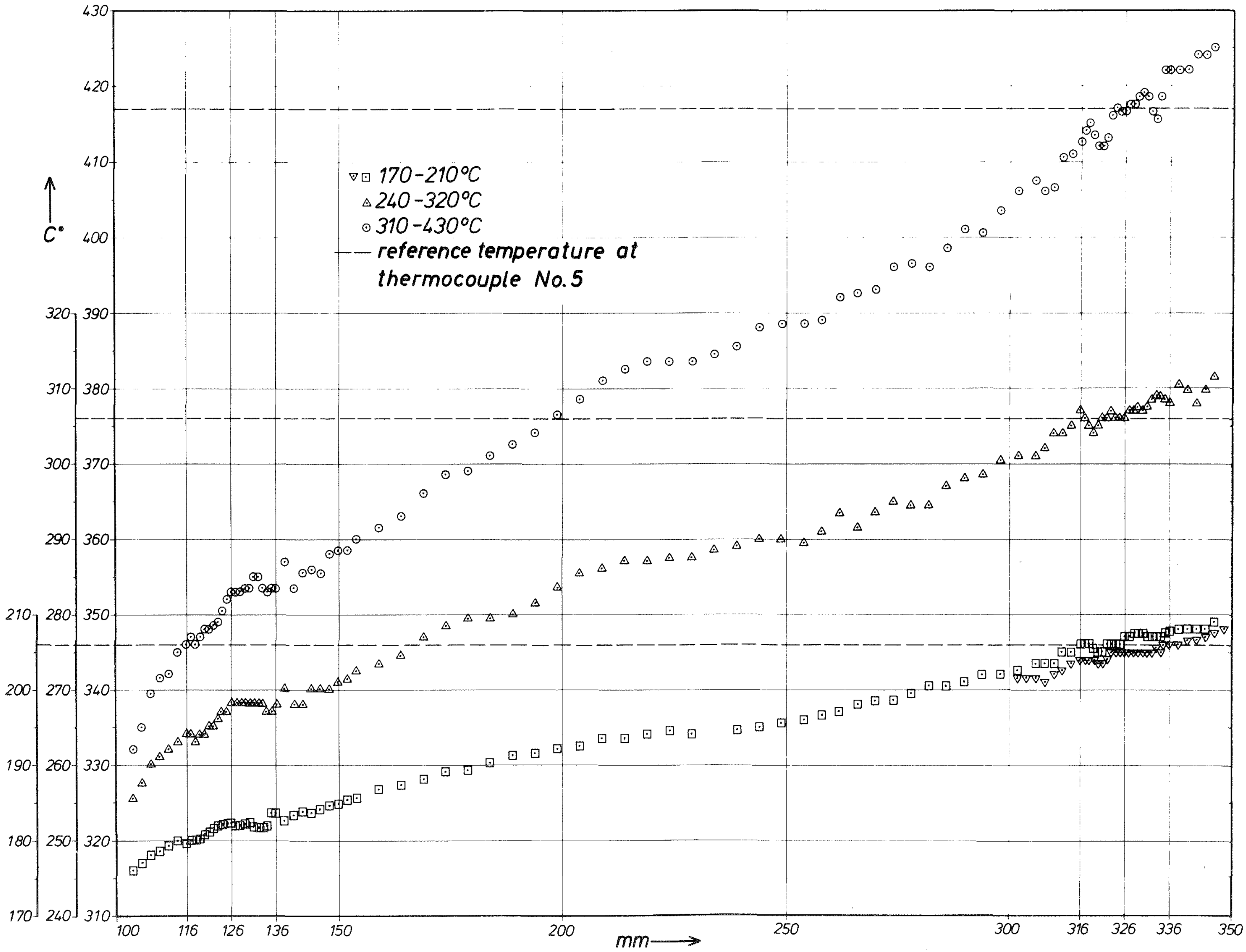

Fig. 6: Pyrometer reading along test rod for experiments with forced convection cooling

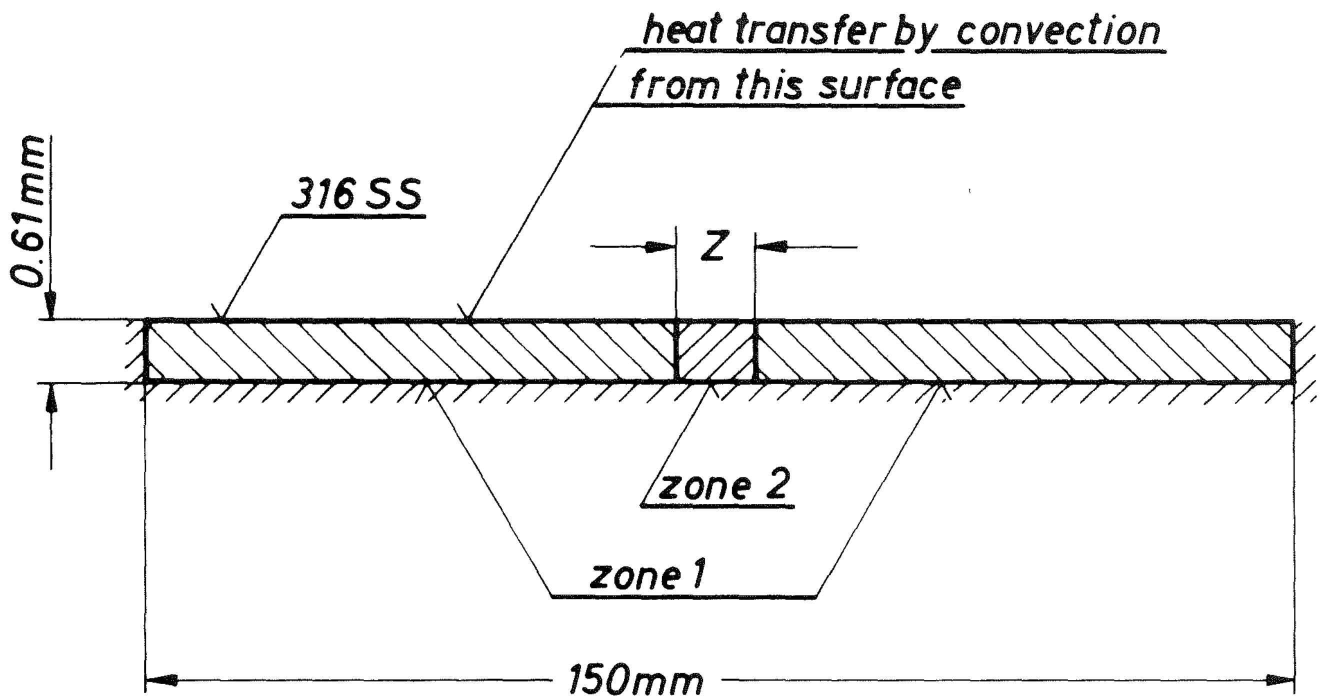

Fig. 7 Analysis Model

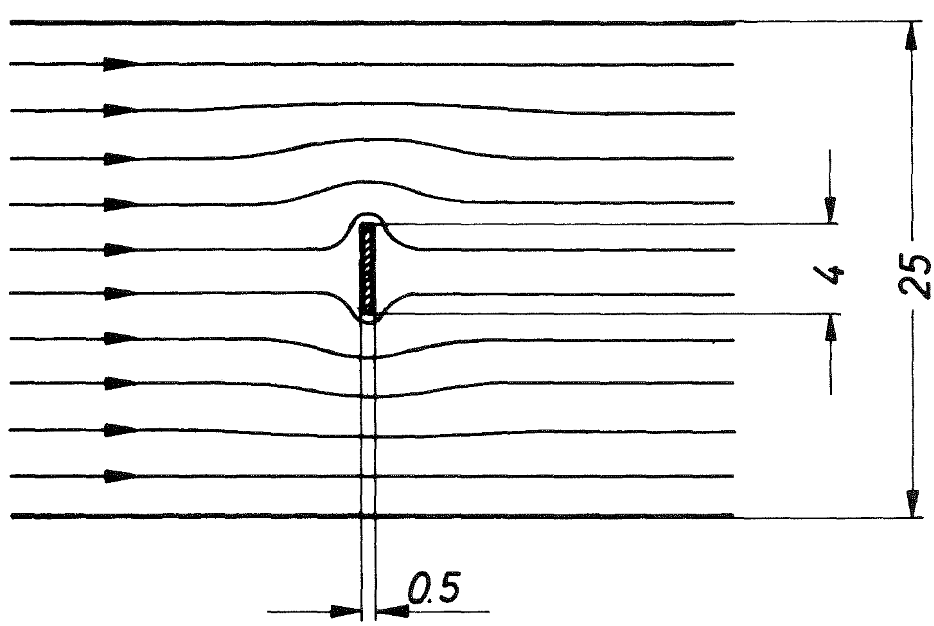

Fig. 8 Flow characteristics of electric current in the vicinity of a thermocouple

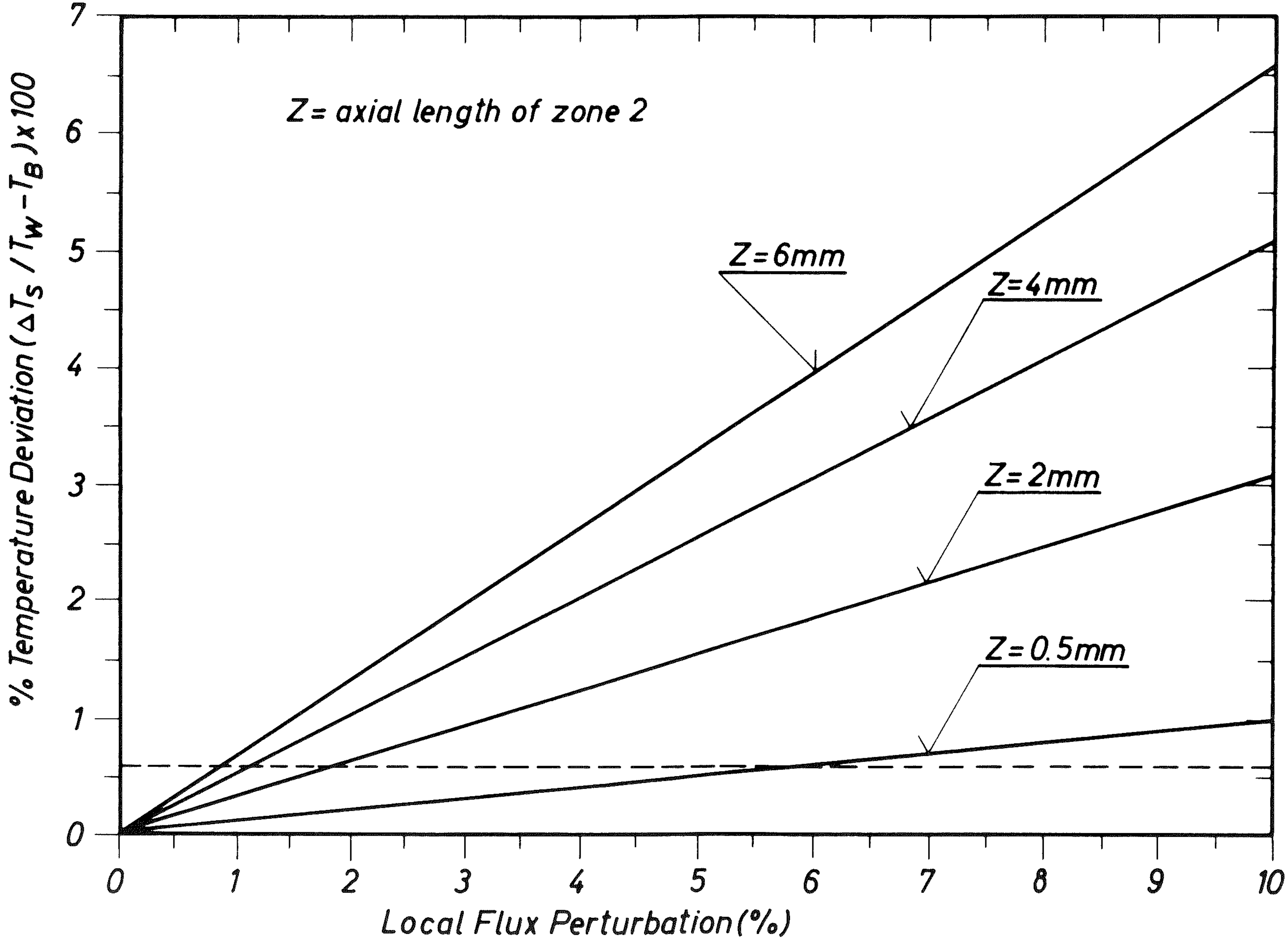

Fig. 9 Local Flux Perturbation VS Resulting Surface Temperature Deviation for BR-2 Rod.