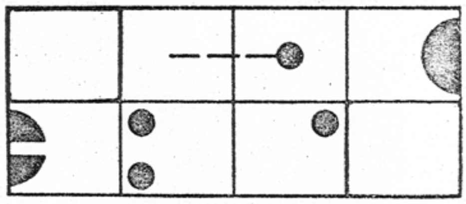

MIXING STUDY IN A HEATED ROD BUNDLE

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ABSTRACT

The aim of this paper is to present research results on thermal mixing between subchannels of a simulated nuclear fuel rod bundle.

Experiments were carried out with single phase freon-12 flowing in-line through a cluster of nine electrically heated steel tubes assembled on a square array. This test section was vertically mounted and the coolant flowed upwards.

System thermodynamic parameters were controlled and recorded. Dry wall and fluid local temperatures, in strategic positions at the top end of the heated length, were particularly measured.

Local fluid temperature charts were obtained with microthermocouples, for different radial power distributions and discrete values of total channel mass flow rate. A constant mean temperature rise along the channel lenght was assured and local boiling was avoided.

Fluid flow and heat transfer conditions for axial turbulent flow were analytically studied. Calculated velocity and temperature fields were used to compute corner, side and central subchannel coolant mass flow rates and enthalpies.

Macroscopic enthalpy balance, based upon the obtained lumped parameters, allowed the calculation of net transversal mixing flows and, consequently, of dimensionless natural mixing coefficients, dependent on flow conditions, then, the proposal of correlations, suitable for application to characteristic corner-side and central-side subchannel interactions, in square rod bundles.

1. INTRODUCTION

Subchannel analysis codes are of great concern in evaluating fluid flow and heat transfer conditions in nuclear reactor fuel bundles. To take into account the coupling of subchannels with different geometries and particular flow and thermal load features, when solving computer programs mass, nomentum and energy macroscopic transport equations, mixing para meters are required for input.

Natural mixing coefficients (S) are defined as the ratio of the net transversal interchannel mass velocity (g) to the main axial stream mass velocity (G), for adjacent sub subchannels connected through a gap (e). Natural mixing phenomenon comprises fictitious turbulent interchange (w') and actual diversion crossflow due pressure gradients (w), both referred to as mass flow rate per channel unit length. In the case of a square bundle model, three different subchannels, from geometrical point of view, can be pointed out: corner (i), side (j) and central (k) ones. Accordingly, natural mixing correlations may be developed to predict corresponding adjacent subchannels ij, jk and kk, the last one for the core of larger bundle interactions.

Up to now, basic studies on natural mixing phenomenon have been performed with single geometries, mostly consisting of two connected subchannels, with no heat generation. Recently, natural coefficients have been obtained from point fluid temperature measurements, in a heated rod bundle mock-up, which better simulates actual fuel clusters [1].

The purpose of this paper is briefly to report selected previous experimental results and analytical procedures concerning the investigation of mixing phenomena and, besides, to propose a set of two natural mixing correlations, which enable considering the interactions between corner-side and central-side subchannel pairs of a square rod bundle.

2. EXPERIMENTAL APPROACH

A thermal loop using freon-12 at an operating pressure of 25 atm as liquid coolant, to be mainly used in the investigation of the water-freon analogy laws, as far as burnout phenomena are considered, was available [2]. Mixing studies have, primarily, been performed with a 3x3 tube bundle test section which simulates the water reactor fuel rod lattices. The tubes were surrounded by a square duct (Figure 1), forming the complex channel flow, with main nominal dimensions:

out diameter	11.10	mm
tube thickness	1.0	mm
gap between tubes (e_{jk})	4.74	mm
gap between tube and shroud (e_{ij})	3.41	mm
heated length	1520	mm

The neutronic fluxes were simulated by Joule effect heating of the tubes, which had nine independent electric circuits.

Static pressures, volumetric flow, mean fluid temperature rise and electric power were measured and heat balance was accomphished in the test section. Local temperatures were measured with thermocouples located at special positions at the top end of the heated length (Figure 1).

At the test section exit level, three dry wall thermocouples per rod were welded to support liquid film temperature calculation and to indicate that local boiling was avoided. Parasitic e.m.f. have been automatically compensated.

Twenty-eight microthermocouples were distributed among nine particular positions, such as subchannel gravity centers, boundaries and other locations in the core of the largest subchannel (Figure 2). Fluid temperature signals were recorded and integrated, during four seconds, to allow for fluctuations due to turbulence.

3. TEST RESULTS

System controlled parameter thresholds were set up in such a way that local boiling was precluded and temperature gradients across the bundle detection were feasible. Operating pressure at the test section outlet was maintained at 25 atm and inlet fluid temperature ranged from 12 to 15ºC. Total mass flow rate were increased from 300 to 3000 g/s, corresponding to Reynolds Numbers from 10^4 to 10^5, respectively. Average heat fluxes varied from 1 to 12 W/cm^2 and total power generation from 5 to 60 kW. Mean temperature rise along the section length was fixed at about 20ºC.

Pre-operational tests assured the limits for single phase experiments (Figure 3) and normal local fluid temperature measurements, upon integration, achieved a reproductibility of 0.1ºC, compared to random turbulent fluctuations of about 2ºC in the test conditions (Figure 4).

Fluid temperatures have been obtained for symmetric configurations, as far as geometry, flow and thermal loads are concerned. Experiments were run with uniform and three steps radial flux distributions with a peak on corner tubes (heating or not the central one) and a peak on the central tube (heating or not the corner ones). The measured values are represented in charts where are shown the nine measuring positions in sub-channels i, j and k (Figure 2), along the dashed line.

A temperature chart family, for one of the aforementioned distributions where corner tubes are heated with fluxes 50% higher than side ones and the central one is unheated, has been selected (Figure 5 to 9). Each point means an average value of 3 to 5 measurements and a hundred of these charts have been obtained.

The observed differences between local measurements from similar positions mainly arise from geometry and thermocouple disposal disturbances, practically impossible to handle.

4. THEORETICAL ANALYSIS

To link lumped subchannel to point measured temperatures in axial turbulent flow across complex cooling channels, as those found in rod bundles, is a rather difficult problem (Figure 10).

Wall shear stress distributions have been determined according to a method proposed by Ibragimov et al [3] which considers secondary flow effects induced by geometry complexities. Besides, Ibragimov et al [4], starting from the determined wall shear stress distributions and a set of classical "universal velocity laws" arrived to a velocity field in a complex channel, experimentally checked latter on.

In the present approach, the same method has been applied to determine wall shear stresses (Figures 11 to 15) and a single "universal velocity law", proposed by Reichardt [5] has been used. Velocity distributions normal to the walls, in elementary cells (Figure 16) have been calculated, to compose a normalized velocity field, constant in the present range of Reynolds Numbers (Figure 17). From this field, average mass flow rates in each subchannel (M_i, M_j, M_k) have been inferred.

To determine fluid temperature fields, Prandtl Turbulent Number concept and momentum turbulent diffusivity correlations proposed by Reichardt [5] have been considered. Energy balance in the elementary cells (Figure 18), where velocity were previously determined, led to temperature distributions normal to the walls, where local measured values were introduced, hence the computation of temperature fields (Figure 19). From these fields average fluid temperatures in each subchannel (T_i, T_j, T_k) have been obtained.

A nonhomogeneous system of three heat balance linear ordinary differential equations, with regard to the subchannel types, has been written, considering lumped mass flow rates and temperatures, thermal loads, geometric characteristics and fluid properties. In this system the natural mixing transversal mass

.flow rate per unit lenght (m), appears twice, corresponding to the interactions ij and jk. Since lumped temperatures have been calculated at the exit of the channel and a common value is given at the inlet, these boundary conditions have been used to resolve the system. The solutions m_{ij} and m_{jk} are used in the calculation of net transversal mass velocities g_{ij} and g_{jk} and, as previously stated, of natural mixing coefficients S_{ij} and S_{jk}.

This system has been solved and explored numerically and analytically [6] in two senses: from lumped temperatures and mass flow rates to natural mixing parameters to provide experiment analyses and, conversely, as the usual practice in reactor analysis procedures.

5. NATURAL MIXING CORRELATIONS

According to previous definitions, a natural mixing coefficient between two adjacent connected subchannels is given by:

$$S = \frac{g}{G}$$

where $$g = \frac{m}{e} \quad \text{and} \quad G = \frac{\sum M}{\sum A}$$

This coefficient can be represented as function of the Reynolds Number, in the form:

$$Re = \frac{4}{\mu} \frac{\sum M}{\sum P}$$

The new symbols represent, obviously, the cross section area (A), the wetted perimeter (P) and the dynamic viscosity (μ).

For each test condition or, otherwise, for each presented temperature chart, two values m_{ij} and m_{jk} have been determined and, then, S_{ij} and S_{jk} and associated Re_{ij} and Re_{jk}, respectively (Figure 20).

The presented results lead to a set of two correlations, for the natural mixing coefficients:

$$S_{ij} = 0.098\ Re_{ij}^{-0.182} \quad \text{(corner-side subchannels)}$$

$$S_{jk} = 0.196\ Re_{jk}^{-0.287} \quad \text{(central-side subchannels)}$$

which are valid for Reynolds Numbers ranging from 10^4 to 10^5 and, naturally, for adjacent connected subchannel couples of the same geometry.

It is to be emphasized that mixing coefficients, in this case of a relatively spaced packed bare rod bundle, are rather dependent upon errors in subchannel temperature gradients (Figure 20). Conversely, to apply the proposed correlations to reactor subchannel analysis lead to unimportant discrepancies in the calculated enthalpy gradients across the channel. A rough comparison with symmetrical square subchannel mixing experiments shows that present coefficient values are about two times higher, what seems to be qualitatively explained by the fact that in that case only turbulent mixing occurs [7].

Last, but not least, one has to strengthen that data upon which the proposed correlations are based refer to an adequate radial power shape factor to provoke temperature gradients according to instrumentation and theoretical model capabilities, without occurence of secondary negative effects. These gradients present a trend to equilibrium for higher Reynolds Numbers and their analysis to arrive to the natural mixing correlations are, relatively, independent from hypotheses concerning mass flow rate distribution among the subchannels [8].

6. CONCLUSIONS

Experiments were run in rather complex conditions simulating and measuring natural mixing between subchannels related phenomena, with a nine tube heated mock-up of a nuclear fuel rod cluster.

A complete sequence of theoretical models, based upon former available experimental and theoretical studies, was suggested, discussed, and applied to experimentally obtained results, to correlate lumped parameters in subchannels to local temperature measurements, in turbulent axial flow. Throughout the solution of this complex problem, assumptions were made and future experimental work should strongly contribute to get more accurate and wider theoretical analysis.

Significant results allowed the statement of a set of two correlations to handle natural mixing interaction phenomena between two characteristic pairs of subchannels, i.e., corner-side subchannels and central-side subchannels, of bare fuel rod bundles disposed on a square lattice.

REFERENCES

[1] P.C. TÓFANI - "Etude du mélange dans un assemblage d'éléments combustibles en grappe de réacteur nucléaire". Thèse de Docteur de l'Université de Grenoble ès Sciences Physiques. Grenoble. 1970.

[2] J.M. COURTAUD - "Boiling crisis in a nine rod bundle". European Two Phase Flow Group Meeting. Milano. 1970.

[3] M.Kh. IBRAGIMOV, I.A. ISUPOV, L.L. KOBZAR, V.I. SUBBOTIN - "Calcul des tensions tangentielles sur les parois d'un canal et répartition des vitesses dans le cas de l'écoulement turbulent d'un liquide". Energie Atomique. Tome 21. Nº 2. 1966.

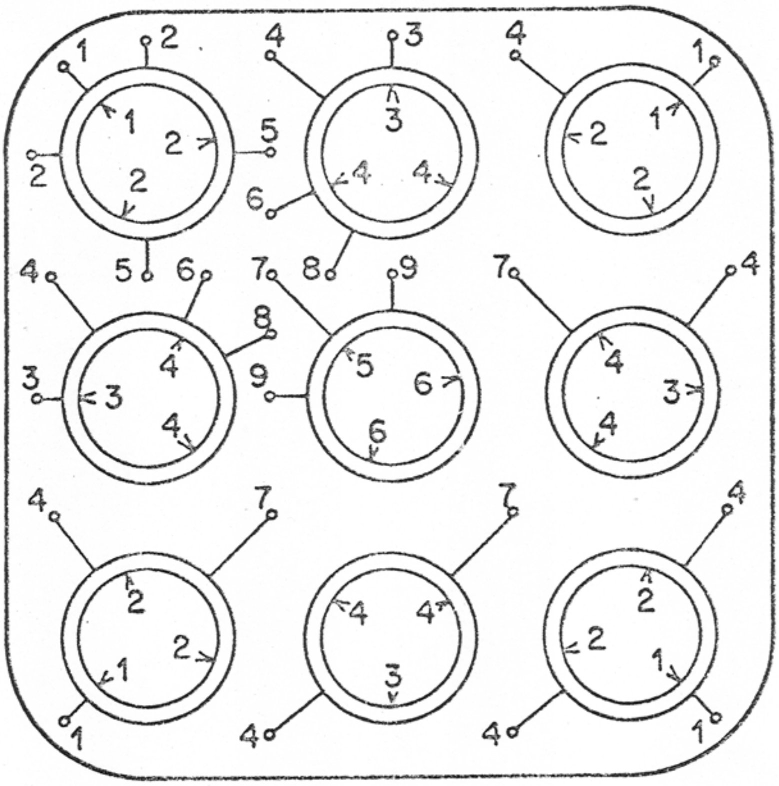
[4] M.Kh. IBRAGIMOV, I.A. ISUPOV, V.I. SUBBOTIN - "Raschet i ehksperimental'noe issledovanie polej skorosti v kanale slozhnoj formy". Zidkie Metally. Atomizdat. 1967.

[5] H. REICHARDT - "Vollständige Darstellung der turbulenten Geschwindigkeitsverteilung in glatten Leitungen". Zeitschrift für Angewandte Mathematik und Mechanik. Bild 31. Nr. 7. 1951.

[6] P.C. TÓFANI - To be published.

[7] P.C. TÓFANI, J.M. COURTAUD - "Mixing in a nine rod bundle". European Two Phase Flow Group Meeting. Milano. 1970.

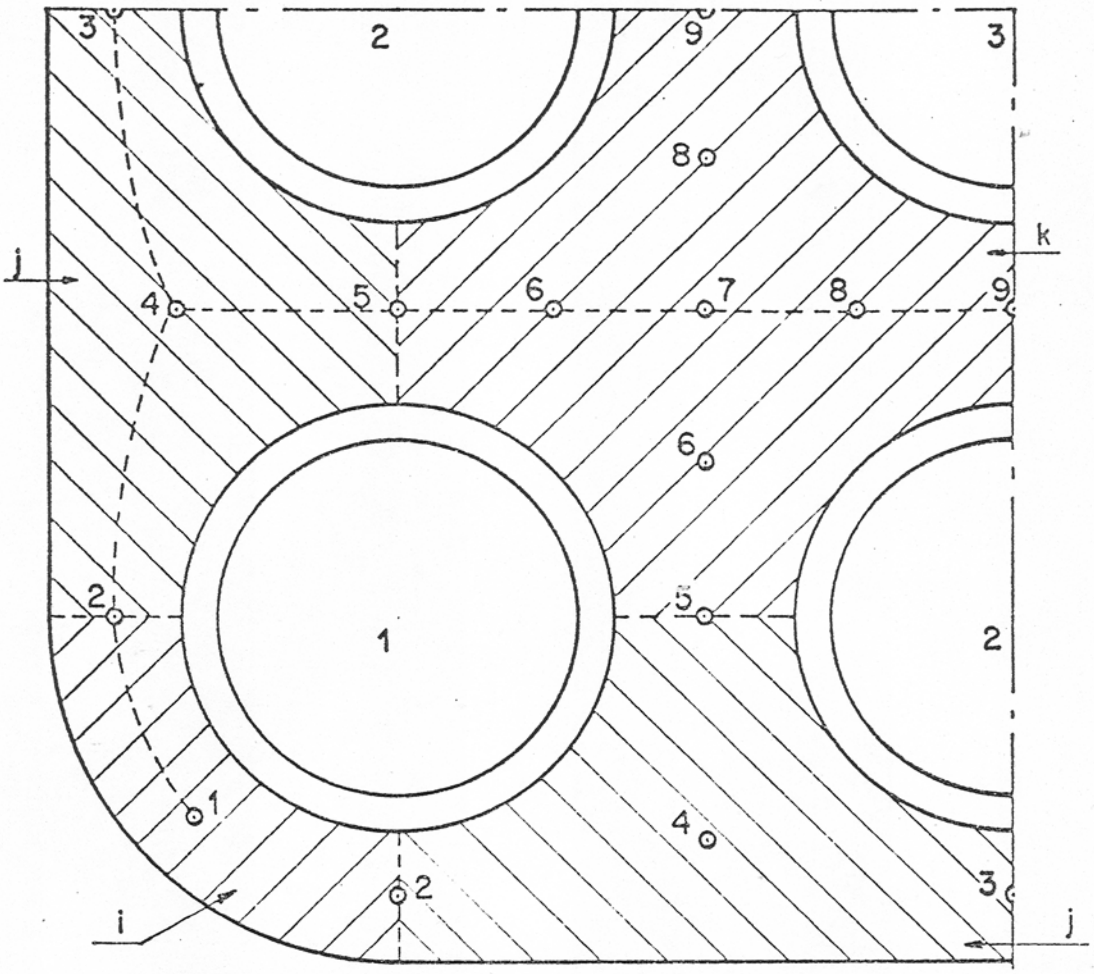
[8] P.C. TÓFANI - "Difusão de calor entre subcanais de elementos combustíveis nucleares em feixe". II Simpósio Brasileiro de Transferência de Calor e Mecânica dos Fluidos. Belo Horizonte. 1971.



o - FLUID THERMOCOUPLES

v - DRY WALL THERMOCOUPLES

FIGURE 1: THERMOCOUPLE DISTRIBUTIONS



KEY FOR TEMPERATURE CHARTS

THERMOCOUPLES

●	1 - 4 - 7
■	2 - 5
▲	3 - 9
▼	6 - 8

FIGURE 2: SUBCHANNEL TYPES AND THERMOCOUPLES DISTRIBUTION

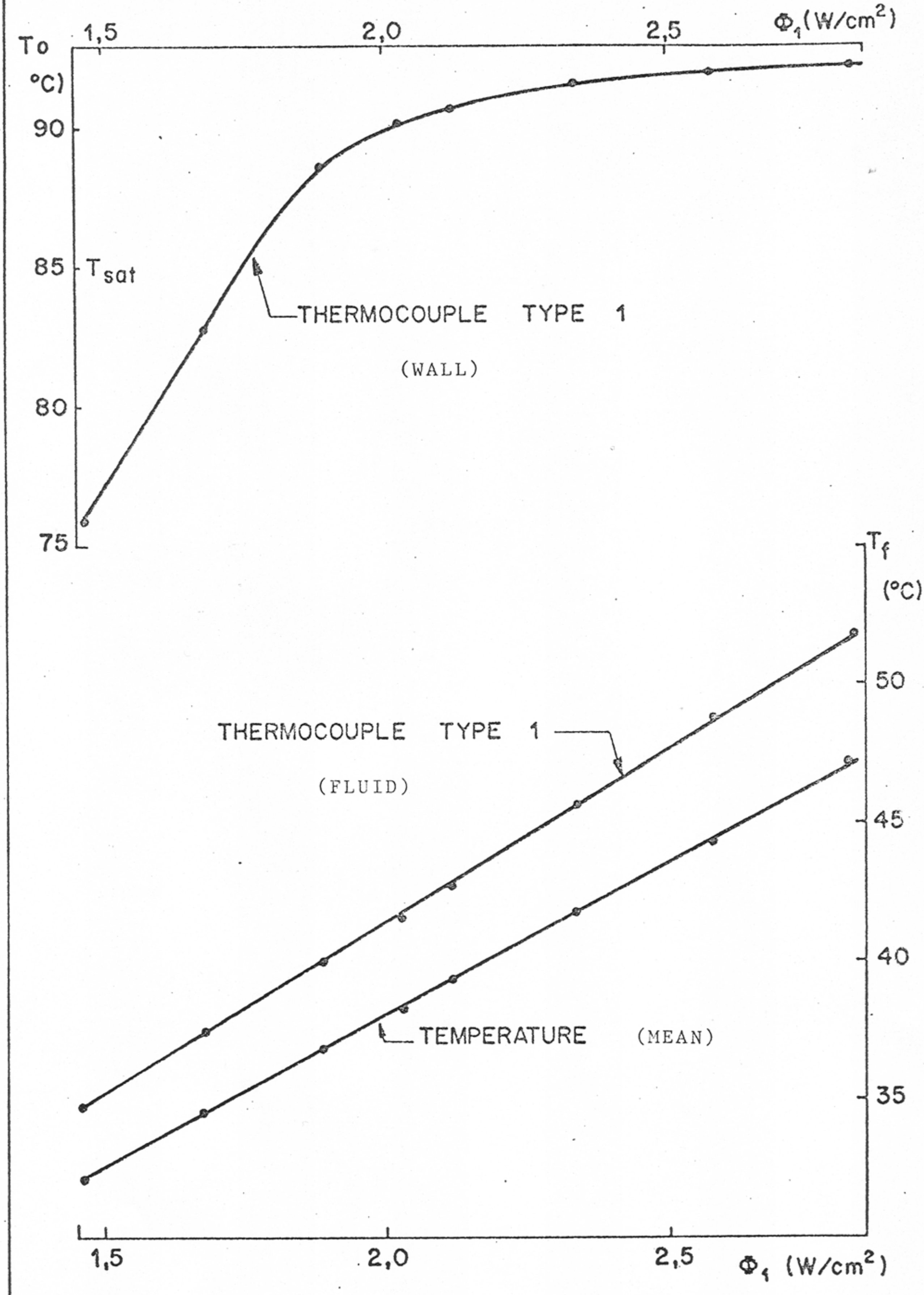


FIGURE 3: FLUID AND WALL TEMPERATURES

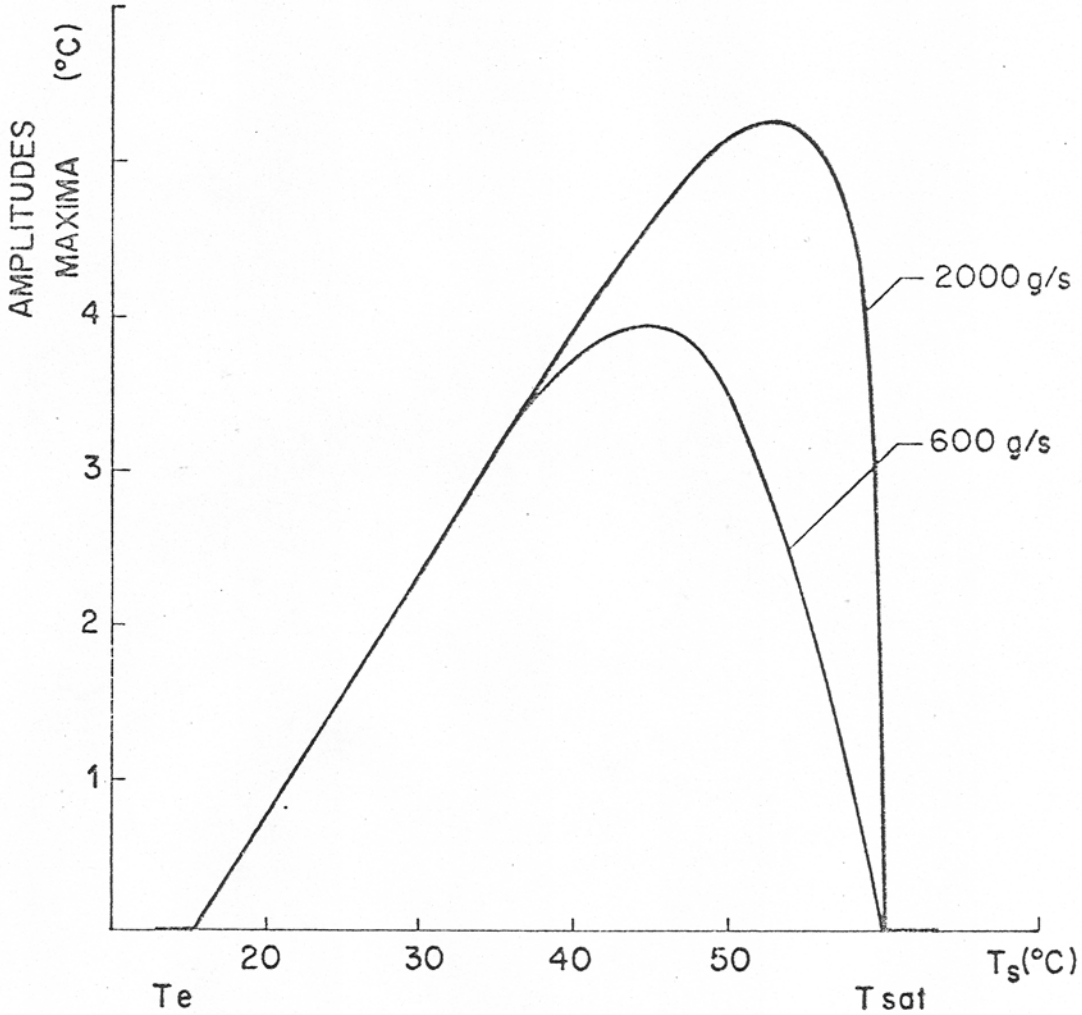


FIGURE 4: AMPLITUDE SPECTRUM FOR FLUID TEMPERATURE FLUCTUATIONS

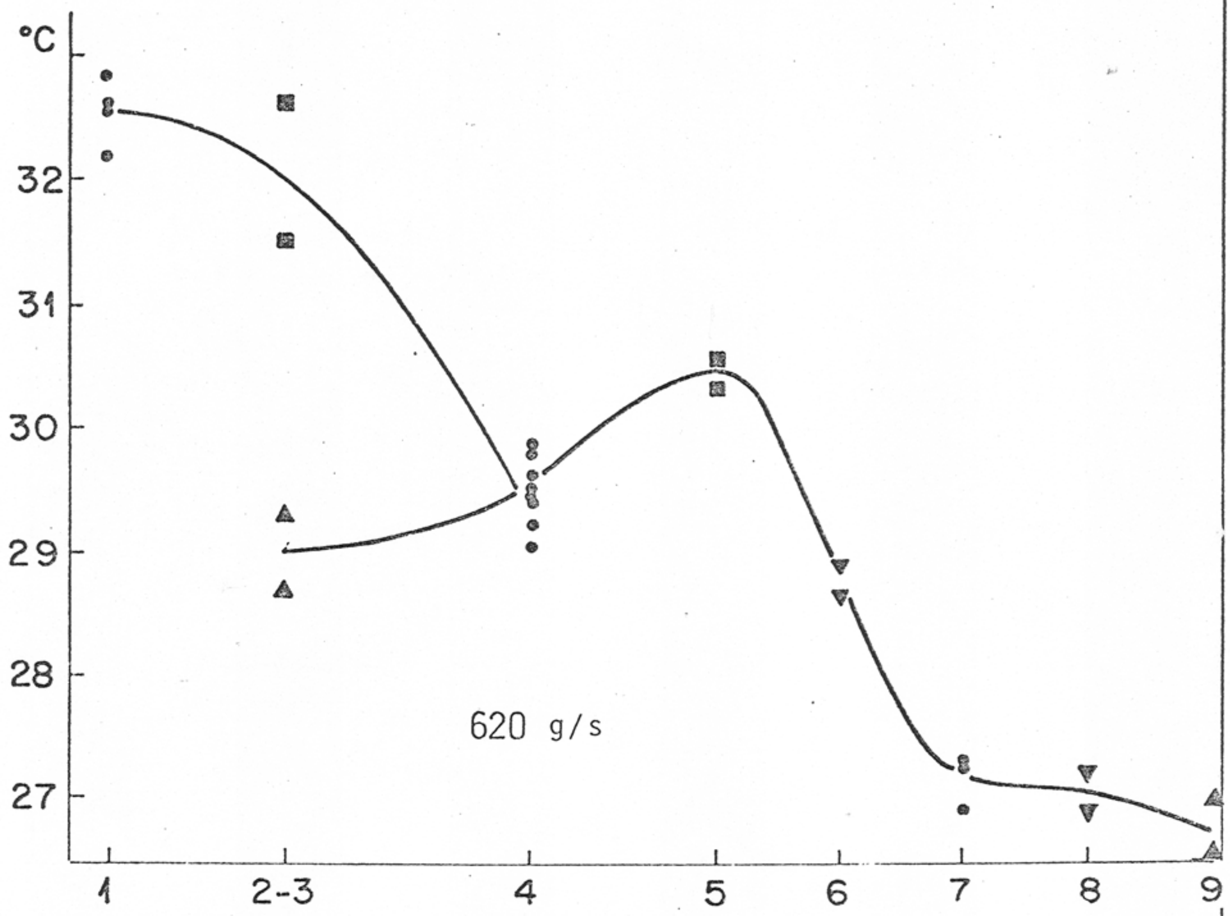


FIGURE 5: FLUID TEMPERATURE CHART

(KEY ON FIGURE 2)

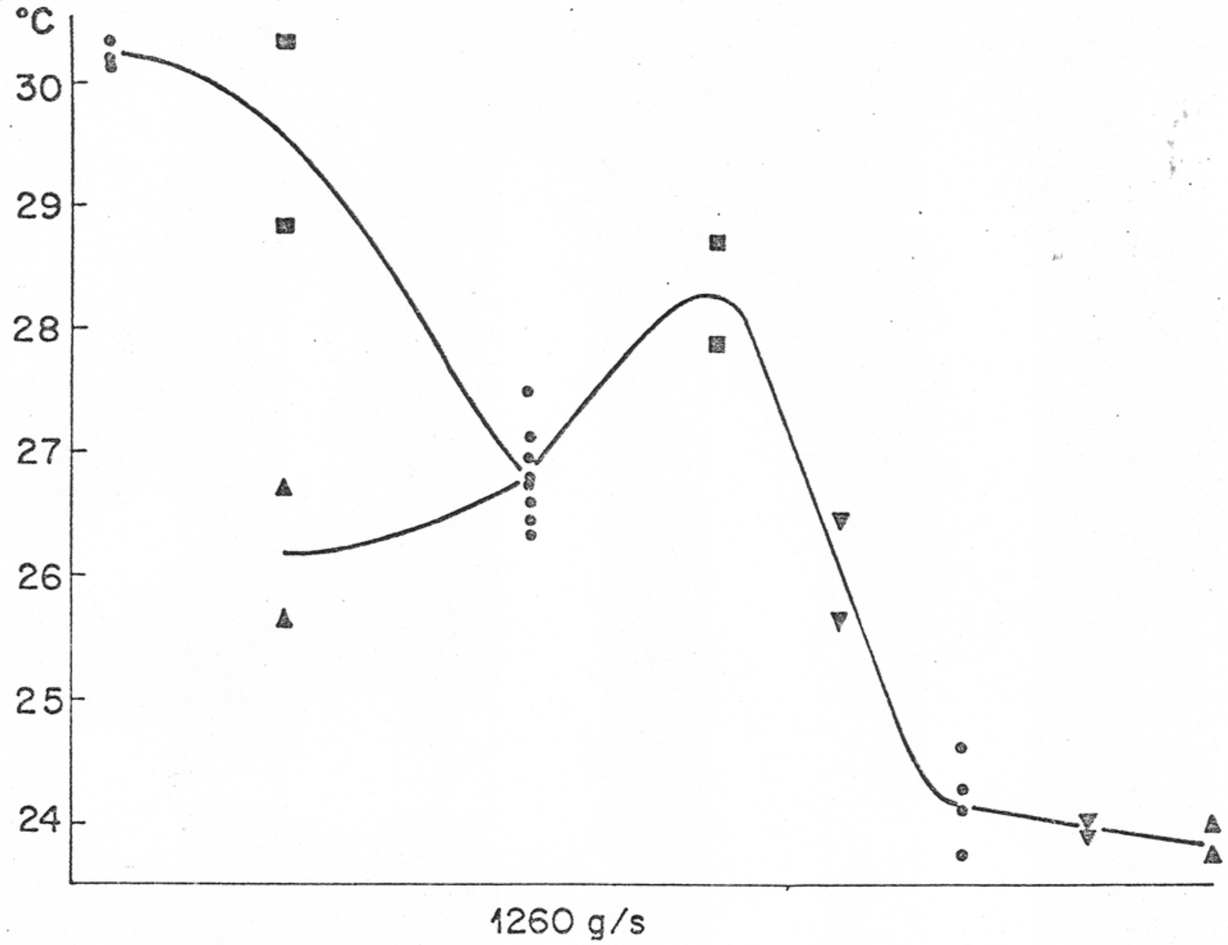


FIGURE 7: FLUID TEMPERATURE CHART

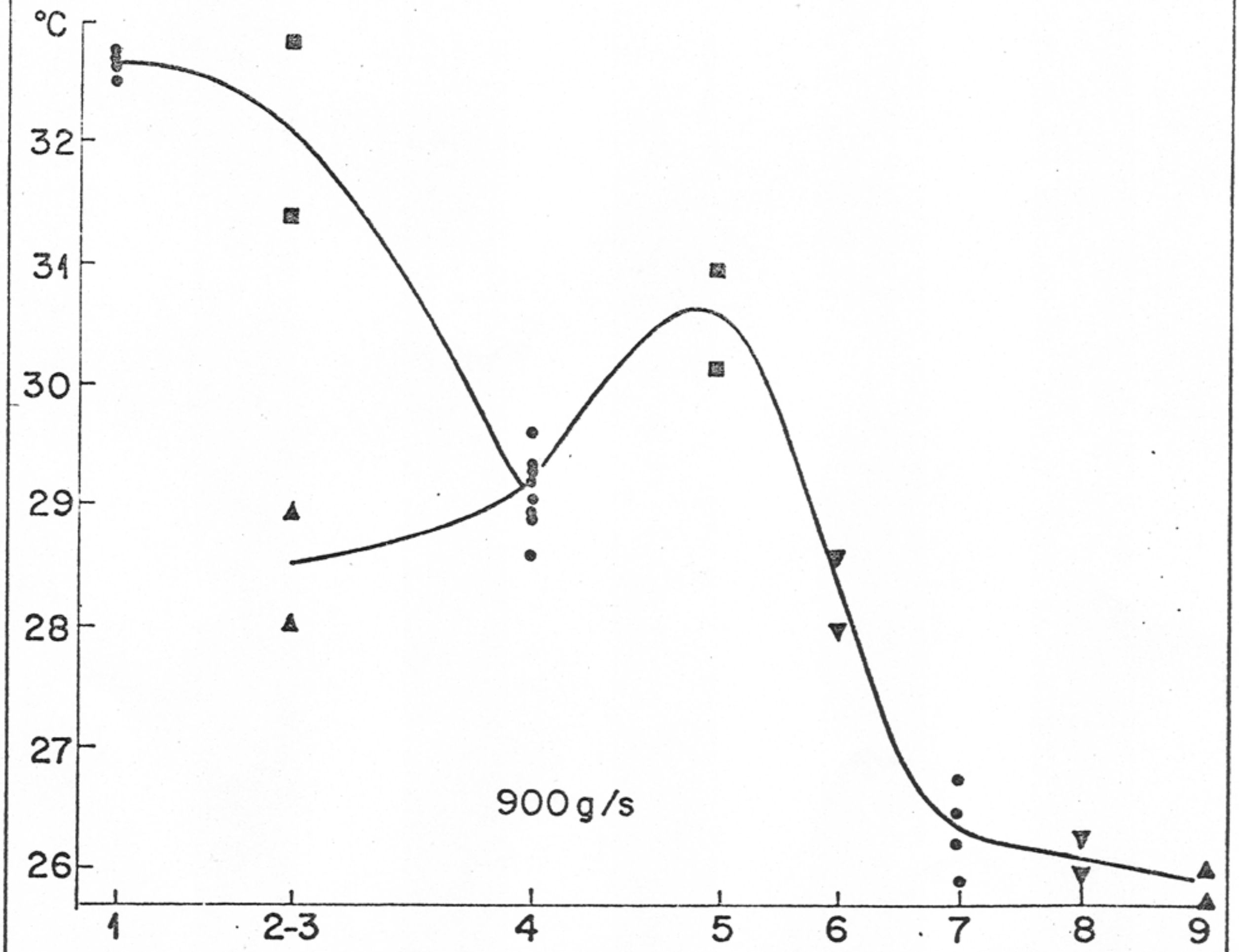


FIGURE 6: FLUID TEMPERATURE CHART

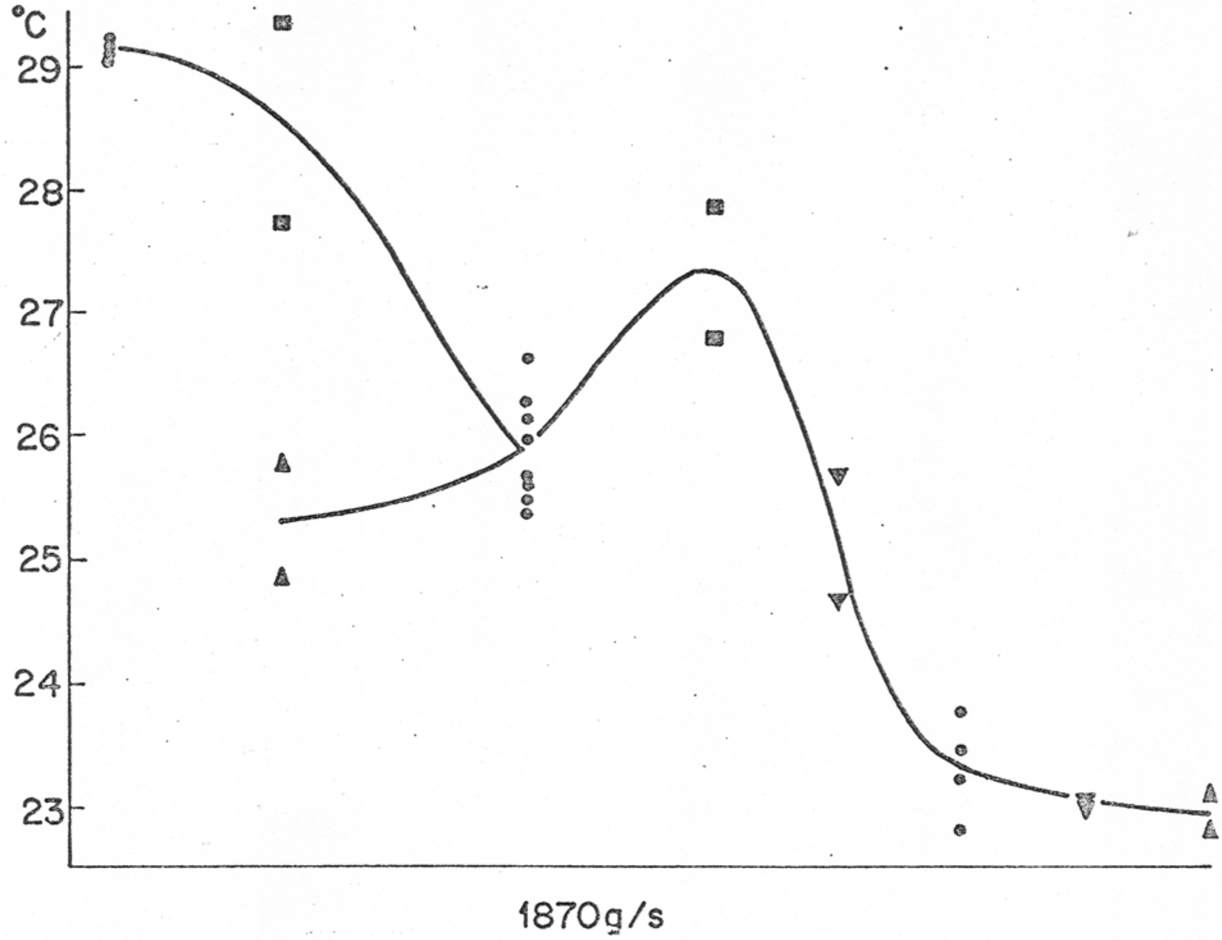


FIGURE 9: FLUID TEMPERATURE CHART

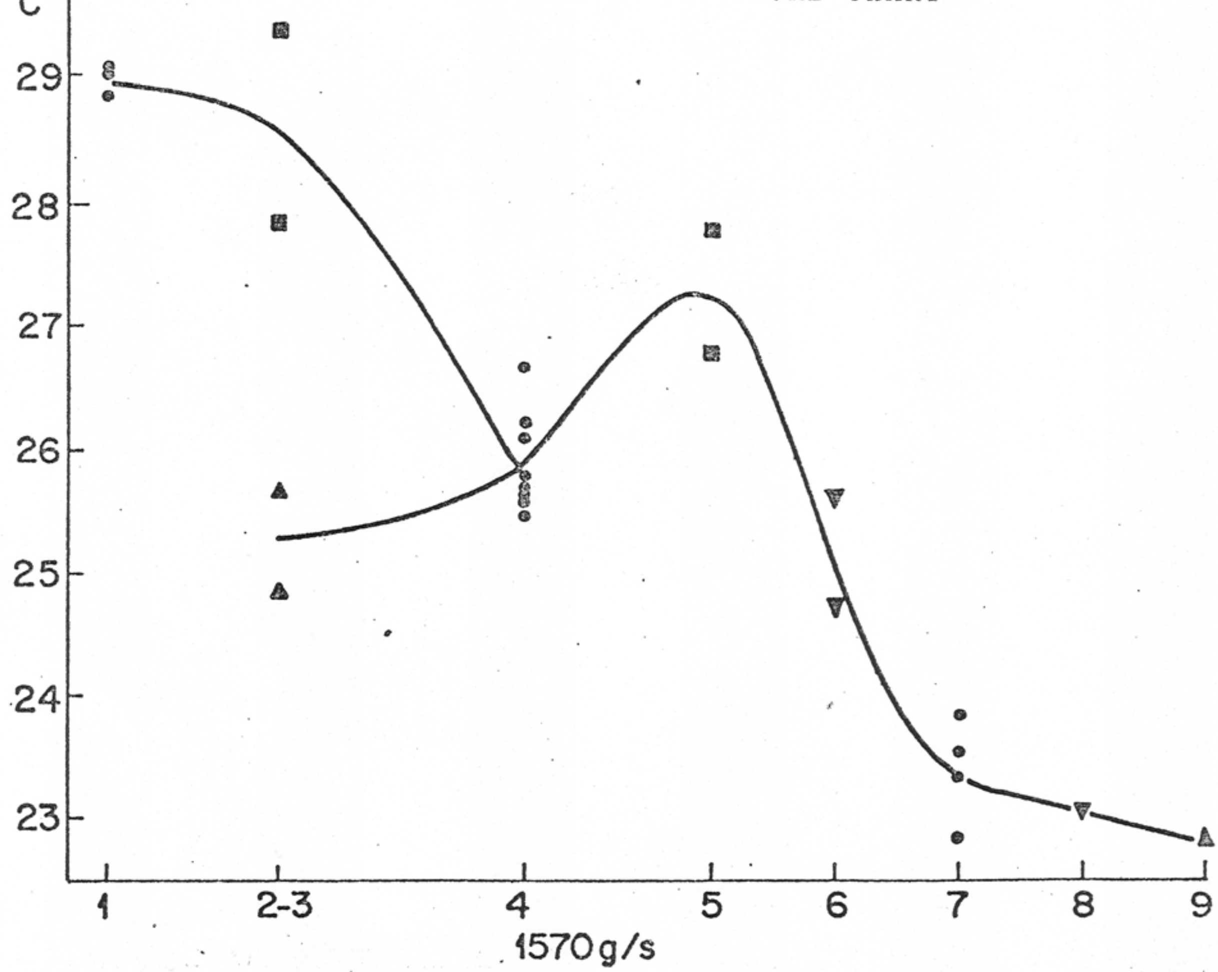


FIGURE 8: FLUID TEMPERATURE CHART

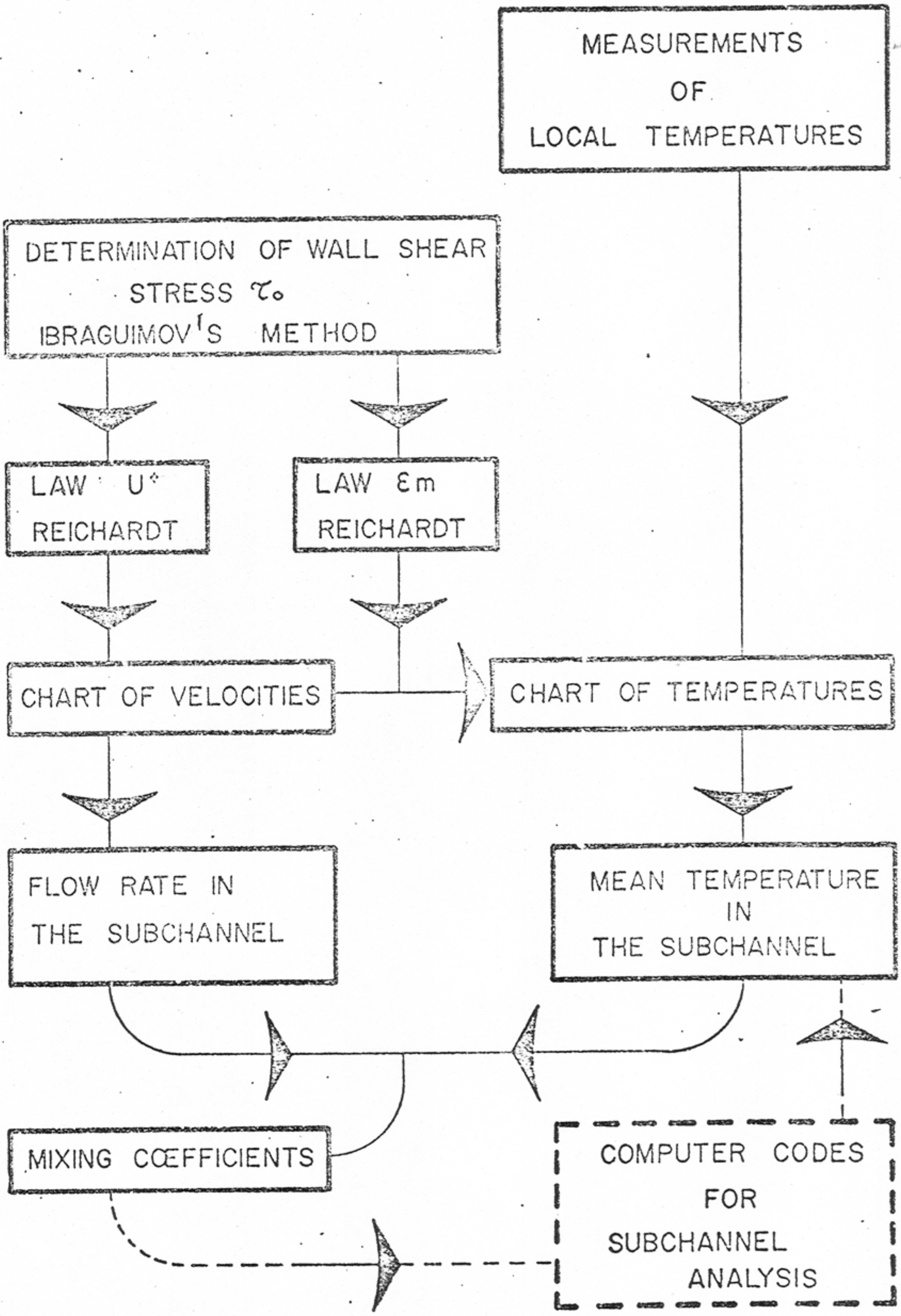


FIGURE 10: SCHEME FOR THEORETICAL ANALYSIS

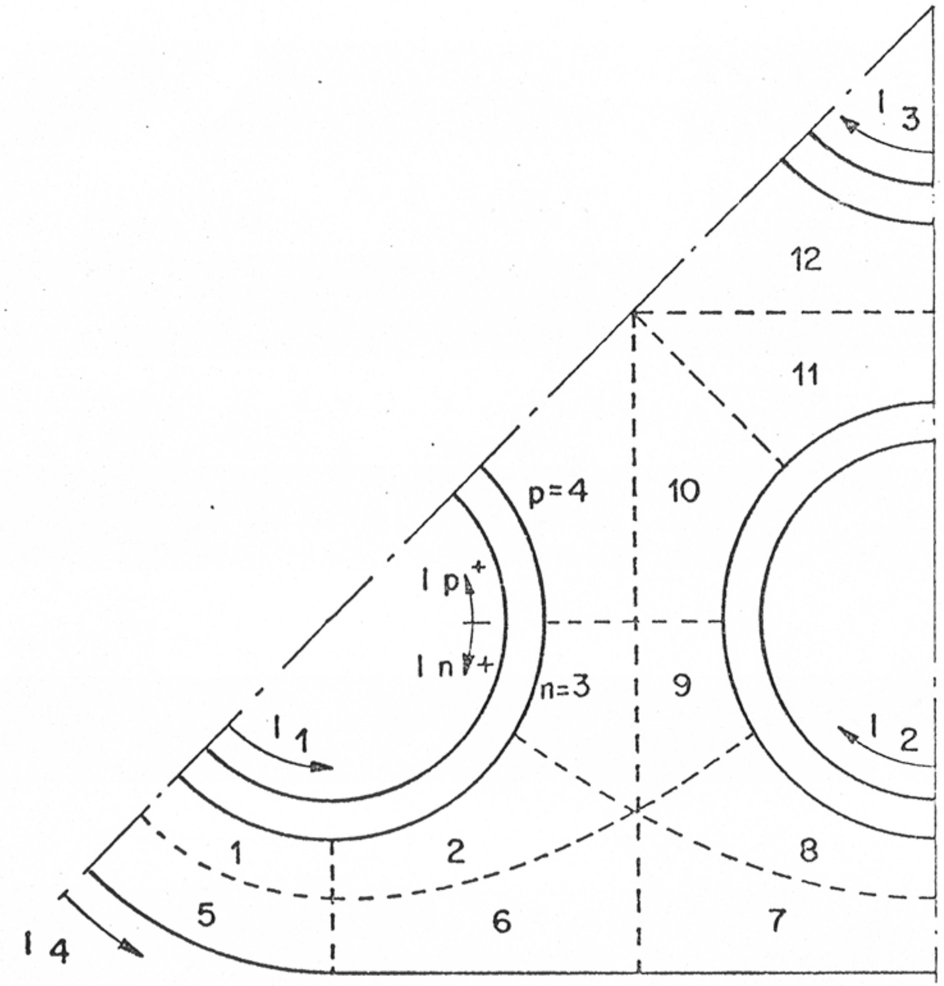


FIGURE 11: CELLS FOR SHEAR STRESS CALCULATION (τ_o)

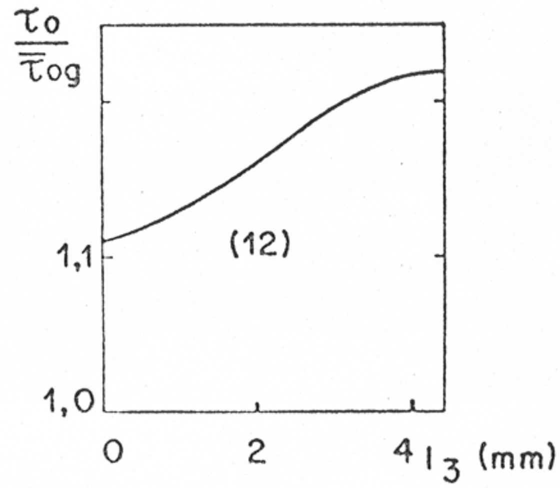


FIGURE 12: CENTRAL TUBE

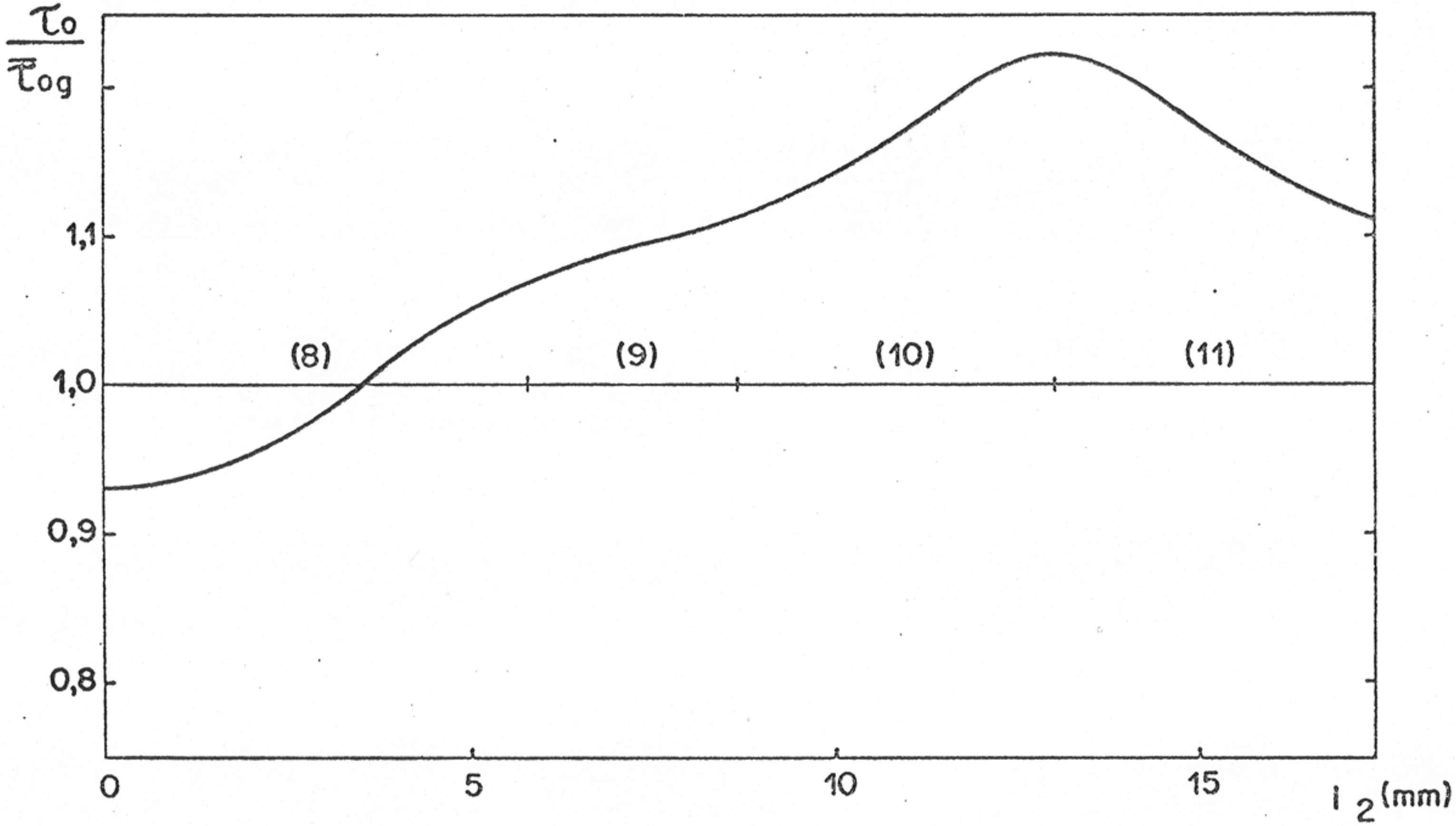


FIGURE 13: SIDE TUBE

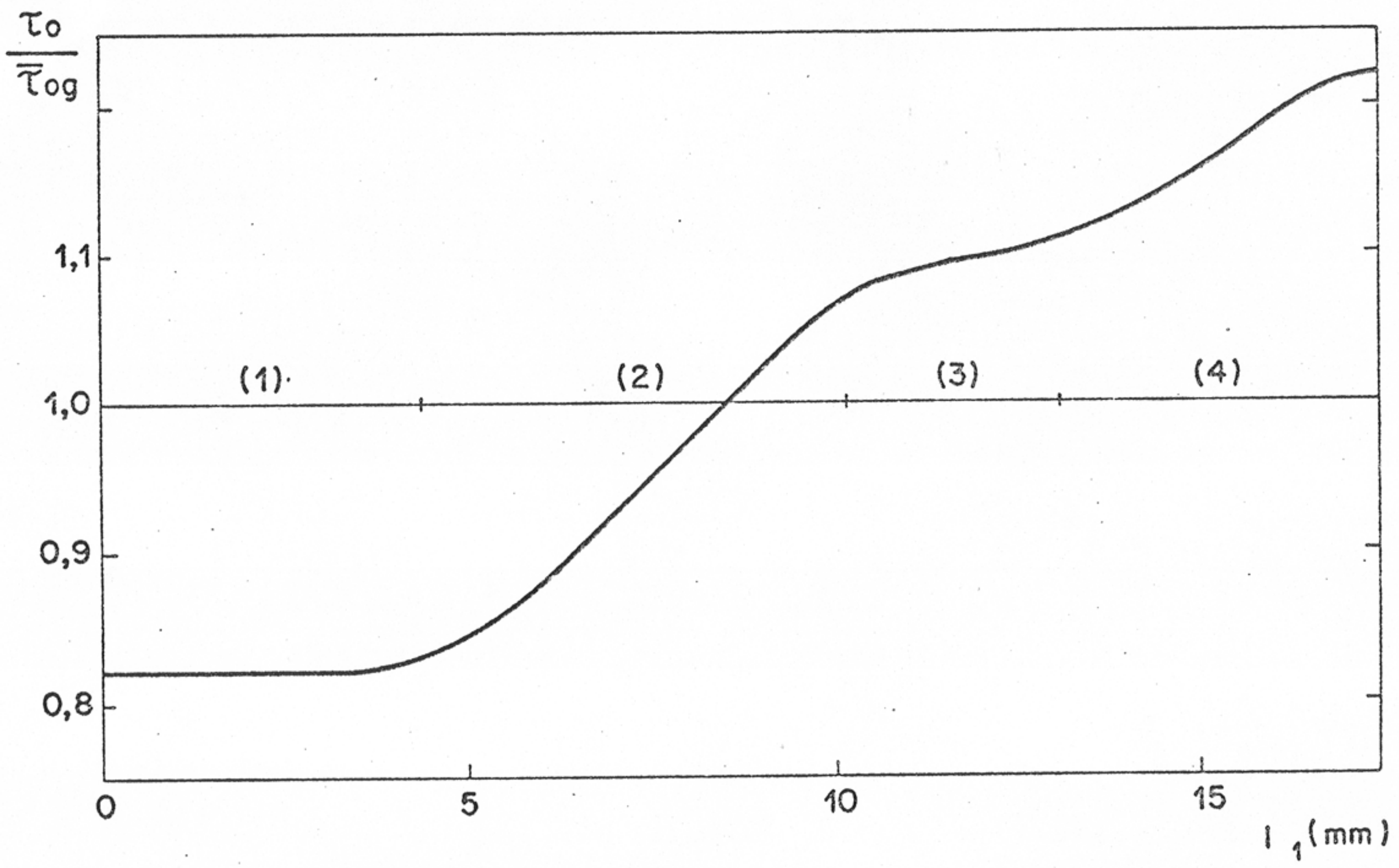


FIGURE 14: CORNER TUBE

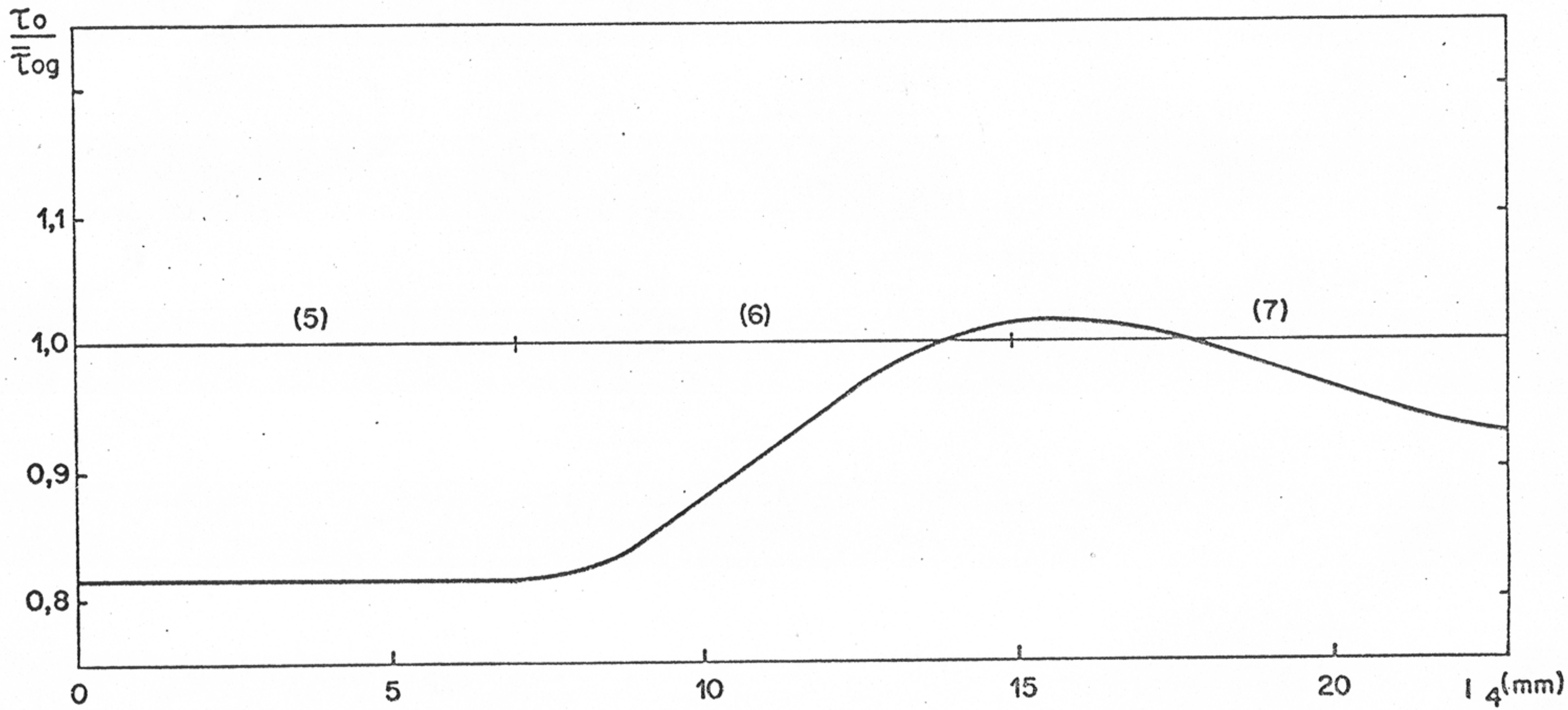
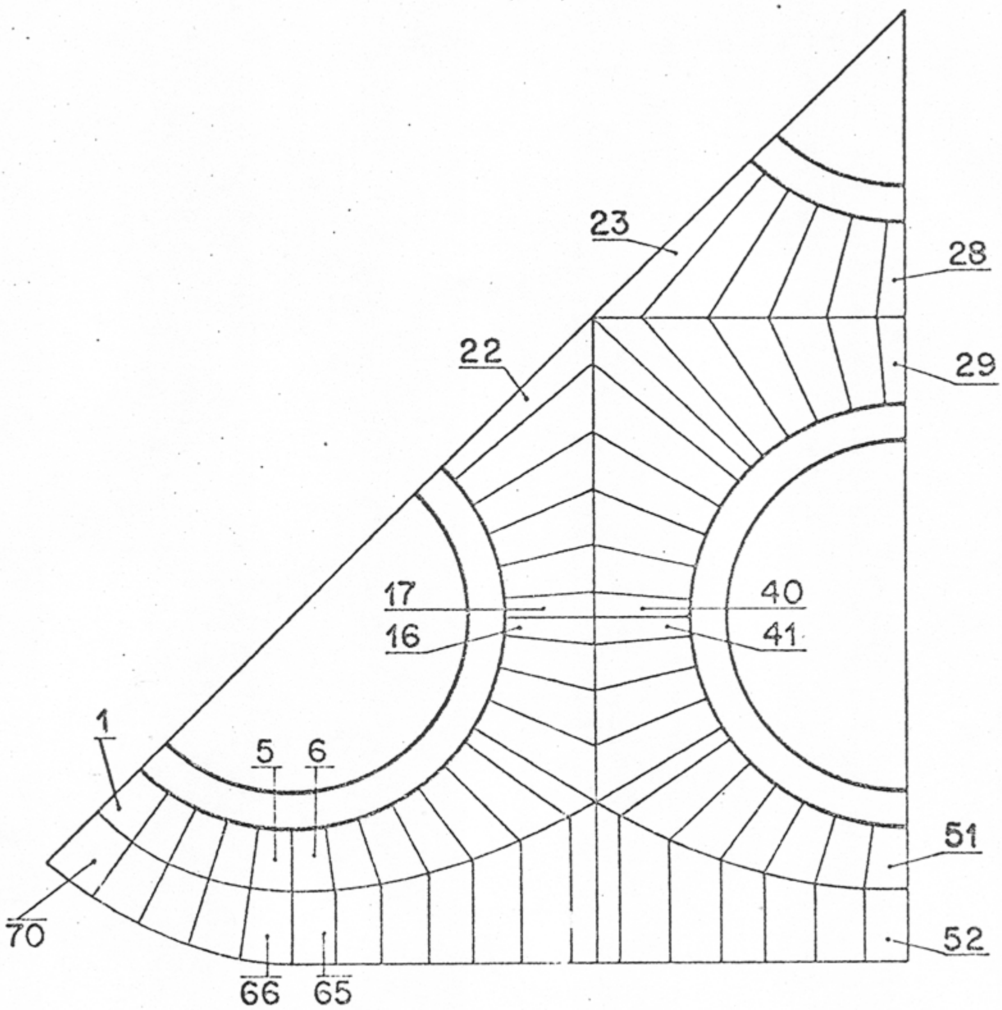


FIGURE 15: SHROUD



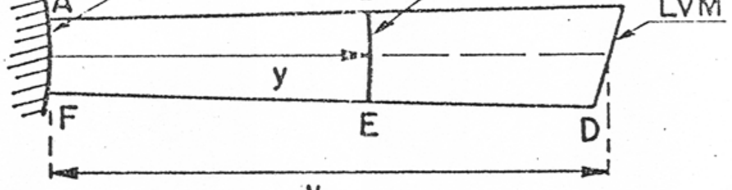


FIGURE 16: CELLS FOR VELOCITY AND TEMPERATURE CALCULATIONS

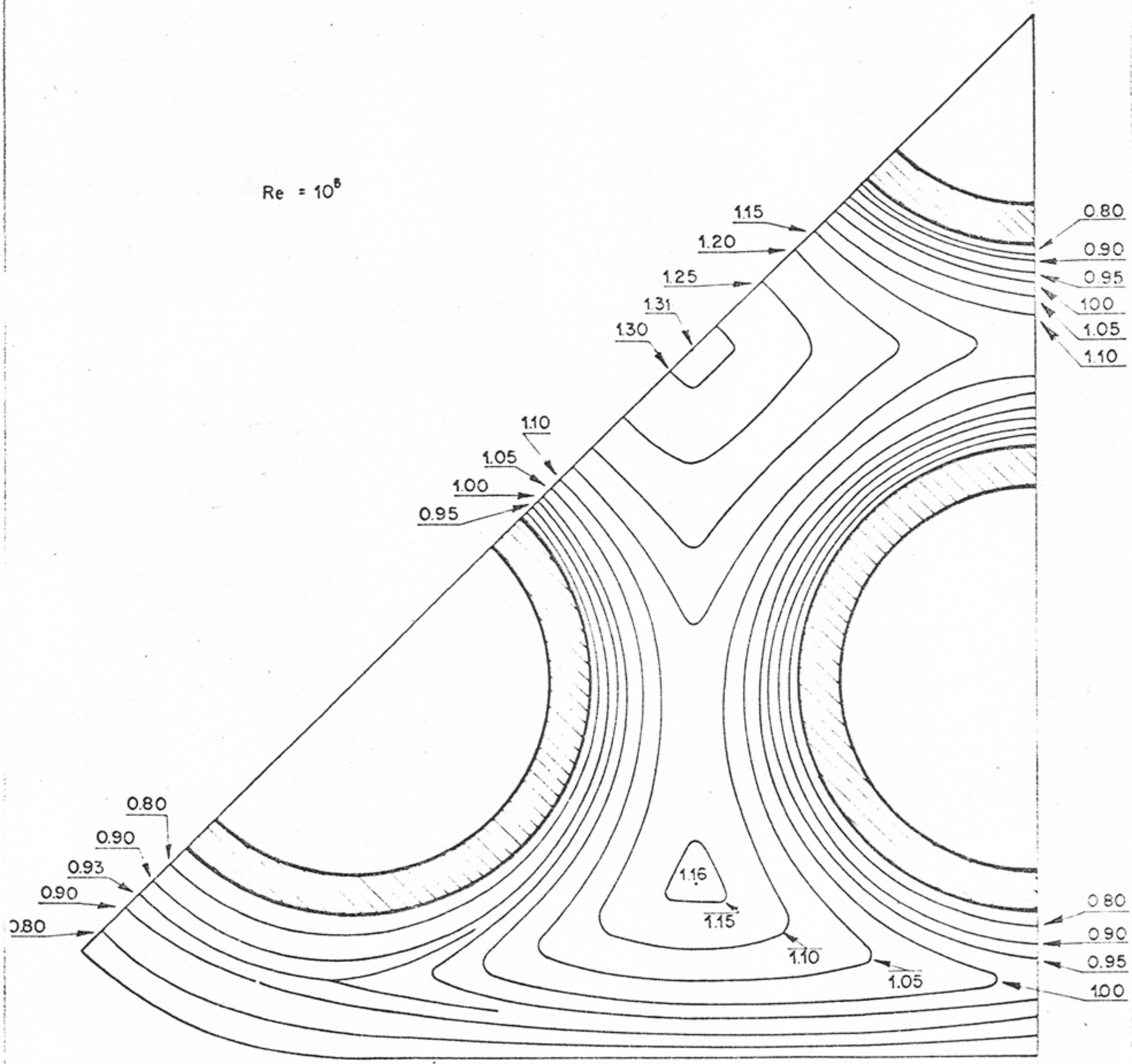


FIGURE 17: NORMALIZED VELOCITY FIELD

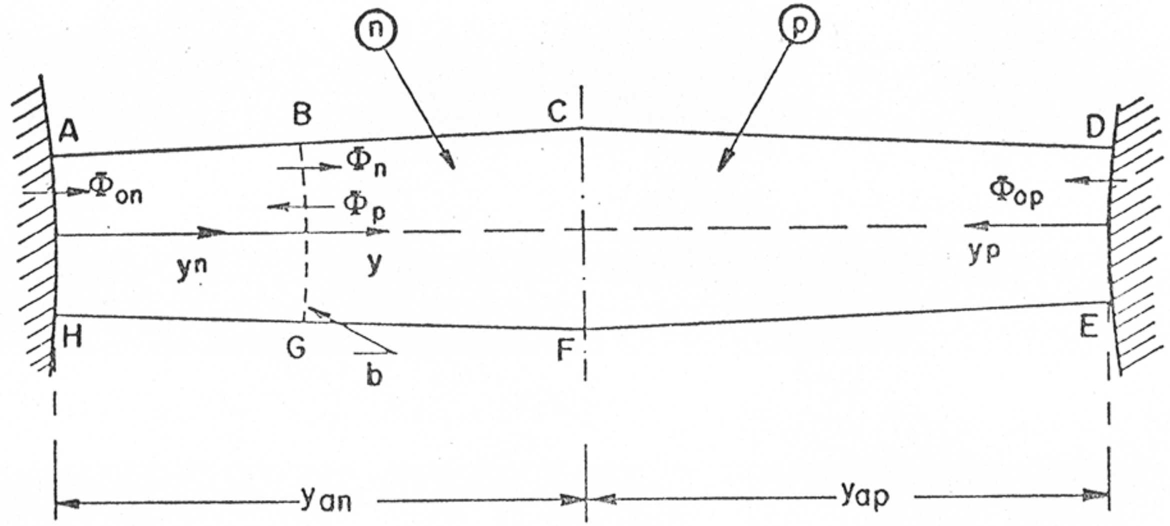


FIGURE 18: DOUBLE CELL FOR TEMPERATURE DISTRIBUTION CALCULATION

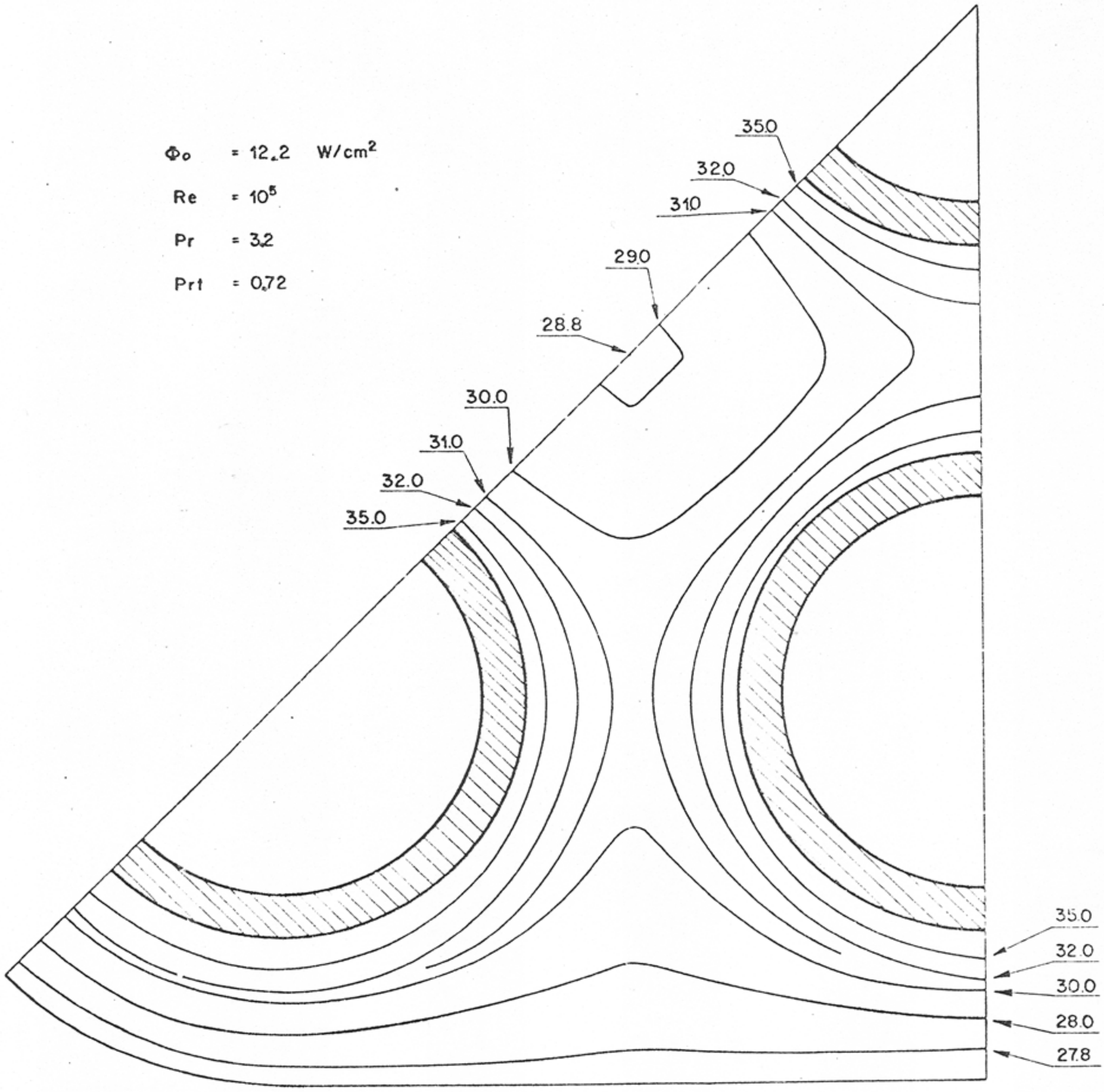


FIGURE 19: TEMPERATURE FIELD (ºC)

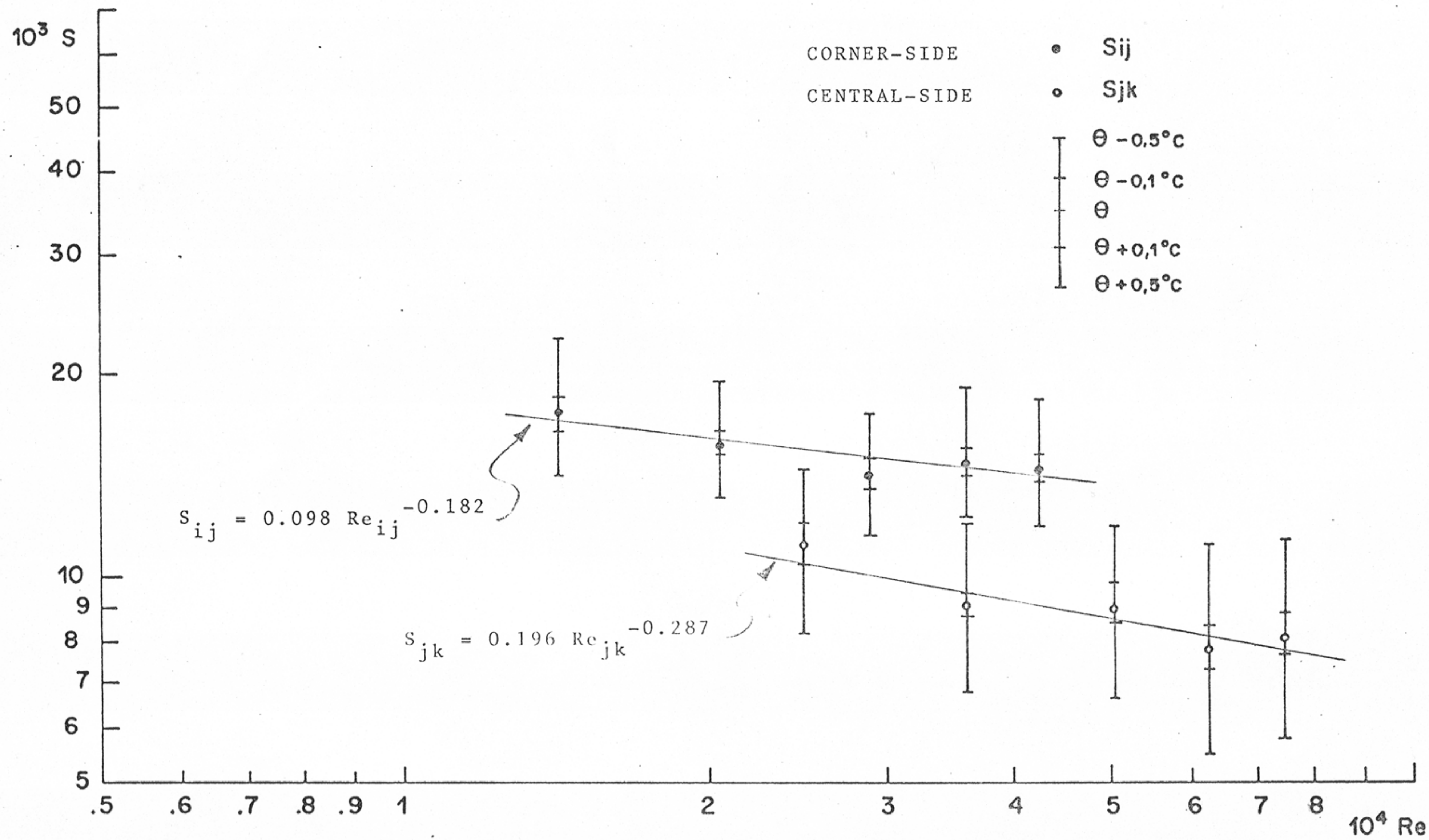


FIGURE 20: NATURAL MIXING COEFFICIENT CORRELATIONS