A METHOD FOR THE DETERMINATION OF THE THERMAL CONDUCTIVITY OF THE HEAVY OIL SANDS OF TRINIDAD

L.N.S. Kunar
Department of Chemical Engineering
The University of the West Indies
and
F.I. Campayne
Department of Physics
The University of the West Indies
St. Augustine, Republic of Trinidad and Tobago.

Summary

A method for the determination of the thermal conductivity of the heavy oil sands of Trinidad is discussed. The conventional Lees' disc apparatus for the determination of the thermal conductivities of poor conductors has been modified to accommodate unconsolidated and partially to totally saturated samples. Application of the method to heavy oil sands from the Penal areas resulted in a value of 0.507 W/mK or 0.294 Btu/hr. ft. $^\circ$F for the thermal conductivity, k_d, of dry sand, of 35% porosity, at 70°C. Variation of the thermal conductivity, k, of the sand with oil saturation, S_o, and water saturation, S_w, has also been investigated. The results can be expressed by equations, $\log k = (\log k_d + 0.973 S_o)$ for $S_w = 0\%$ and $\log k = (\log k_d + 0.341 S_o + 0.479)$ for $S_w = 19.5\%$. With the assumption of water wet sands, the ratio of the thermal conductivities of an oil saturated sand to that of an oil saturated sand with 19.5% water is approximately 1.7. An extension of the method for measurements at high steam temperatures is also suggested.

INTRODUCTION

In southern Trinidad there are several heavy oil bearing reservoir sands, $12^\circ - 18^\circ$ API, which are being produced or will be produced by the steam injection method. These sands lie at depths of 300m to 800m, where the temperatures range from about 40°C to 60°C or 104°F to 140°F.

The overall thermal efficiency of steam injection is to a large extent influenced by the thermal conductivities of the reservoir sand matrix with its fluid filled pore spaces and the strata rocks constituting the overburden and under-burden. There is therefore a need to measure the thermal conductivities of these. This is particularly so in the case of Trinidad where the sands are fine-grained and loosely consolidated in nature and where there is a paucity of data for project evaluation.

LITERATURE SURVEY

In 1906 Carslaw contributed significantly to the development of the mathematical theory of heat conduction. (Carslaw 1921, Carslaw and Jaeger 1959). Since then, many laboratory methods have been used to measure the thermal conductivity of rocks. Basically these can be classified as either steady state (e.g. Somerton 1958; Zierfuss and van der Vliet 1956) or unsteady state (e.g. Somerton and Boozer 1960; Parker and Jenkins 1961) methods.

The early work on thermal conductivity of rocks and its dependence on temperature and composition was conducted by Birch and Clark (1940). Subsequent to this study, many investigators (Francl and Kingery 1954; Asaad 1955; Von Herzen and Maxwell 1959; Khan and Fatt 1965; Beck 1965; Luikov 1966; Akhmedova 1966; Tikhomirov 1968; Luikov et al 1968; Huang 1971; Somerton et al 1974) have reported on the thermal conductivity of consolidated and unconsolidated rocks. Some experimental techniques, such as the needle-probe and divided-bar methods, are described in Beck (1957), Mongelli (1969) and Sass et al (1971). A CO_2 laser operating in a pulsed mode and used as a heat source is described by Strack et al (1982) for rapid variable state measurements.

METHOD

The method used in this work is based on the steady state technique. To determine the thermal conductivity, the steady-state heat flow characteristics of the unconsolidated sand samples from the Penal area were compared to those or a glass standard.

Since the samples were of relatively low conductivities when compared to conductors, such as brass, the standard laboratory form of the Lees' Disc apparatus seemed an appropriate measuring device. In order to accommodate un-consolidated and partially to totally saturated samples, the conventional Lees' Disc apparatus was modified. The total modification included the use of a glass disc making all measurements comparative. Figure 1 shows the final configuration of the adapted Lees' Disc apparatus.

A cylindrical slab of brass C_3 is suspended by strings from a heavy stand. On this rests (i) a hollow brass cylinder C_1 with a thick base and through which steam from a steam heater is passed; (ii) a glass disc; (iii) a solid brass disc C_2; (iv) cylindrical sample holder, P, and the samples. The outer surfaces exposed to the surroundings, the glass, sample holder, and brass discs were all coated with lacquer to give them the same emissive power. The sample holder, P, was glued to the bottom disc, C_3, to provide a seal for the fluids contained in Sample, S.

Thermometers were placed in holes in C_1, C_2, and C_3 and when steady state conditions prevailed, the temperatures T_1', T_2', and T_3' were taken.

All parts in juxtaposition were smeared with glycerine to ensure good thermal contacts.

The calculation of the thermal conductivity of the sample necessitated a calibration of the apparatus.

CALIBRATION PROCEDURE

The calibration consisted of two stages:—

(i) a measurement of the thermal conductivity of the glass, K_G,

and (ii) a measurement of the thermal conductivity of the material of the sample holder, K_p.

(i) K_G:

The sample holder and C_3 were disconnected from the system leaving the glass, G, sandwiched by C_1, and C_2. Steam was passed through the system until the temperatures T_1', and T_2' were steady. Cylinder C_2 was now removed and a bunsen flame used to raise its temperature by about $10^\circ C$ above the steady state temperature T_2' previously recorded. It was then allowed to cool and its temperature was taken at definite time intervals until the temperature fell to about $10^\circ C$ below T_2'. This is the standard Lees' Disc method. Experimental details were similar to those recommended in Tyler (1969).

From the cooling curve, the rate of fall of temperature with time at T_2', $(\frac{dT}{dt})_{T_2'}$ was evaluated and K_G computed from the heat balance equation:

$$K_G \cdot \pi r^2 \cdot \frac{(T_1' - T_2')}{X_G} = Mc(\frac{dT}{dt})_{T_2'}$$

where M and c represent the mass and specific heat of C_2 respectively.

The thermal conductivity of the glass was found to be;

$$K_G = 0.984 \text{ Wm}^{-1} \text{ K}^{-1}$$

(ii) K_p:

The entire apparatus was set up as shown in figure 1 with air taking the place of the sample. Steam was passed

and the final equilibrium temperatures, T_1', T_2' and T_3', as well as the ambient temperature, T_a, were noted. Using K_{air} = 0.026 W m^{-1} K^{-1} (Bayley et al. 1972) and the theory developed in the next section, the thermal conductivity of the sample holder material was found to be:

$$K_p = 2.263 \ W \ m^{-1} \ K^{-1}$$

THEORY OF METHOD:

Let $T_1 = (T_1' - T_a)$; $T_2 = (T_2' - T_a)$; $T_3 = (T_3' - T_a)$ $^{\circ}$C

$\qquad\qquad$ (T_a = ambient temperature)

K = thermal conductivity, W m^{-1} K^{-1}

h = heat loss per m^2 per $^{\circ}$C excess of temperature of the apparatus over that of the surroundings

H = heat received per sec, W

1, 2, 3, G, P, S = subscripts referring to component parts of apparatus and sample. Under equilibrium conditions heat gained equals heat lost.

Using this principle and referring to figure 1 we have:

$$H_3 = \pi r^2 h \left(1 + \frac{2X_3}{r}\right) T_3$$

(H_3 expresses the heat received by disc C_3 in one second)

$$H_S = 2\pi r \ X_S h \left(\frac{T_2 + T_3}{2}\right) + H_3$$

Therefore the heat following through the sample, S, can be taken as:

$$\frac{H_3 + H_S}{2} = \pi r^2 h \left[T_3 + \frac{2}{r}\left\{\left(X_3 + \frac{X_S}{4}\right)T_3 + \frac{X_S}{4} T_2\right\}\right] \qquad (1)$$

But also,

$$\frac{H_3 + H_S}{2} = K_S \pi R^2 \frac{(T_2 - T_3)}{X_S} + K_p \pi (r^2 - R^2) \frac{(T_2 - T_3)}{X_S} \qquad (2)$$

Equating (1) and (2) and re-arranging gives:

$$K_T \frac{(T_2 - T_3)}{X_S} = h \left[T_3 + \frac{2}{r}\left\{\left(X_3 + \frac{X_S}{4}\right)T_3 + \frac{X_S}{4} T_2\right\}\right] \qquad (3)$$

where:

$$K_T = \frac{R^2}{r^2} \cdot K_S + \left(1 - \frac{R^2}{r^2}\right) K_p \qquad (4)$$

Similarly it can be shown that for the thermal equilibrium of the glass disc that:

$$K_G \frac{(T_1 - T_2)}{X_G} = h \left[T_3 + \frac{2}{r}\left\{\left(X_3 + \frac{X_S}{2}\right) T_3 + \left(\frac{X_S}{2} + X_2 + \frac{X_G}{4}\right) T_2 + \frac{X_G}{4} T_1\right\}\right] \qquad (5)$$

Dividing equation (4) by (5) leads to:

$$\frac{K_T}{K_G} = \left[\frac{T_1 - T_2}{T_2 - T_3}\right] \frac{X_S}{X_G} \cdot \frac{[T_3 + 2/r \{(X_3 + X_S/4) T_3 + X_S/4 T_4\}]}{[T_3 + 2/r \{(X_3 + X_S/2) T_3 + (X_S/2 + X_2 + X_G/4) T_2 + X_G/4 T_1\}]} \qquad (6)$$

All the parameters on the right hand side are experimentally determined quantities and K_G is known. Hence K_T can be calculated after which equation (4) is used to obtain the thermal conductivity of the sample. In this investigation, K_S was determined, after substituting for R, r, and K_p, from:

$$K_S = (K_T - 0.305)/ 0.865 \ W\,m^{-1}K^{-1}$$

For air in place of the sample, K_p was determined from:

$$K_p = \frac{K_T - (R^2/r^2) K_{air}}{(1 - R^2/r^2)} \qquad (7)$$

The value of K_S determined by this method is quoted at a sample temperature

$$(T_1' + T_2')/2\,^oC \ \text{or} \ T_a + (T_1 + T_2)/2 \ ^oC.$$

SAMPLE PREPARATION:

The 14° API oil contained in a heavy oil sand from the Penal area was extracted using gasoline and toluene. The sand was then washed in water and dried at a temperature of 100^oC. Known volumes of the fluids (oil/water) were added to the dry sand and thoroughly mixed with it to provide an even saturation. From preliminary measurement of the bulk density of the sand, the densities of oil and water, and appropriate masses and volumes, the porosity (35%) and the oil/water saturations were determined for each sample. The sample was placed in the PVC holder, P(Fig. 1) after which the apparatus was assembled and the experiment started.

RESULTS:

Using the steady state temperatures (T_1', T_2', T_3') and the theory developed previously, the thermal conductivities $(Wm^{-1}K^{-1})$ of dry and partially to fully saturated sand samples were calculated. The results are shown in Tables 1 and 2. The conductivity of the 35% porosity dry sand, k_d, was found to be 0.507 W/mK or 0.294 Btu/hr. ft. ^oF, a value which is in general agreement with that reported in the literature for unconsolidated sands (Somerton et al 1974; Somerton, 1958). Using the correlations of Tikhomirov (1968), we estimated that:

$$K_d = 1.387 \times 10^{-3} \ \theta + 0.0409 \ W/mK \qquad (8)$$

where θ is in degrees Celsius. Equation (8) indicates a small rise in conductivity with increase in temperature. This seems to be the case for unconsolidated sands (Tikhomirov 1968; Somerton et al. 1974). Regression analyses of the results in Tables 1 and 2 yielded the following equations:

$$\log K = (\log K_d + 0.973 \ S_o) \pm 10\% \qquad (9)$$

for $S_w = 0\%$ and,

$$\log K = (\log K_d + 0.341 \ S_o + 0.479) \pm 5\% \qquad (10)$$

for $S_w = 19.5\%$. K is measured in W/mK.

It is clearly seen from these tables and extrapolated values using equations (9) and (10) that a liquid saturant markedly increases the thermal conductivity of an unconsolidated rock. For example, K increases by a factor of 10 when the saturant is 14° API oil. Using Asaad's (1955) empirical correlation, a cementation factor m = 1.3, and a

thermal conductivity of the rock solids (quartz) of 5 Btu/hr.ft. $^{\circ}$F (8.65 Wm^{-1}K^{-1}) (Somerton, 1958), the thermal conductivity of the API oil at 70°C was estimated to be in the range 2—3 W/mK. This latter value is much greater than the conductivity of the water (0.669 Wm^{-1}K^{-1}) used. From the results, wettability of a sand, as reported by other workers (Somerton et al, 1974), seems to play a significant role in determining the overall thermal conductivity of a rock. Assuming that the sands used were water wet, the ratio of thermal conductivities for an oil saturated sand to that for an oil saturated sand with 19.5% water is approximately 1.7. This ratio indicates that "wetting" water substantially reduces the sand conductivity even when the conductivity of the oil is much higher. This conclusion was also made by Somerton et al.

DISCUSSION

The modified Lees' Disc apparatus for the measurement of the thermal conductivities of oil sands seems viable as is demonstrated by preliminary results and their general comparisons with the results of other investigators. It now remains for the apparatus to be modified further for measurements under reservoir conditions. Since pressure has little effect on thermal conductivity (Anand et al, 1973; Somerton et al 1974), the apparatus can easily be modified for measurements at high steam temperatures ($\simeq 600^{\circ}$F). Figure 2 shows the proposed arrangement. The entire apparatus is housed in an air enclosure whose temperature can be varied to $\simeq 600^{\circ}$F ($\simeq 316^{\circ}$C) and heat is supplied by a heating coil. The entire sample is sealed in a vermiculite sample holder to prevent distilled products from leaving the sample. Thermocouples replace the mercury in glass thermometers. Knowing the current flowing into the coil, the voltage applied to it, and the steady state temperatures, the thermal conductivity can be calculated for any temperature. The theory of this method has already been developed by the authors. It indicates a result similar to the one described in this paper except that a correction factor is now necessary. Also the heat losses (h) are evaluated directly from the power given to the heating coil so that the method becomes non-comparative.

CONCLUSION

In this paper, measurement of the thermal conductivity of a heavy oil sand from the Penal area, by a modified form of the conventional Lees' disc method, has been shown to be feasible.

The results indicate a value of 0.507 W/mK or 0.294 Btu/hr. ft. $^{\circ}$F for the thermal conductivity, K_d, of unconsolidated dry sand, of 35% porosity, at 70°C. This value is in general agreement with that reported in the literature for unconsolidated sands.

Variation of the thermal conductivity of dry sand with temperature has been estimated to be

$$K_d = 1.387 \times 10^{-3}\, \theta + 0.409 \text{ W/mK}.$$

Variation of the thermal conductivity of sand with the oil saturation S_o and with water saturation S_w can be summarized by:

$$\log K = (\log K_d + 0.973\, S_o) \pm 10\%, \text{ for } S_w = 0\%$$

$$\text{and } \log K = (\log K_d + 0.341\, S_o + 0.479) \pm 5\% \text{ for } S_w = 19.5\%.$$

The results show that a liquid saturant increases significantly the thermal conductivity of an unconsolidated rock. In addition, the effect of water "wetting" oil saturated sands is to reduce the thermal conductivity, even when that of the oil is much higher than that of water.

TABLE 1
THERMAL CONDUCTIVITY, K, AS A FUNCTION OF OIL SATURATION, S_o, AT 70°C (158° F)

S_o (%)	K(W/ mK)	K (Btu/hr—ft—°F)
0.0	0.507	0.293
19.3	0.805	0.465
36.0	1.095	0.633
44.4	1.400	0.809
63.6	1.908	1.103
83.0	3.045	1.760
99.1	5.073	2.932

TABLE 2
THERMAL CONDUCTIVITY, K, AS A FUNCTION OF OIL AND WATER SATURATIONS, $S_o + S_w$, AT 70° C (158°F)

S_w = 19.5%

S_o (%)	K(W/mK)	K(Btu/hr—ft—°F)
17.9	1.814	1.049
43.7	2.034	1.176
59.1	2.419	1.398
76.6	2.861	1.654

REFERENCES

1. AKHMEDOVA, S. G., "An Experimental Investigation of the Thermal Conductivity of Rocks as a Function of Liquid Saturation and Temperature" (in Russian), Azerbaidjanskoe Neftyaneo Khozaistov, 45 (9), Sept 1966, pp. 32.

2. ANAND, J., SOMERTON, W.H. and GOMAA, E., "Predicting Thermal Conductivities of Formations from Other Known Properties", SPE Journal, Oct., 1973, pp. 267—273.

3. ASAAD, Y., "A Study of the Thermal Conductivity of Fluid-Bearing Porous Rocks", Ph.D. Thesis, University of California, 1955.

4. BAYLEY, F. J., OWEN, J. H. and TURNER, A. B., "Heat Transfer", Pub. Nelson, 1972.

5. BECK, A. E., "A Steady State Method for the Rapid Measurements of the Thermal Conductivity of Rocks", Journal of Scientific Instruments 3, 1957, pp 186—189.

6. BECK, A. E., "Techniques of Measuring Heat Flow on Land", pp. 24—57 in Terrestrial Heat Flow, Geophysical Monograph Series No. 8, ed. Lee, W. H. K., American Geophysical Union 1288, 1965.

7. BIRCH, F. and CLARK, H., "The Thermal Conductivity of Rocks and Its Dependence Upon Temperature and Composition: Part II", Am. J. of Science, 238 (9): 613, September, 1940.

8. CARSLAW, H. S., "Introduction to Mathematical Theory of the Conduction of Heat in Solids", MacMillian, London and New York, 1921.

9. CARSLAW, H.S. and JAEGER, J.C., "Conduction of Head in Solids", 2nd ed., University Press, Oxford, 1959.

10. FRANCL, J. and KINGERY, W. D., "Thermal Conductivity: IX, Experimental Investigation of Effect of Porosity on Thermal Conductivity", J. of Am. Ceramic Soc., 37 (2): 99, Feb., 1954.

11. HERZEN, R. Von and MAXWELL, A. E., "Measurements of Thermal Conductivity of Deep-sea Sediments by a Needleprobe Method", Journal of Geophysical Research 64, 1959, pp. 1557—1563.

12. HUANG, J. H., "Effective Thermal Conductivity of Porous Rocks", Journal of Geophysical Research 76, 1971, pp. 6420—6427.

13. KHAN, A. M. and FATT, I., "A Thermo-electric Device for Measuring Thermal Conductivity of Rock", Trans. AIME, 234 (II): 113, 1965.

14. LUIKOV, A. V., "Heat and Mass Transfer in Capillary Porous Bodies", Pergamon Press Ltd., 1966.

15. LUIKOV, A. V., SHASHKOW, A. G., VASILIEV, L. L. and FRAIMAN, Y. E., "Thermal Conductiviry of Porous Systems", International Journal of Heat Mass Transfer II, 1968, pp 117.

16. MONGELLI, F., "Thermal Conductivity Measurements of Some Apulin Limestones by the 'Cut Core" Method", Atti XVIII Convegno Annuale di Associazione Geofisica Italiana, 1969, pp. 137—154.

17. PARKER, W. J. and JENKINS, R. J., "A Flash Method for Determining Thermal Diffusivity Over a Wide Temperature Range", WADD Technical Report 65—91, Directorate of Materials and Processes, 1961.

18. SASS, J. H., LACHENBRUCH, A. H. and MUNROE, R. J., "Thermal Conductivity of Rocks from Measurements on Fragments and its Application to Heat-Flow Determination", Journal of Geophysical Research 76, 1971, pp 3391—3401.

19. SOMERTON, W. H.: "Some Thermal Characteristics of Porous Rocks", Trans., AIME, 1958, pp. 213, 61.

20. SOMERTON, W. H. and BOOZER, G. D., "Thermal Characteristics of Porous Rocks at Elevated Temperatures", Trans. AIME 219:164, 1960.

21. SOMERTON, W. H., KEESE, J. A. and CHU, S. L., "Thermal Behaviour of Unconsolidated Oil Sands", SPE Journal, Oct., 1974, pp. 513—520.

22. STRACK, K. N., IBRAHIM, A. W., KELLER, G. V. and STOYER, C. H., "A Method for the Determination of the Thermal Conductivity of Sandstones Using a Variable State Approach", Geophysical Prospecting 30, 1982, pp. 454—469.

23. TIKHOMIVOV, V. M., "Thermal Conductivity of Rock Samples, and Its Relation to Liquid Saturation, Density and Temperature" (in Russian), Neftyanoe Khozaistvo, 46 (4): 36; April, 1968.

24. Tyler, F., "A Laboratory Manual of Physics", Pub. Edward Arnold, London, 3rd Ed., 1967.

25. ZIERFUSS, H. and van der VLIET, G., "Laboratory Measurements of Heat Conductivity of Sedimentary Rocks", Bull., APPG 40, No. 10, 1956, pp. 2475.
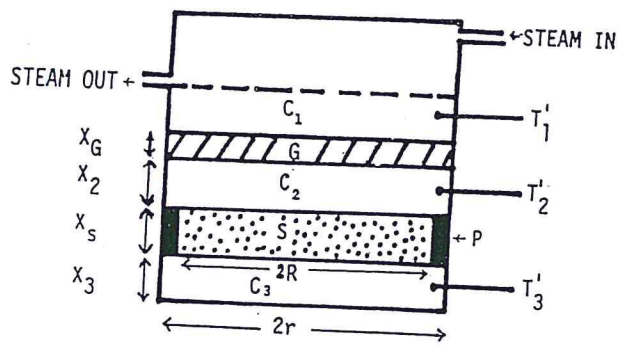
FIGURE 1: MODIFIED LEES' DISC APPARATUS

LEGEND:

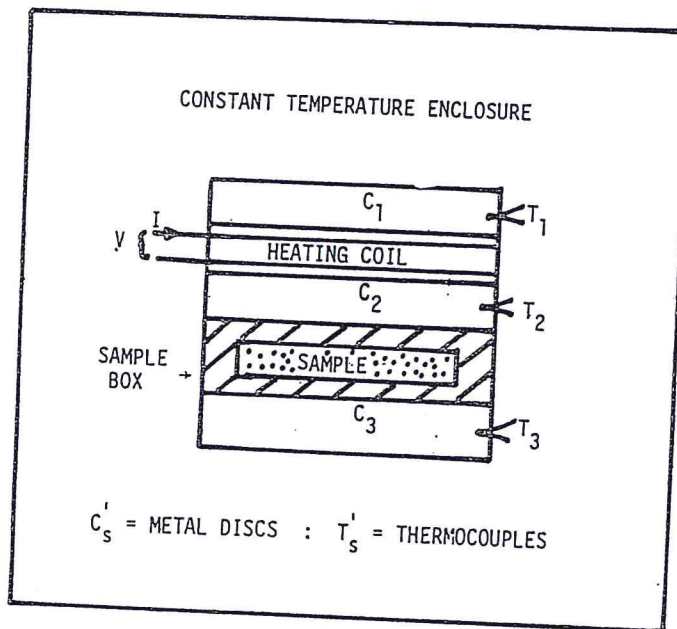|		
C_1, C_2, C_3	=	Nickel plated brass discs
S	=	Sand sample
G	=	Glass Disc
P	=	PVC holder
r	=	Radius of C_1, C_2, C_3, and G
R	=	Radius of Sample, S
X_G, X_2, X_s, X_3	=	Thicknesses of G, C_2, S, and C_3 respectively
T_1', T_2', T_3'	=	Steady state temperatures of C_1, C_2, C_3 resp.

FIGURE 2: PROPOSED ARRANGEMENT FOR HIGH TEMPERATURES

NOTES FOR THE GUIDANCE OF AUTHORS OF PAPERS FOR THE WEST INDIAN JOURNAL

1. **Editorial Policy**

   The editorial board welcomes the submission of papers in all engineering disciplines and related fields. Preference will be given to papers which the board considers to contain material of specific interest to engineers and other parties interested in the industrial development of the Caribbean region.

2. **Types of Papers**

   The following types of papers will be considered:

   (i) *Scientific Papers:*

   These will describe original contributions to the advancement of engineering science.

   (ii) *Applications Papers:*

   These describe novel and significant practical achievements in the design and application of engineering equipment and engineering systems.

   (iii) *Subject Reviews*

   These present a critical survey of the current state of knowledge in the fields covered by the papers.

   (iv) *Industrial Development Papers:*

   These are papers which are in some ways directly concerned with, or may be related to, industrial development in the region.

   (v) *Shorter Communications:*

   These are shorter contributions which will be related to one of the classifications given above

3. **Length of Papers**

   Contributors are requested to make their presentation as concise as possible. The normal maximum length of papers accepted for publication will be the space equivalent of 5000 words.
   Shorter communications should not exceed 1000 words.

4. **Typescript**

   The submitted manuscript should be typed with double line spacing and a left hand margin. The whole text — apart from the Abstract — should preferably be sectionalised and numbered using the decimal system. Tables and equations should be numbered in sequence.

5. **Diagrams**

   Diagrams, graphs, drawings and figures should be completely separate from the typescript. All graphs, diagrams etc, must be drawn neatly on tracing paper of size no bigger than 18 cm by 14 cm. Titles of drawings, figures etc, must be given in a List of Figure Titles preceeding the originals of the drawings. Author's name and title of the paper must be on the list for identification. Photographs will not be accepted unless absolutely necessary. Glossy black and white prints approximately 10 cm by 7 cm must be supplied if photographs are essential to the paper.

   The drawings may be reduced to a size down to 8 cm by 6 cm before printing. The author must consider the visibility of lines, lettering and detail when the figure is reduced. Graphs must be drawn with wide black lines and printed letters. The axes of the graphs may be drawn with lighter lines and marked with various values at equal intervals. The lines for the curves should be appreciably wider than other lines. Wide lines and letters are required to make them readily visible after reductions.

6. Submission

Three copies of the manuscript along with the original diagrams and drawings should be submitted to the editor.

7. Presentation

    (a) *Title:*

    Brief titles are desirable, i.e. not more than 10 words.

    (b) *Abstract:*

    This should be as brief as possible (normally not more than 150 words) and should summarize the conclusions of the paper. It should be self-explanatory and not require reference to the paper itself.

    (c) *Nomenclature and Symbols:*

    Authors are requested to use, wherever possible, standard forms of symbols and nomenclature as suggested by the relevant international standards.

    (d) *Units:*

    System International (SI) units are obligatory in all manuscripts submitted.

    (e) *References:*

    Bibliographical references should be numbered, (indicated in the text within square brackets) and listed in a special section as in the following examples:

        1.   BARKER, J.J. "Heat Transfer in Fluidised Beds", Ind. Eng. Chem. 1956, 57 (5), 33-39.

        2.   MORRIS, J.E. and GEWARTOWSKI, J.W. "A 1W 6Ghz IMPATT Amplifier For Short Haul Radio Applications", Proceedings of the IEEE International Conference on Communication, Washington D.C., 1973, Vol. 1 pp. 8-27.

        3.   GAJRAJ, A.M. "Numerical Studies of Non-Newtonian Flows", Ph.D. Thesis, University of Exeter, 1973.

        4.   CUTTERIDGE, O.P.D. "Computer Synthesis of Lumped Linear Networks of Arbitrary Structure" in SKWIRZYNSKI, J.K. and SCANLON, J.O. (Eds.): Network and Signal Theory (Peter Peregrinus, 1973) pp. 105-111.

It is desirable that papers be published without avoidable delay, and authors are asked, wherever possible, to assist in this aim at all stages of the process.