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A Plasto-Hydrodynamic Investigation of the
Lubrication and Coating of Wire Using a
Polymer Melt During Drawing

A Thesis Submitted for the Degree of

MASTER OF PHILOSOPHY

BY

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SYNOPSIS

Wire drawing has been the subject of much research and development but there is evidence that conventional methods of lubrication may have reached the limit of development.

This project investigates the advantages and problems of lubricating the wire drawing operation hydrodynamically using a polymer as the lubricant. The experimental results are compared with results generated by an existing theory and the theory developed in the light of those experimental results. Design equations are suggested based on the modified theory.

LIST OF CONTENTS

LIST OF FIGURES

NOTATION

A,B = Constants

  h = Radial gap, between the wire and the bore of the tube, unless stated otherwise.

L = Length of Christopherson Tube

p = Pressure

Q = Flow rate per unit circumference

R = Radius of wire at inlet, unless otherwise stated

U = Wire speed

v = Axial flow velocity

y = Distance from surface of wire

z = Axial distance

n = Apparent viscosity

σ = Direct stress in the wire

T = Shear Stress

x = Distance across the gap

Y = Yield stress of the wire

SUFFIXES

c = Critical Value

d = Value after drawing

f = At commencement of flow

z = At the inlet section to the die

max = Maximum value

o = At the surface of the wire

y = At yield point of wire

CHAPTER I

1.   INTRODUCTION

1.01 Review of Lubrication Techniques in Wire Drawing

The wire drawing industry has sought to increase the drawing speed, the reduction in area per die, whilst maintaining product quality in order to reduce production costs.

The most successful way of achieving this is by improved lubrication of the operation. Temperature, which is detrimental to the metallurgical structure of the wire, is produced by the work done against friction and the deformation of the wire.

Weistreich[1] demonstrated that the relative importance of the two heat producing factors depends on the die angle used. If the die angle is large then the friction between the wire and the die is small but there is a great deal of redundant deformation, where as a small die angle causes a large friction force, but the redundant deformation produced in the wire is small. The die angle used in industry, therefore, is a compromise designed to give the smallest total heat generation.

If, however, the lubrication is improved and the coefficient of friction reduced then the relative importance of the friction force and the redundant deformation changes and the optimum die angle is reduced. This results in a reduction in heat generated by both friction and redundant deformation

The most common method of lubricating wire drawing at present, is to coat the wire with a dry sterate or borate soap placed in a hopper in front of the die. Adhesion between

the wire and the soap is improved by pre-coating the wire
with a phosphate or oxylate coat to key the soap to the wire
surface. Soap lubrication technology has become more
sophisticated as new and more specialized soaps are developed.
This improvement of soaps has been very successful, but there
are indications that soap technology is reaching the limits
of its application in modern industry. This is due mainly
to the problems of moisture absorbance by the soap which
destroys the lubrication properties of soap. More recently
there has been a move away from the more complex and expen-
sive soap, and attempts have been made to find suitable
general soaps.

In 1972 Bleir and Finnegan[7] suggested soaps had
become too specialized and that economies could be made by
reducing the number of soaps used and relying on a few
general purpose soaps. Their reasons for this conclusion
were, the high cost per unit weight of specialized soaps
bought in relatively small quantities, high warehousing costs
of carrying a wide variety of soaps and the large percentage
of scrap wire produced because of wrong soap . They tested
their theory at the Mid-State Steel Wire Company, Florida
and found, the mill which used 15 highly specialized lubri-
cants could operate using just 2 general purpose soaps with
no loss of product quality and so operate more efficiently.

Even though soaps are used for most of the wire drawn
in industry today, the limitations stated above have prompted
a great deal of work into new methods of lubricating wire.

One of the most radical approaches to the problem
resulted from Atkins[8] research on the friction in electro-
lytic cells. Farr and Lowe[9] suggested electrochemical

lubrication on wire drawing was possible. Several combinations of electrolyte were tested without success until Atala and Laditan[10] found that an electrolyte consisting of Thioacetamide and Ammonium Molybdate in sulphuric acid produced a satisfactory coating, which was found to be as effective as heavy graphited oil. The system however has problems when the transition to the industrial situation is attempted, in that the time required to coat the wire is in the order of 2 seconds which would necessitate an electrolyte of unmanageable length. This project, therefore, remains in the experimental stage until means of accelerating the deposition process are found.

A method of lubrication first proposed by Christopherson and Naylor[11] in 1955 created a great deal of interest and further development work. They demonstrated that a relatively thick film of oil could be induced hydrodynamically between the wire and the die by passing the wire through a reservoir of oil and long tube with a small clearance immediately preceding, and connected via a seal to the die. Experiments performed showed that hydrodynamic lubrication greatly reduced die wear, but when applied in an industrial situation several problems became apparent. Hydrodynamic lubrication is only possible when the wire is travelling at a velocity sufficient to generate high pressures in the lubricant, and so the lubrication at start-up is dependent on boundary lubrication which is poor when using a mineral oil, due to its low viscosity. The tube clearance required to provide effective hydrodynamic lubrication has to be small (0.03 mm), in the same order of magnitude as the diameter

tolerance of the wire. The length of tube required to generate the pressure in the oil made it cumbersome, and if the tube clearance were to be increased to solve the problem of wire tolerance then the tube has to be even longer. These problems defeated attempts to introduce this method on a wide scale, although modified Christopherson tubes, as they are known, were introduced to improve soap lubrication.

An alternative method of creating thick film lubrication is by using high pressure oil supplied from an external source, usually a pump. This can be supplied to an entry vessel next to the die, such that the high pressure is transmitted to the die. The flow of oil will take the path of least resistance and therefore a seal is required upstream.

Middlemiss[1, 2, 3] attempted hydrostatic lubrication by injecting oil under pressure into a special die unit and between two dies.

The first of these achieved a small reduction in area (approximately 3%) and its principal purpose was to seal the unit against losses in oil pressure. The second die achieved the bulk of the reduction in area, and was lubricated by the establishment of a thick oil film created by the applied oil pressure. The mean die pressure in the seal die was very high due to the very small reduction in area, and so creating lubricating conditions which are more severe than that attempted in one die. As the sealing die is more difficult to lubricate than the main die it is subject to severe wear which cannot be eliminated. Hence, such a double die device is not a practical lubricating system.

1.02 Note on Polymer Lubrication

In recent years polymers have been used for lubrication at metal forming processes, notably extrusion. The properties of polymers differ from traditional lubricants in many ways and so the analysis of the polymer lubrication presents new problems, but these different properties can also offer considerable practical advantages.

When considering a polymer as a lubricant, it is profitable to note the rheological differences between polymers and traditional lubricants and to consider the resulting difference in lubricating properties.

The higher viscosity of polymers is due to the long chain tube molecules which intertwine and so offer a much higher resistance to motion than the relatively short oil molecules. As the shear stress on the polymer molecules increases they become orientated in the direction of flow of the polymer, that is to say disentangled, and so offer less resistance to motion. As with oil, the viscosity of a polymer is reduced as its temperature increases, however the viscosity of a polymer is extremely sensitive to pressure. Westover[13] found that the viscosity of a polymer increases by a factor of between 5 and 100, depending on its molecular weight, when subjected to typical injection moulding pressures.

When subjected to very high shear rates polymers display a further non-newtonian property, known as boundary slip. Boundary slip occurs when the shear force of the molecules in flow on the molecule fixed to the boundary wall, becomes greater than the attraction between the stationary molecule

and the boundary wall. This occurs at a lower shear rate in polymers with high molecular weight because of the greater area of contact between the molecules in flow and the stationary molecule. This phenomenon is also known as melt fracture.

The problems associated with the oil fed Christopherson tube are due mainly to the relatively low viscosity of oil. It is these problems, related to the rheology of the oil which prompted this research into the use of a polymer melt in conjunction with a Christopherson tube for lubrication of wire drawing and to establish the advantages and disadvantages of this method.

A polymer was chosen because of its high viscosity and with a view to shortening the tube, increasing the clearance between the wire and the tube, and improving 'start-up' lubrication. This is achieved by both lowering the speed required for hydrodynamic conditions and improving boundary lubrication when compared to oil. In addition to these improvements there could be added advantages if a well adhered coating of polymer can be obtained. This will act as a protection against corrosion and, possibly as a solid lubricant during further metal working processes, such as cold-heading or redrawing.

The object of the research is not to select the most suitable polymer but to establish the effects on lubrication and polymer coating of changing physical parameters such as length and clearance of tube, the yield stress of the wire and viscosity of polymer melt. These results could be compared to existing theories so as to be in a position to

CHAPTER II

2. ANALYSIS OF THE PROCESS

2.01 Introduction

The original analysis for hydrodynamic lubrication of
wire drawing was developed by Christopherson and Naylor[11],
this was further developed, and applied to polymer flow,
by Symmons and Thompson[12]. The following analysis is an
extension of Symmons and Thompson's previous work and in-
cludes the phenomenon of critical shear stress which was not
considered before.

In the following analysis it has been assumed that:

1) The flow characteristics of a polymer melt can be
   treated as a Newtonian fluid using the concept of
   apparent viscosity.

2) The apparent viscosity is constant.

3) Flow of the polymer is laminar.

4) Flow is fully developed and steady at all times.

5) Flow of the polymer is axial.

6) Thickness of the polymer layer is small when compared
   with the dimensions of the Christopherson tube.

7) Pressure in the polymer is uniform in the thickness
   direction.

As the thickness of the polymer melt layer contained in
the Christopherson tube is small compared with the dimensions
of the tube the analysis of the flow is carried out in
rectangular rather than cylindrical co-ordinates. Combining
the equation of equilibrium with the equation for continuity
of flow, bearing in mind the above assumptions, gives the
following equation of motion.

2.02 <u>Analysis</u> - The equation of motion for a viscous fluid is :-

$$\frac{\partial^2 v}{\partial x^2} = \frac{1}{\eta} \frac{\partial p}{\partial z} \qquad \qquad \text{.... 1}$$

From the definition of apparent viscosity we have

$$T = -\eta \frac{\partial v}{\partial x} \qquad \qquad \text{.... 2}$$

Integrating Equation 1 gives

$$\frac{\partial v}{\partial x} = \frac{1}{\eta} \frac{\partial p}{\partial z} x + A$$

and $\qquad v = \dfrac{1}{2\eta} \dfrac{\partial p}{\partial z} x^2 + Ax + B \qquad \text{.... 3}$

It is known that at the tube bore the velocity of the polymer is zero so this can be used as a boundary condition. If the flow of the polymer is sub-critical then it can be assumed that the velocity of the polymer at the surface of the wire is equal to that of the wire, but if the polymer has reached a critical shear stress then slip will occur. Therefore the only boundary condition which can be used at this stage is to say the shear stress at the wire boundary is equal to $T_{(x = 0)}$

When $x = 0$ $\quad T = T_{(x = 0)} = T_0$

∴ From Equations 2 and 3

$$A = \frac{-T_0}{\eta} \qquad \qquad \text{.... 4}$$

When $x = h$ $v = 0$

∴ From Equations 3b and 4

$$0 = \frac{1}{2\eta} \frac{\partial p}{\partial z} h^2 - \frac{T_o h}{\eta} + B$$

∴ $$B = \frac{T_o h}{\eta} - \frac{1}{2\eta} \frac{\partial p}{\partial z} h^2 \qquad \text{.... 5}$$

Combining Equations 3 to 5 gives:-

$$v = \frac{T_o}{\eta} (h - x) - \frac{1}{2\eta} \frac{\partial p}{\partial z} (h^2 - x^2) \quad \text{... 6}$$

The rate of flow of polymers melt through the die may be obtained by integrating equation 6 thus

$$Q = \int_0^h v \, dx \qquad \text{.... 7}$$

From Equations 6 and 7

$$Q = \left[\frac{T_o h^2}{\eta} (hx - \frac{x^2}{2}) - \frac{1}{2\eta} \frac{\partial p}{\partial z} (h^2 x - \frac{x^3}{3}) \right]_0^h$$

$$Q = \frac{T_o h^2}{2\eta} - \frac{1}{3\eta} \frac{\partial p}{\partial z} h^3 \qquad \text{.... 8}$$

When the polymer is passing through the die the flow can be defined as :-

$$Q = h_d \cdot U_d \qquad \text{.... 9}$$

∴ The coating thickness of the polymer on the wire may be expressed thus

$$h_d = \frac{h^2}{\eta U_d} \left[\frac{T_o}{2} - \frac{1}{3} \frac{h \partial p}{\partial z} \right] \qquad \text{.... 10}$$

∴ From Equation 10 it can be seen that for coating to occur

$$T_o \geqslant \frac{2}{3} h \frac{\partial p}{\partial z}$$ 11

Melt Flow Criterion

The 'polymer' melt flows between the wire and the drawing die if the melt pressure at the inlet section to the die is equal to the die pressure. The die pressure at the inlet section can be found by applying either the Maxwell -von Mises or Tresca yield criterion thus:-

$$Y = p_i + \sigma_i$$ 12

Where σ_i is the back stress caused by the viscous drag of the polymer on the wire. Applying the concept of axial equilibrium to the length of wire contained within the Christopherson tube gives:

$$\sigma_i = T_o \frac{2L}{R}$$ 13

Combining equations 12 and 13 and using the relationship

$$\frac{\partial p}{\partial z} = \frac{p_i}{L}$$

then $$\frac{\partial p}{\partial z} = \frac{Y}{L} - \frac{2T_o}{R}$$ 13a

Which enables Equation 11 to be rewritten

$$T_o \geqslant \frac{2h}{3} \left(\frac{Y}{L} - \frac{2T_o}{R} \right)$$ 14

$$\therefore \quad T_o \gg \frac{2hY}{3L\left(1 + \frac{4h}{3R}\right)} \qquad \dots \ 15$$

Equation 10 when combined with Equation 13a gives:

$$h_d = \frac{h^2}{\eta\, U_d}\left[\frac{T_o}{2} - \frac{hY}{3L} + \frac{2hT_o}{3R}\right] \qquad \dots \ 16$$

To Calculate T_o During Sub-Critical Flow

If the polymer is flowing in a sub-critical situation then it can be assumed that there is no slip at the boundary between the polymer and the wire. There, the boundary conditions can be taken to be

When $\quad x = o \qquad v = U$

and $\quad x = h \qquad v = o$

$\therefore$ Referring to equation 3b

$$B = U$$

$$A = \frac{-h}{2\eta}\frac{\partial p}{\partial z} - \frac{U}{h} \qquad \dots \ 17$$

$$\therefore \quad \frac{\partial v}{\partial x} = \frac{1}{2\eta}\frac{\partial p}{\partial z}(2x - h) - \frac{U}{h} \qquad \dots \ 18$$

$\therefore$ At the polymer/wire boundary (i.e. $x = o$)

$$\left(\frac{\partial v}{\partial x}\right)_{x=o} = \frac{-1}{2\eta}\cdot\frac{\partial p}{\partial z}h - \frac{U}{h} \qquad \dots \ 19$$

Substituting from $\left(\dfrac{\partial v}{\partial x}\right)_{x=o}$ and $\dfrac{\partial p}{\partial z}$ from Equations 2

and 13a respectively gives

$$\frac{T_o}{\eta} = \frac{h}{2\eta} \left[\frac{Y}{L} - \frac{2T_o}{R} \right] + \frac{U}{h}$$

$$\therefore \quad T_o = \frac{(h^2Y + U_d \eta L)}{2Lh \left(1 + \frac{h}{R}\right)} \qquad \ldots\ldots 20$$

A rearrangement of Equation 20 gives an expression to enable the calculation of V flow and V crit.

$$U_d = \frac{T \, 2Lh \left(1 + \frac{h}{R}\right) - L^2Y}{2\eta L} \qquad \ldots\ldots 20a$$

The above equation in conjunction with equations 14 and 16 can be used to calculate the coating thickness.

$$T_o \geqslant \frac{2h}{3} \left(\frac{Y}{L} - \frac{2T_o}{R} \right)$$

$$h_d = \frac{h^2}{\eta U_d} \left[\frac{T_o}{2} - \frac{hY}{3L} + \frac{2hT_o}{3R} \right]$$

CHAPTER III

3.   DESIGN AND MANUFACTURE OF TEST APPARATUS

3.01 Design Requirements of Draw Bench

No existing apparatus within the department was suit-
able to be adopted to satisfy the requirements of this work,
therefore the draw bench was purpose built. It was decided
that the draw bench should ideally be able to draw a wide
range of wire with the speed infinitely variable between
0 and 2.5 m/s. This speed should be rapidly attained after
start-up, accurately measured and not aversly affected by
a change in torque.

It would be also necessary to measure the drawing
force required to pull the wire through the die. The
temperatures of the wire, polymer and Christopherson tube
must not only be measured but also controlled. The
dimensions of the tube itself must be known to within a
close tolerance, particularly the diameter.

It was hoped to measure the pressure of the polymer
at the die end of the Christopherson tube but this was
not possible as the pressure generated at that point would
be beyond the range of any existing transducer.

3.02 Description of Test Equipment

The ideal motor to satisfy the design requirements
would have been a 15 hp thyrister controlled D.C. motor
which would be capable of running at all speeds between
zero and full speed but this was not feabible for economic
reasons. It was decided, therefore, to use a second-hand
'shraga' motor (BTH 18/4.5 hp VSC) capable of running at
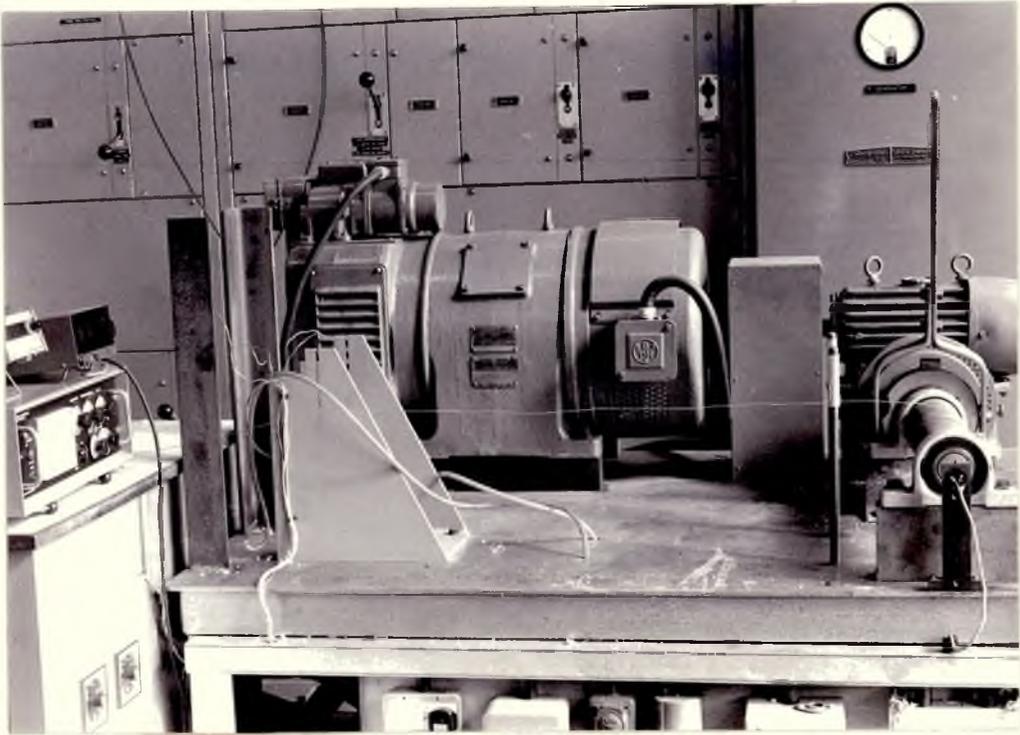
GENERAL VIEW OF RIG WITH SMALL BULL BLOCK
Fig 1a
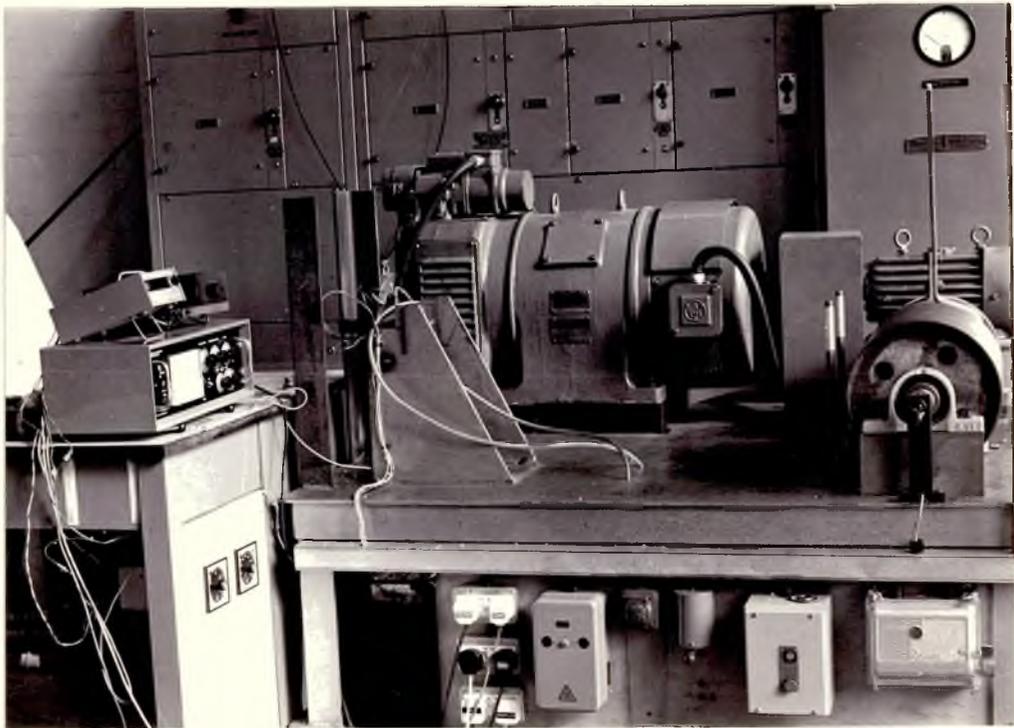
GENERAL VIEW OF RIG WITH LARGE BULL BLOCK
Fig 1b
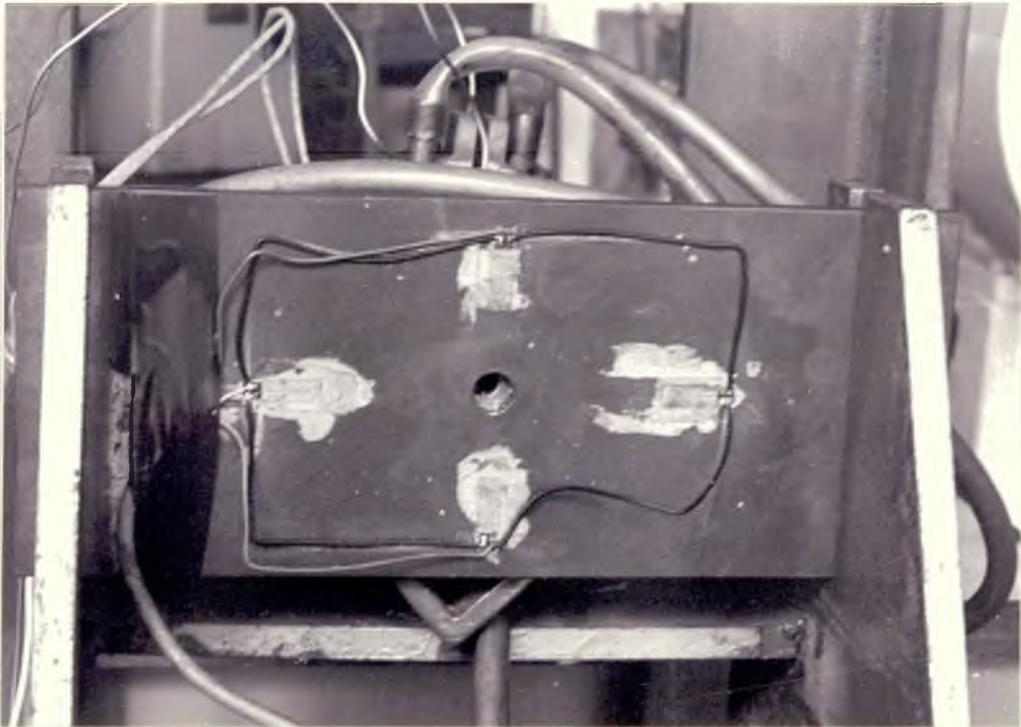
INSTRUMENTATION FOR DRAWING LOAD MEASUREMENT
VIEWED FROM BULL BLOCK   Fig 2
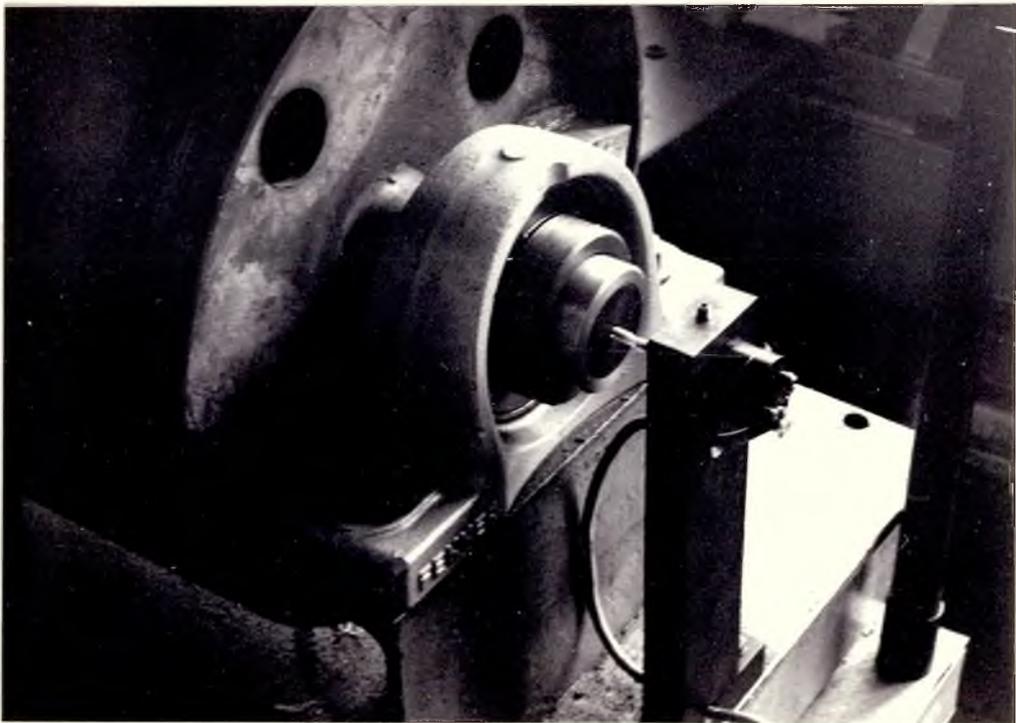
DETAILED VIEW OF TACHOGENERATOR   Fig 3

speeds between full speed and $\frac{1}{4}$ full speed. This was
thought at the time to be adequate but results showed that
information was required from tests run at slower than $\frac{1}{4}$
speed. These results were obtained using a bull block one
quarter of the diameter of the original which effectively
gave a speed range of $\frac{1}{16}$ full speed to full speed and
this proved to be satisfactory.

The power was passed from the motor to the 305 mm
(12") bull block via a flexible tyre coupling (Fenner F80),
a 10:1 reduction worm gear (Croft 5" centre, Type No.
41/551/05) and a coupling clutch (Broadbent Type DP 25)
which enabled the drum to be engaged when the motor was
running at the required speed and so ensured an almost
instantaneous build up to full speed.

This was measured using a tachogenerator (servo products
Type SA 740A/7) connected to a digital voltmeter. The
drawing load was measured by placing strain gauges on the
die retaining plate which was designed to flex during drawing.
This system was calibrated using static loads to give a direct
read out in kN.

The polymer was heated by an electric band heater and
the temperature controlled by a thermostat (Thorn 0-200°C
temperature controller) and measured by a thermocouple.

The wire to be drawn was stored on a wheel placed in an
insulated base and hot air, heated by an industrial air
heater (Secomark 3 kW), passed over it. The temperature was
controlled and measured by the same method as the polymer.

The Christopherson tube was designed to allow it to be
heated or cooled as experiments dictated. The heater and

controller used were the same as for the polymer, but when cooling was required a water jacket was fitted and water circulated from a large tank using a standard washing machine pump. This enabled the Christopherson tube to be kept only 10°C above ambient when separated from the polymer reservoir by a 6 mm asbestos disc.

The components described above were mounted on a solid steel table and the moving parts covered with suitable guards.

3.03 <u>Design and Manufacture of Die Unit</u>

The die unit (Fig. 4 and 6) contains the die, the Christopherson tube and the polymer reservoir. The polymer reservoir through which the wire passes first is approximately 100 mm long by 15 mm diameter, the reservoir being filled through a hole at the top. Consideration was given to automatic methods of feeding the polymer into the reservoir but considering the small quantities involved it was decided to feed the polymer by hand. The reservoir was connected by 3 screws to the Christopherson tube (an insulating disc was placed between the reservoir and the tube when the tube was to be cooled). The Christopherson tube was 60 mm long and between 1.85 mm and 2 mm $\emptyset$, depending on the tube in use. The wall of the tube was made thick enough to withstand the high pressures developed by the polymer during drawing. The tube was sealed to the die using a copper Bridgeman seal and held in position by the die block and 3 large screws. The copper was expanded slightly by the pressure generated to create the seal. Eventually after a long series
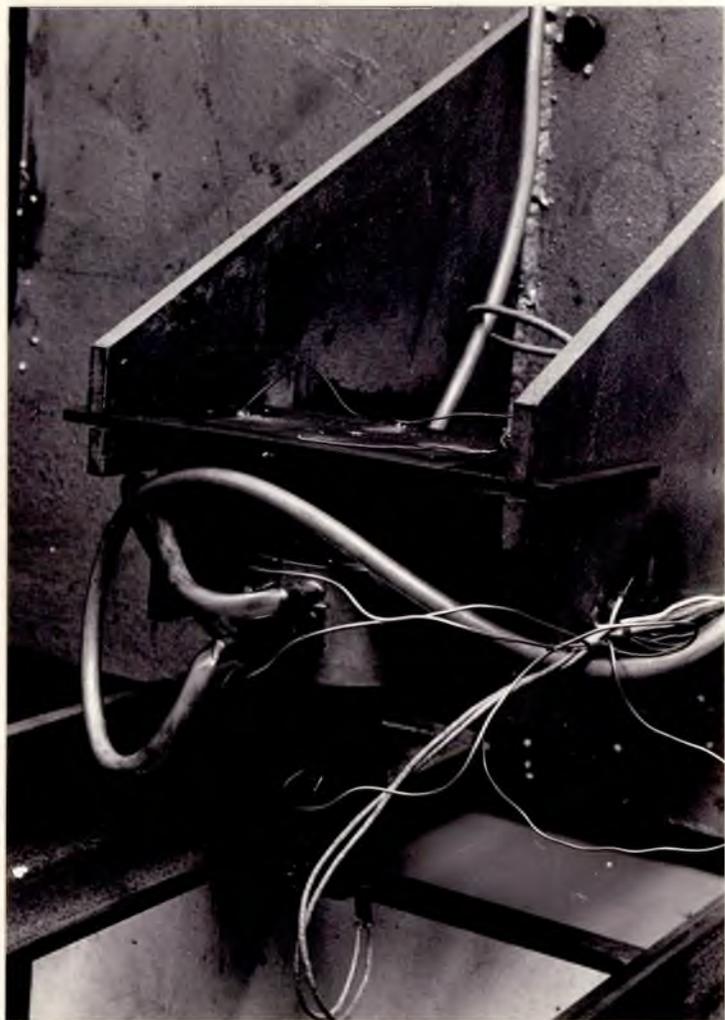
Fig 5

Fig 4 DIE UNIT WITH COOLING
JACKET (above)
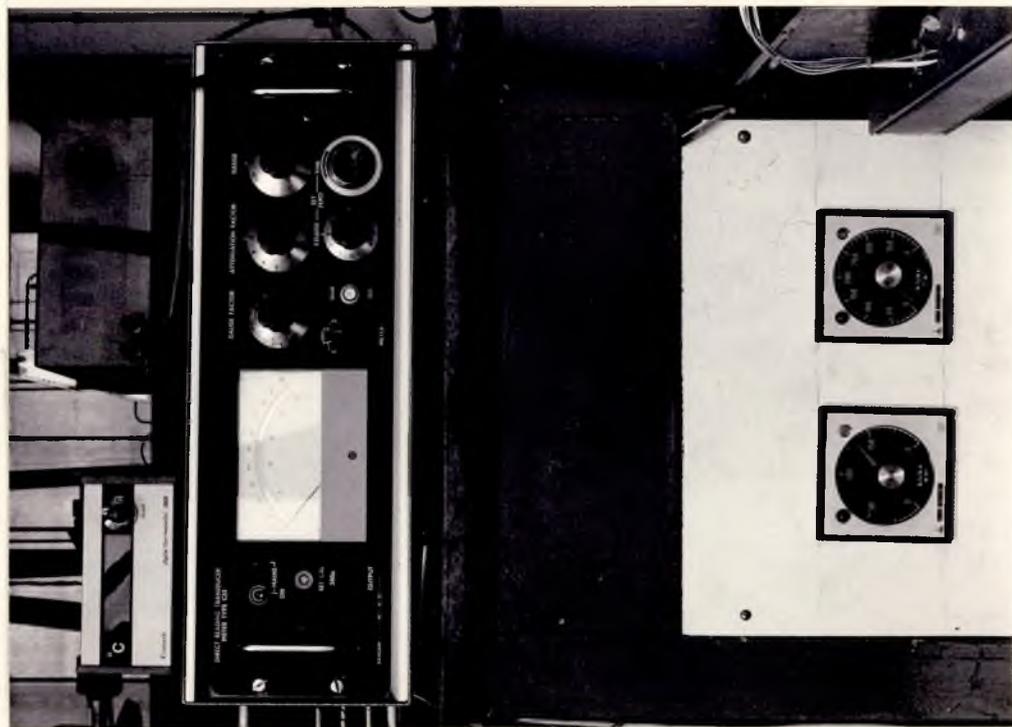
CONTROL AND INSTRUMENT
PANEL (right)

DIE

THERMOCOUPLES

POLYMER FEED

COPPER SEAL

HEATER
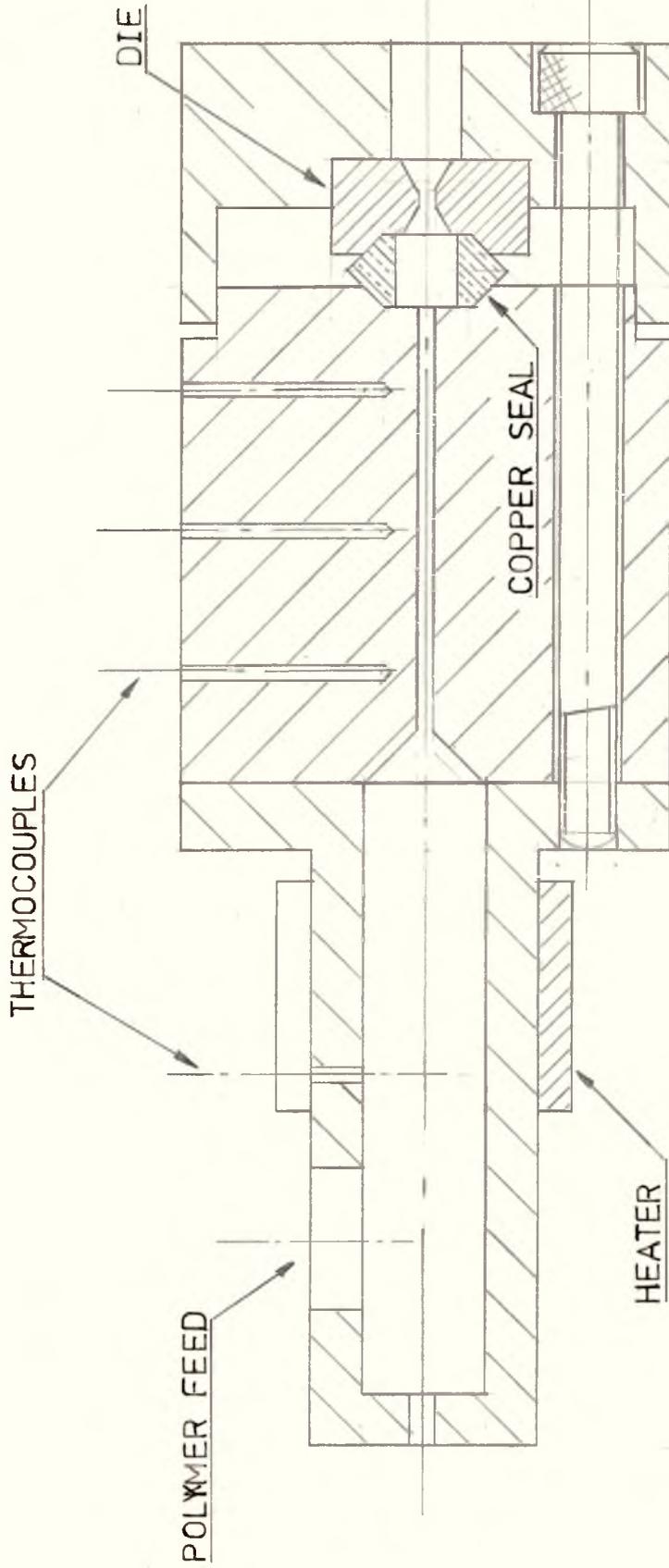
SECTION THROUGH THE DIE UNIT

Fig 6
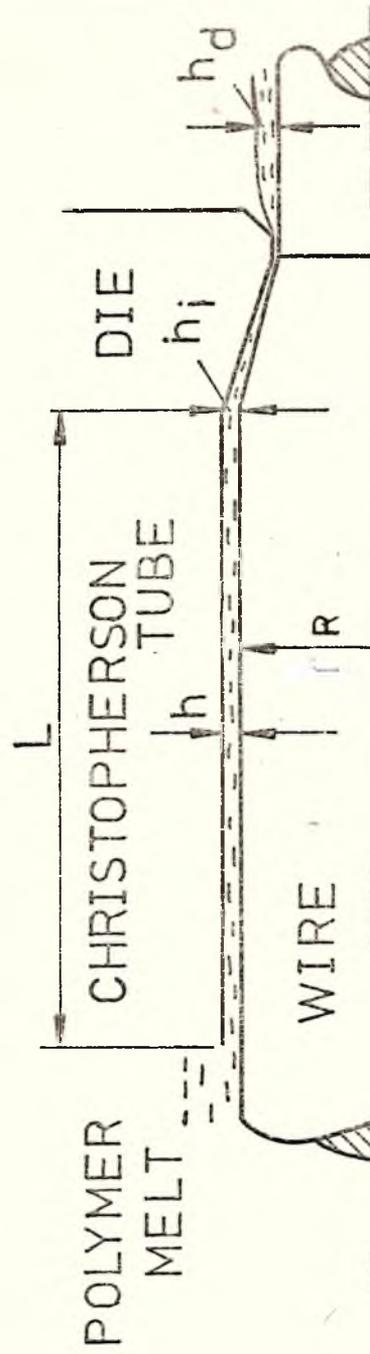
(b) GEOMETRY CONSIDERED IN THE ANALYSIS

FIG (7)

of tests the seal became extruded through the gap between the end of the tube and the die end and had to be replaced.

The die block and polymer reservoir were machined from mild steel bar. The Christopherson tube was machined from oversized high alloy tool steel BD2(D2) with a composition of

Chromium	12.0%
Carbon	1.5%
Molybdenum	1.0%

Problems were experienced drilling a hole less than 2 mm diameter and 60 mm long. The drill tended to 'drift' slightly leaving the exit of the hole up to 1 mm off centre. To combat this the hole was drilled first in the oversized bar and then the outside diameter skimmed using the hole already drilled as a centre. The ends of the tube block were then squared to the newly skimmed outer diameter. The rest of the tube block was then finished in the conventional way. Several blocks were made each with a different tube diameter. The tube material was chosen because it was known to harden in air and not be subject to great distortion. The tube blocks were heated in argon to 1030°C for 2 hours and then cooled in a jet of argon to prevent surface scaling. The tempering of the block was carried out at 425°C to give a final hardness of around 735 Hv. The dimensions of the tube itself were measured after hardening and tempering using an engineers microscope.

The seal was machined from copper and annealed. The hardness required to give both a good seal and long service depended on the pressure which had to be sealed and hence the material to be drawn i.e. the higher the yield stress of the wire to be drawn the harder the copper required.

CHAPTER IV

4. EXPERIMENTAL METHOD

4.01 Introduction

The hydrodynamic lubrication of wire drawing depends on
so many variables, and the taking of results is so time
consuming it was necessary to severely limit the number of
variables investigated experimentally. The variables
involved are tube length, gap between wire and tube, wire
diameter, yield strength of wire, polymer temperature/
viscosity, wire temperature, tube temperature and reduction
area of the wire.

The variables chosen for investigation were:-
(a) The gap between the wire and the Christopherson tube,
which appeared to be the most critical factor.
(b) The yield stress of the wire, to ascertain the range
of wire capable of being lubricated by this method.
(c) The temperature/viscosity of the polymer, because it
is the viscous property of the polymer which generates the
pressure in the tube.

4.02 Determination of the Polymer Rheology

The viscosity of the polymer melt is an important
parameter in determining the coating thickness of the
polymer on the wire. The polymer viscosity is not only
affected by the temperature of the polymer but also the shear
stress to which the polymer is subjected. The effects
of temperature and shear stress were determined using an
extrusion rheometer, which measured the force required to
extrude the polymer, held at constant temperature, through

a capillary tube at a range of speeds. From these results
the viscosity and shear stress of the polymer were calculated.
The test was repeated with the polymer at a different temp-
erature and the result is shown in Fig. 8.

4.03 Determination of Wire Yield Stress

The yield stress of a wire increases during drawing,
due to the effects of work hardening. In the preceding
analysis a mean value was assumed for the wire yield stress.
This value was determined by subjecting a short length of
wire (l=1.5 d) to a standard compression test and plotting
the resulting stress-strain curve. The strain induced in
the wire by drawing was calculated from the empirical
formula

$$\varepsilon_D = \ln \left(\frac{A_o}{A} \right) + \frac{2}{3} \alpha$$

Where A_o = Initial wire cross sectional area

 A = Final wire cross sectional area

 α = Semi die angle

The average yield stress of the wire was then calculated
using the area under the stress strain curve between 0 and ε_D
divided by ε_D. The results of this test for the steel and
copper wires used can be seen in Fig. 9.

4.04 Drawing of Wire

The wire to be drawn was cleaned by one of two methods.
The stainless steel and copper wires were degreased using
trichloroethylene and the steel wire by immersion in 50%
hydrochloric acid.

GRAPH OF VISCOSITY v SHEAR STRESS

FOR POLYMER WVG23

Fig 8

VISCOSITY (Ns/m2)

SHEAR STRESS (N/m2)

130°c

230°c
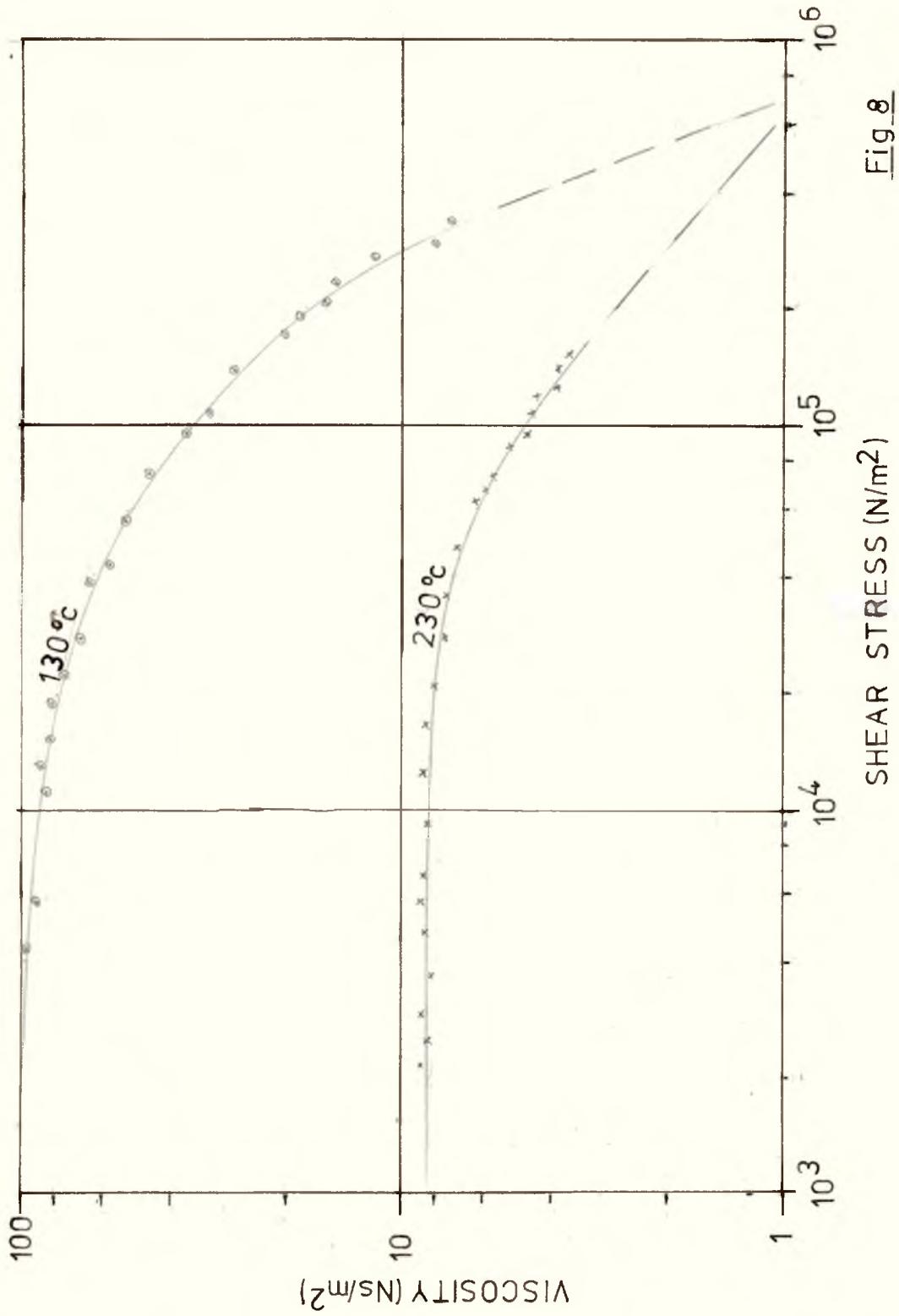
GRAPH SHOWING STRESS/STRAIN CURVES
FOR TEST MATERIALS
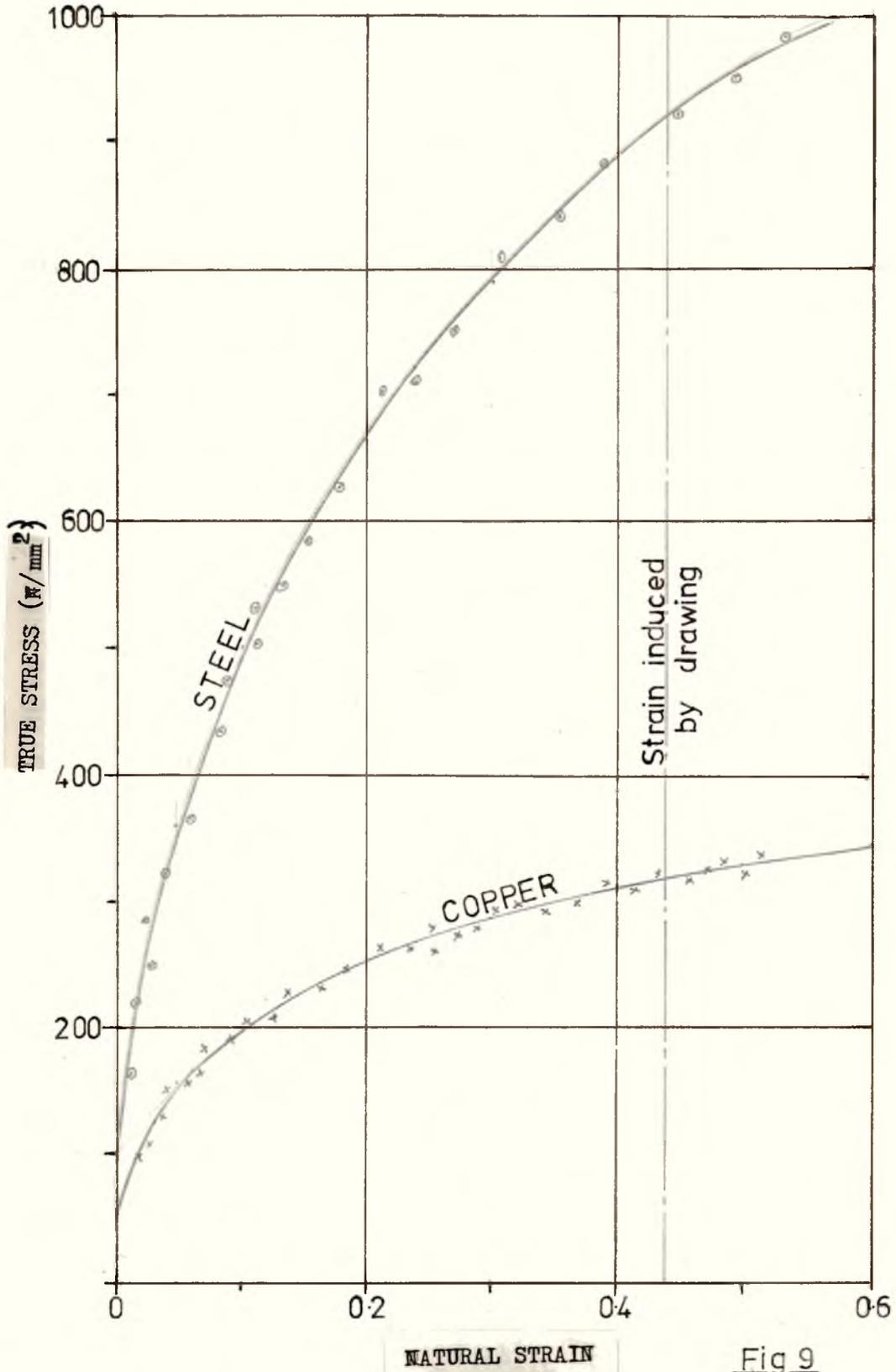
Fig 9

The wire was then swaged and fed through the polymer reservoir, Christopherson tube and die and fastened to the bull block. The polymer was loaded into the polymer reservoir, heated to the required temperature and held at that temperature thermostatically. The temperature of the tube was noted and when this reached a steady state the apparatus was deemed ready for drawing, this usually took around 20 minutes. The clutch was disengaged, the motor started and adjusted to the approximate drawing speed by changing the position of the commutator brushes. This speed was checked using a hand held tacho generator. When the motor was running at approximately the desired speed, the clutch was engaged and the speed was then measured more accurately using the tacho generator and digital voltmeter described earlier. The drawing load was also noted at this point. Both the speed and the wire load were constantly checked for signs of variation, but none were detected. When approximately 15 metres of wire had been drawn, the clutch was disengaged and the drawn wire was removed from the drum. The first 5 metres of wire was discarded, leaving the wire which was representative of the steady state drawing. This was coiled and labelled for later analysis. The wire protruding from the die was reconnected to the bull block, the motor speed changed and the operation repeated. This method was adopted because of the problems involved in threading a swaged wire through the loaded polymer reservoir, the tube and the die. These were full of partly solidified polymer transported there in the wake of the previous pull. The alternative was to strip down the die unit

and remove the offending polymer, but it was not feasible to do this after every pull and so whenever possible three or four readings were taken between stripping down the die unit.

In addition to changing the parameters mentioned above, a limited number of tests were carried out with the wire raised above room temperature. This improved adhesion between the polymer coat and the wire but greatly reduced the coating thickness. Attempts were made to counteract this by cooling the Christopherson tube but this led to the polymer solidifying in the tube before drawing commenced. As heating the wire is not desirable in industry for metallurgical reasons, and the in-ordinate length of time taken to perform these tests it was decided not to persue this line of investigation.

4.05 Measurement of Coating Thickness

Several methods of measuring the coating thickness of the polymer on the wire were considered, but because of the very thin coating (10^{-4} m) and the small diameter of the wire, most of the usual methods were unsuitable. Attempts were made to measure the coat thickness by means of a comparitor. This involved fixing the wire into a specially machined jig, taking a reading using the comparitor, removing the wire from the jig, stripping the polymer coating from the wire, replacing the wire on the jig and taking a further reading. The results from this method were very erratic due to the difficulty experienced in ascertaining the greatest reading on the comparitor as the small diameter

wire was passed beneath it. It was not possible to pass the wire under the comparitor repeatedly and take the maximum reading as the comparitor progressively destroyed the polymer coating due to the rubbing action involved.

The possibility of using the magnetic method was investigated. This is used to test paint thickness on steel by measuring the force required to separate a magnet from the wire. Again the small diameter of the wire made the area of contact very small which made this method unreliable.

Commercially produced instruments are available for measuring coating thicknesses using ultra-sonic techniques, but the models designed to measure coatings on wire less than 2 mm diameter were prohibitively expensive.

It was decided, therefore, to measure the average coating thickness over a short length by a weight loss method. This method proved to be successful giving a high degree of consistency. To demonstrate this, a sample of coated wire 250 mm long was cut into 5 pieces approximately equal in length. Each piece was weighed using an electronic balance, reading to 0.0001 gm, stripped of its coating, reweighed and its length measured using an engineer's microscope. When these results were placed in the simple formula.

$$\text{Coat Thickness} = \frac{W_L}{\pi \times D \times L \times \rho}$$

Where W_L = Weight Loss

 D = Wire Diameter

 L = Sample Length

 ρ = Density of Polymer

the results showed very good repeatability. For example,

when the resulting average thickness was 0.04 mm all the results were within the range ± 0.002 mm or ± 5.0% which compared with the errors involved in measuring such parameters as h and To this is very small, and does not significantly increase the overall error. This method had the added advantage of giving an average reading when the polymer coating was uneven or 'fish scaled'. Once this method had proved to be adequate, it was applied to all test pieces with samples being taken from five different points along the wire.

CHAPTER V

5.   COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS

5.01 Introduction

The theoretical results were calculated using equations
14, 20, 20a and the computer program, (see Appendix I),
the flow diagram of which can be seen in Fig. 10.

From the input parameters the shear stress (T flow)
which must be developed to generate sufficient pressure to
cause the polymer to flow between the wire and the die was
calculated. This value was checked against the critical
shear stress of the polymer to check the flow was possible.

The velocity at which flow commenced was calculated
from equation 20a with T equal to T flow. The same
equation was used to calculate the oil velocity for maximum
coating thickness (with $T = Tc$) V_{CRIT} . The shear stress
and coating thickness were then calculated for the velocities
between V flow and V crit, using equations 14 and 20
respectively. The coating thicknesses for velocities greater
than the critical velocity were calculated by setting the
shear stress equal to Tc and using equation 20 again. The
calculation ended when the velocity was equal to three
times the critical velocity.

This simple program was later modified to generate data
to be stored on a data file in suitable form for use with
the advanced graphing facility of the computer (See
Appendix II). The graphing program was designed to produce
theoretical curves, from the data stored on the data file,
to cover the range of velocities at which the experimental
work was performed.

FLOW DIAGRAM OF COMPUTER PROGRAM TO GENERATE

THEORETICAL PREDICTIONS

Fig 10

START

READ h, R, Y, T_c, L, η

CALCULATE T_{flow} FROM EQ.14

IS
$T_c > T_{flow}$

NO

NO COATING POSSIBLE

YES

CALCULATE V_{flow} FROM EQ.20A
WHERE $T = T_{flow}$

CALCULATE Vcrit FROM EQ.20A
WHERE $T = T_{crit}$

CALCULATE T FROM EQ.14

CALCULATE h_d FROM EQ.16

PRINT V & h_d

1   2   3
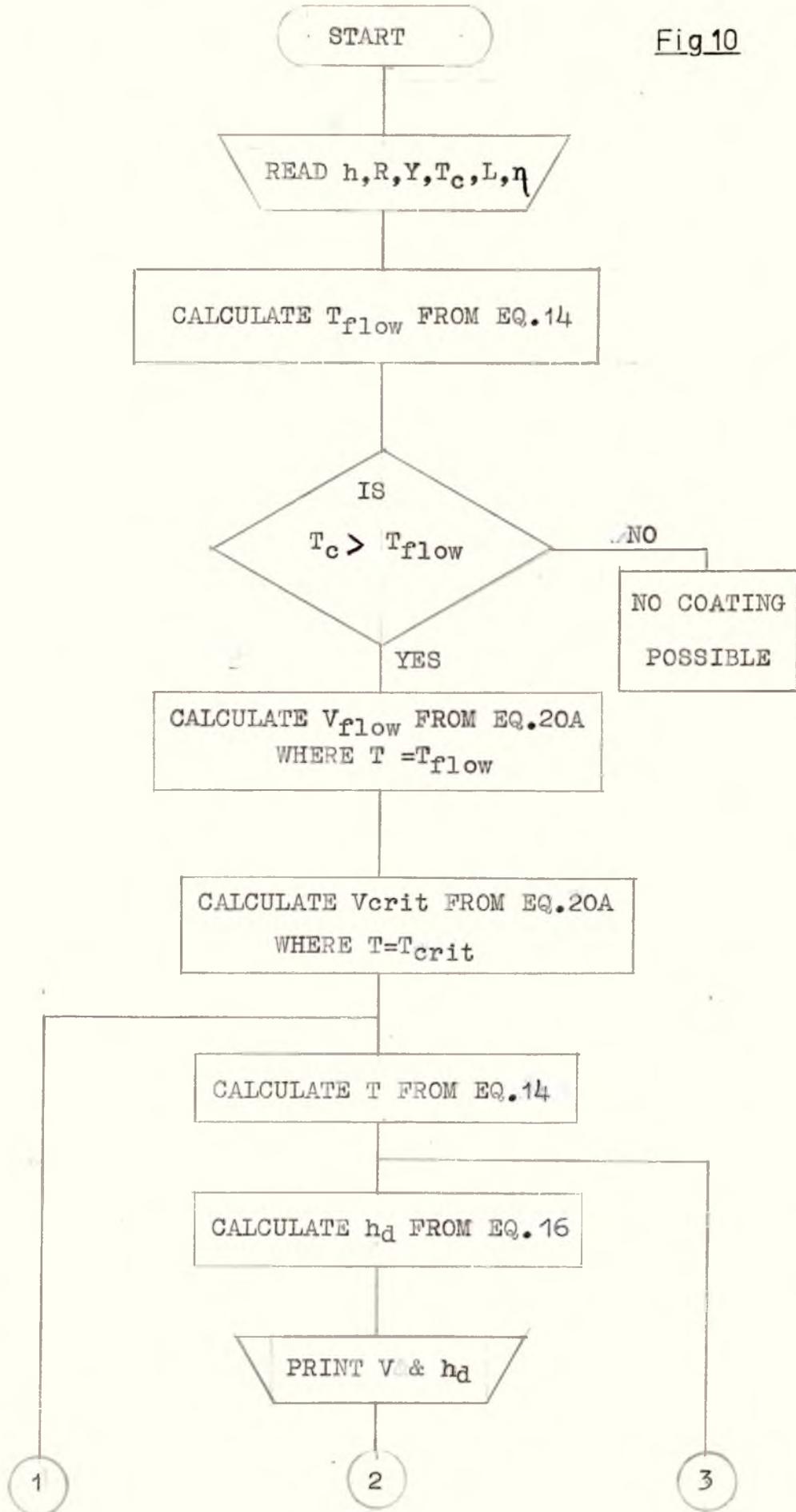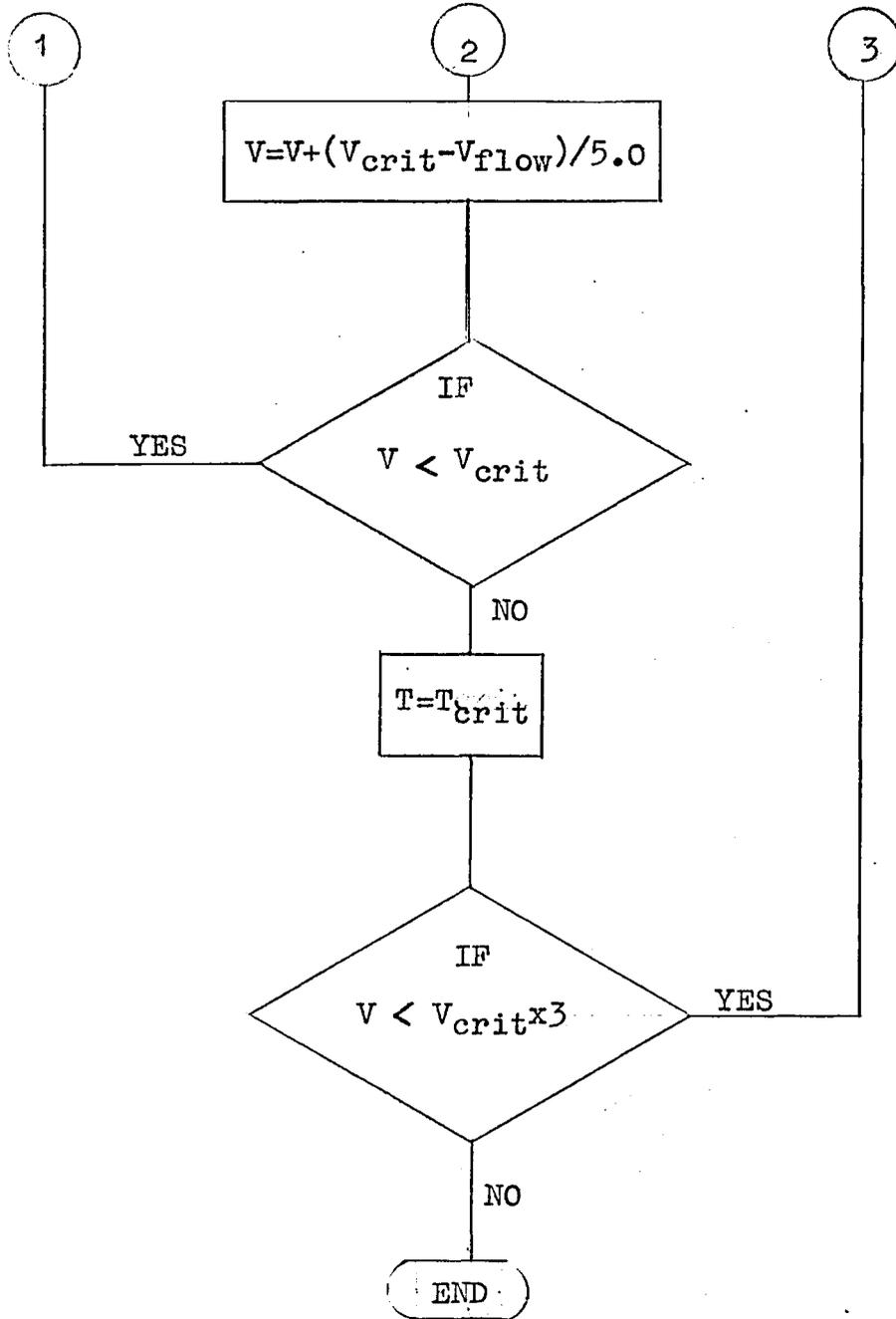
Fig 10 cont.

The parameters used for all theoretical graphs were, unless stated otherwise:

$$\text{Gap } (h) = 0.1 \text{ mm}$$
$$\text{Wire Radius } (R) = 0.825 \text{ mm}$$
$$\text{Wire Yield Stress } (Y) = 245 \text{ MN/m}^2$$
$$\text{Tube Length } (L) = 60 \text{ mm}$$
$$\text{Polymer Viscosity } (n) = 50 \text{ Ns/m}^2$$
$$\text{Critical Shear Stress } (Tc) = 0.6 \times 10^6 \text{ N/m}^2$$

These values can be considered 'typical' and were also used when estimating the experimental error (see Chapter 6.01). To aid comparison between the effects of changing various parameters the same graph axes were used throughout.

Assumptions were made, further to those already described in Chapter II, when calculating the theoretical results explained above.

Firstly the viscosity was assumed to be constant when in fact it is reduced by shear stress and increased by pressure. The effect of shear stress on viscosity can be measured (see Fig. 8) and a mean value may be assumed. It is impossible, however, to measure the combined effect of both high shear stress and high pressure although there is reason to believe they may, to some extent, cancel each other out. This problem is discussed more fully later.

It was also assumed that the transition from no slip to total slip takes place instantaneously at the velocity Vc when in practice it is more likely to take place over a small range of velocities. This gives the theoretical graphs a sharp peak where as the effect of the slip taking place over a range of velocity would be to "round-off" this peak.

The polymer flow in the Christopherson tube was divided into three phases depending on the wire speed. At very small wire speeds insufficient pressure is developed in the melt to overcome the die pressure and so the wire is not coated. As the drawing speed is increased laminar flow occurs with normal boundary adherence between the polymer and the wire. Over this range of speeds the shear stress is rising with increased wire speed but is still below Tc. This means that the wire is covered with a coating of increasing thickness. When the shear stress in the polymer reaches the critical values Tc the maximum flow rate of polymer through the die is also attained, hence any further increase in wire speed can only reduce the coating thickness.

The experimental results show a reasonable agreement with the theoretical predictions considering the experimental error involved.

It was noted that when the wire speed was in the lower end of the critical flow range, the flow of the polymer was prone to discontinuity causing defects in the coating, which have the appearance of either fishscale or bamboo (see Figs. 11 and 12). This was probably due to melt fracture of the polymer. This is caused by the drag force on the polymer molecule becoming greater than it's adhesion to the wire. The drag force is approximately proportional to the shear stress in the melt and the length of the polymer molecule concerned. There is, at present, no explanation as to why the coating should become smooth again but the same observation was made when polymers were extruded at very high shear rates by Du Pont (U.S.P. 2, 991, 508 (1961)). It was
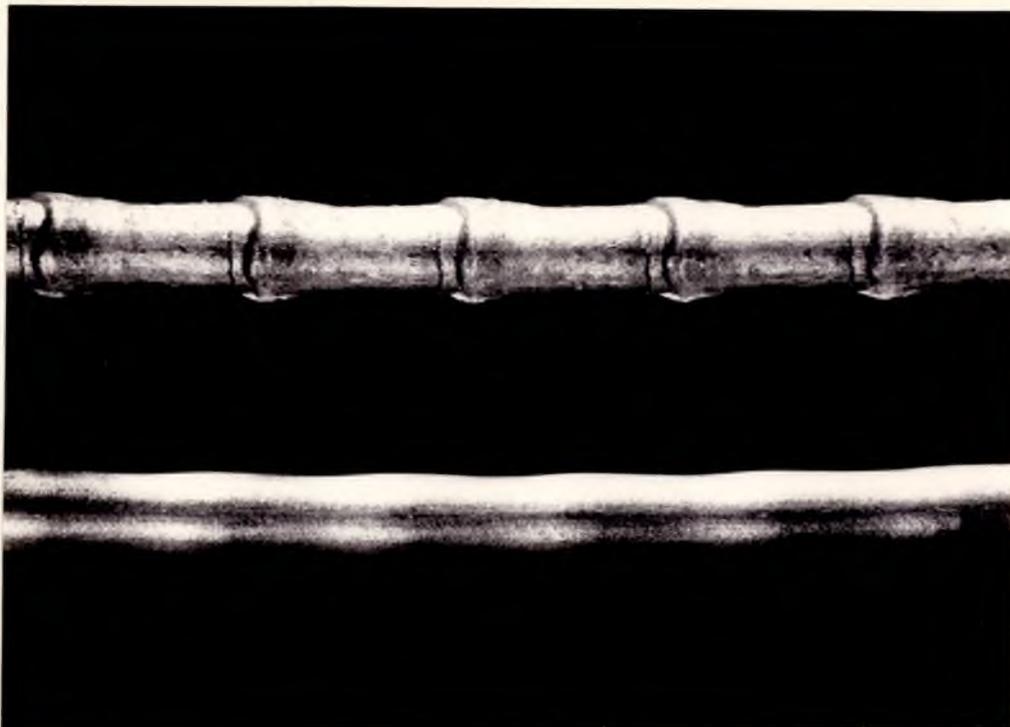
COPPER WIRE WITH FISHSCALE COATING/COATING REMOVED
V= 0.98 M/s   Fig 11
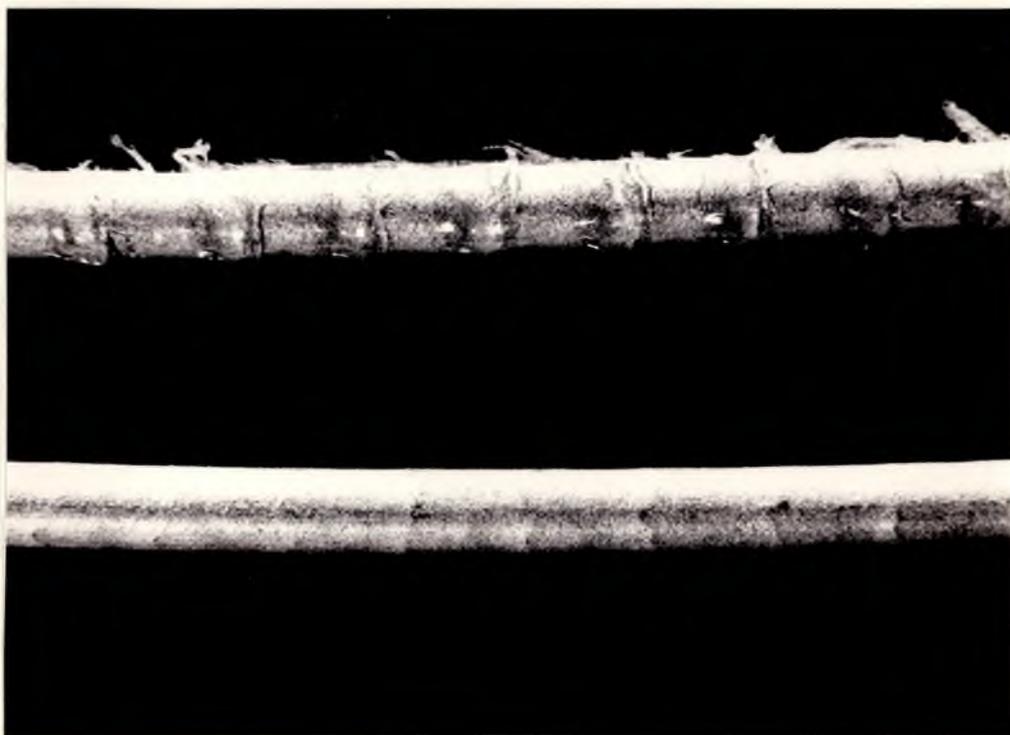
STEEL WIRE WITH FISHSCALE COATING/COATING REMOVED
V= 0.45 M/s   Fig 12

Direction of Drawing

A DETAILED VIEW SHOWING FORM OF
FISHSCALE COATING

Fig13

also noted that when the 'fishscaling' was particularly heavy
on the softer copper wire, the wire itself was hammered into
an uneven surface, which must have occurred in the Christopherson
tube as a result of the pressure pulsating above the yield stress
of the wire.

The drawing load was measured in all tests, but it was
found that provided the polymer was lubricating the wire,
the drawing load was not affected by the coating thickness.

Although it has been shown possible to coat wire with
a polymer over a wide range of speeds, a well adhered coating
was not achieved. It was not possible to measure the force
required to remove the coatings from the wire. It was
decided, to define a well adhered coat as one which would remain
adhered to the wire and lubricate it during a further 25%
reduction in area. All the wire drawn failed this test.
Subjectively it was noted that the 'fishscale' coating
appeared better adhered than those coatings applied at high
drawing speed. These fishscale coatings were particularly
well adhered to the steel wire. The adhesion between the
wire and the polymer coating was improved when the wire was
drawn at an elevated temperature, but this still was not
sufficiently strong to pass the test described above.

5.02 <u>The Effect on Coating Thickness of Changing Yield Stress</u>
     <u>of Wire</u>

Figs. 14 and 15 show the effect of changing wire yield
stress on coating thickness. It can be seen that the
maximum coating thickness that can be obtained was very
sensitive to the yield stress of the wire and was reduced
as the yield stress increased until no coating was possible.

- 47 -

GRAPH SHOWING EXPERIMENTAL RESULTS AND THEORETICAL

PREDICTIONS FOR CHANGING YIELD STRESS OF WIRE

Fig 14
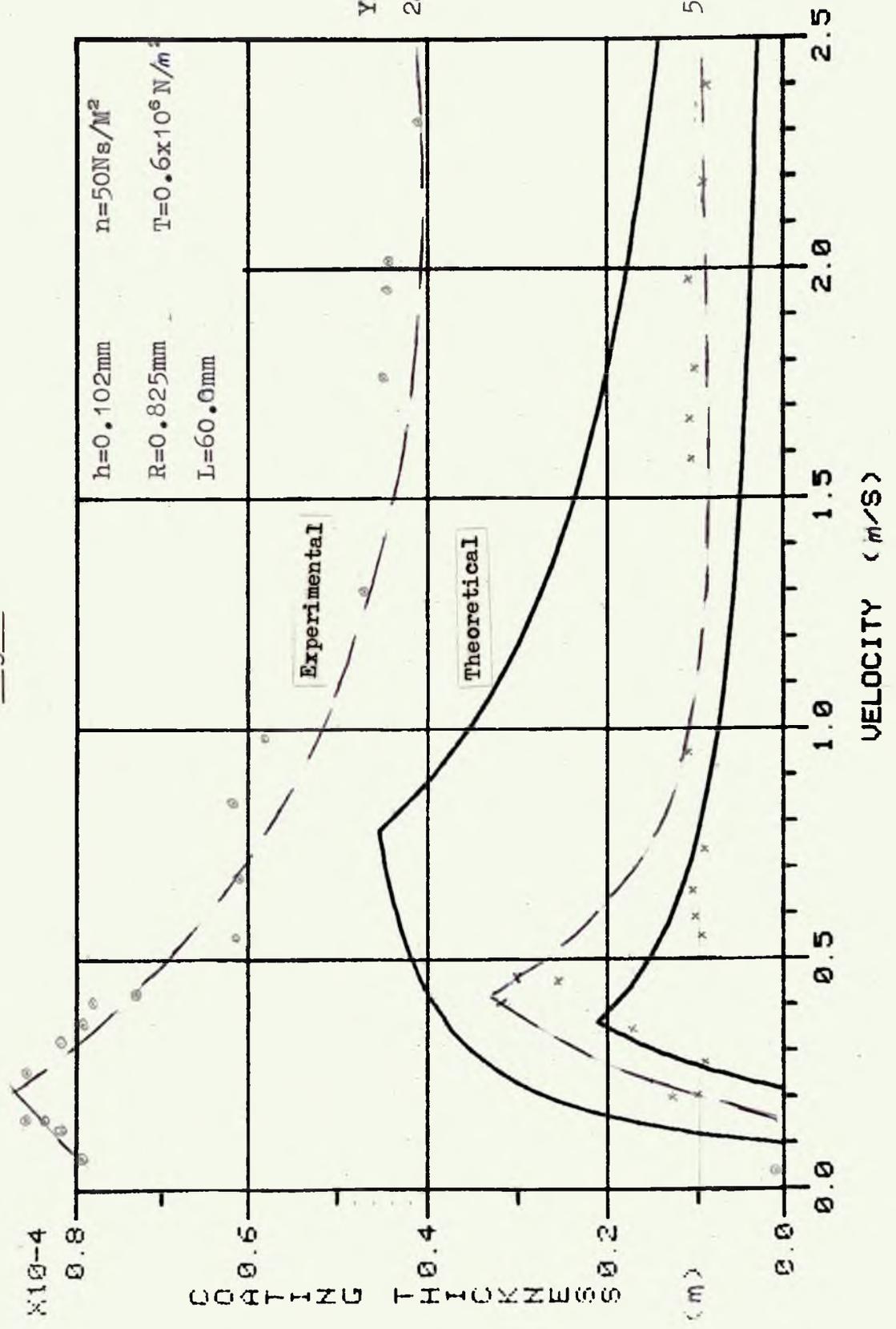
THEORETICAL GRAPH SHOWING THE EFFECT ON COATING THICKNESS

OF CHANGING YIELD STRESS OF WIRE

Fig 15
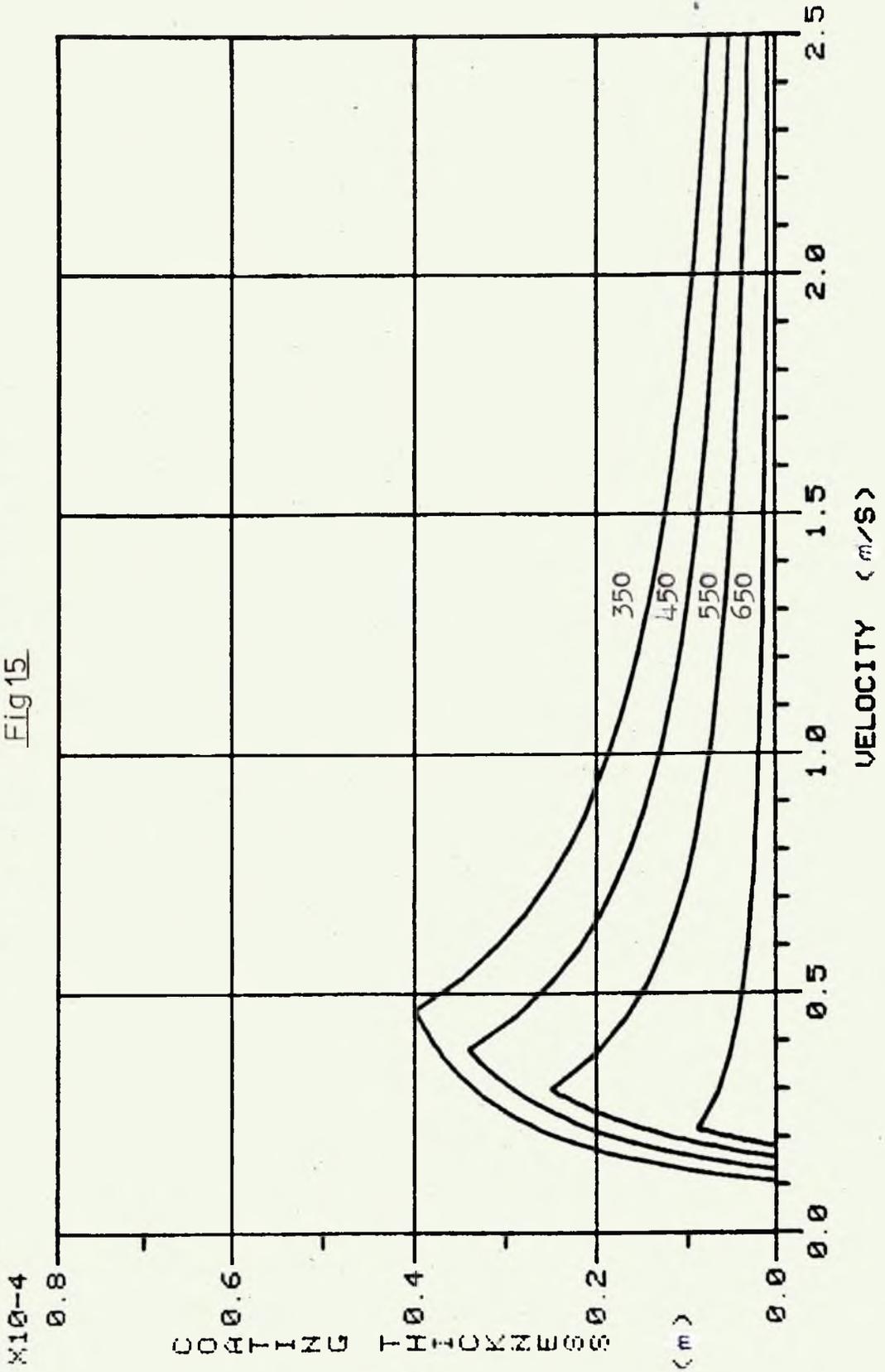
The higher yield stresses also reduced the region of laminar flow by both increasing the velocity at which flow occurred and reducing the velocity at which the critical shear stress required in the polymer was reached.

The experimental results support the theoretical predictions with regard to the reduction of coating thickness with increasing yield stress, especially when it is noted that no coating was achieved with wires of yield stresses greater than 800 N/mm^2.

5.03 The Effect on Coating Thickness of Changing Gap

Figs. 16 and 17 show the theoretical predictions and experimental results when the gap between the wire and the Christopherson tube was changed with everything else remaining constant. The theory predicts that an increase in gap will give, in the critical region, an increase in coating thickness. This is confirmed by the experimental results, although the theory underestimates the coating thickness achieved by as much as 50%. If, however, the length of the tube is kept constant and the gap is increased beyond 0.14 mm a maximum is reached and any further increase in gap reduces the coating thickness until no coating is possible.

Fig. 18 shows the maximum coating thickness, for a given wire strength and tube length, plotted against gap. The optimum gap is smaller than that which gives the maximum coating, because in this region the coating thickness is less sensitive to a change in gap. If the gap is chosen to give maximum coating thickness, then a slight increase in gap size, such as could be caused by a change in wire diameter within tolerance, could reduce the coating thickness drastically.

GRAPH SHOWING EXPERIMENTAL RESULTS AND THEORETICAL

PREDICTIONS FOR CHANGING GAP

Fig 16
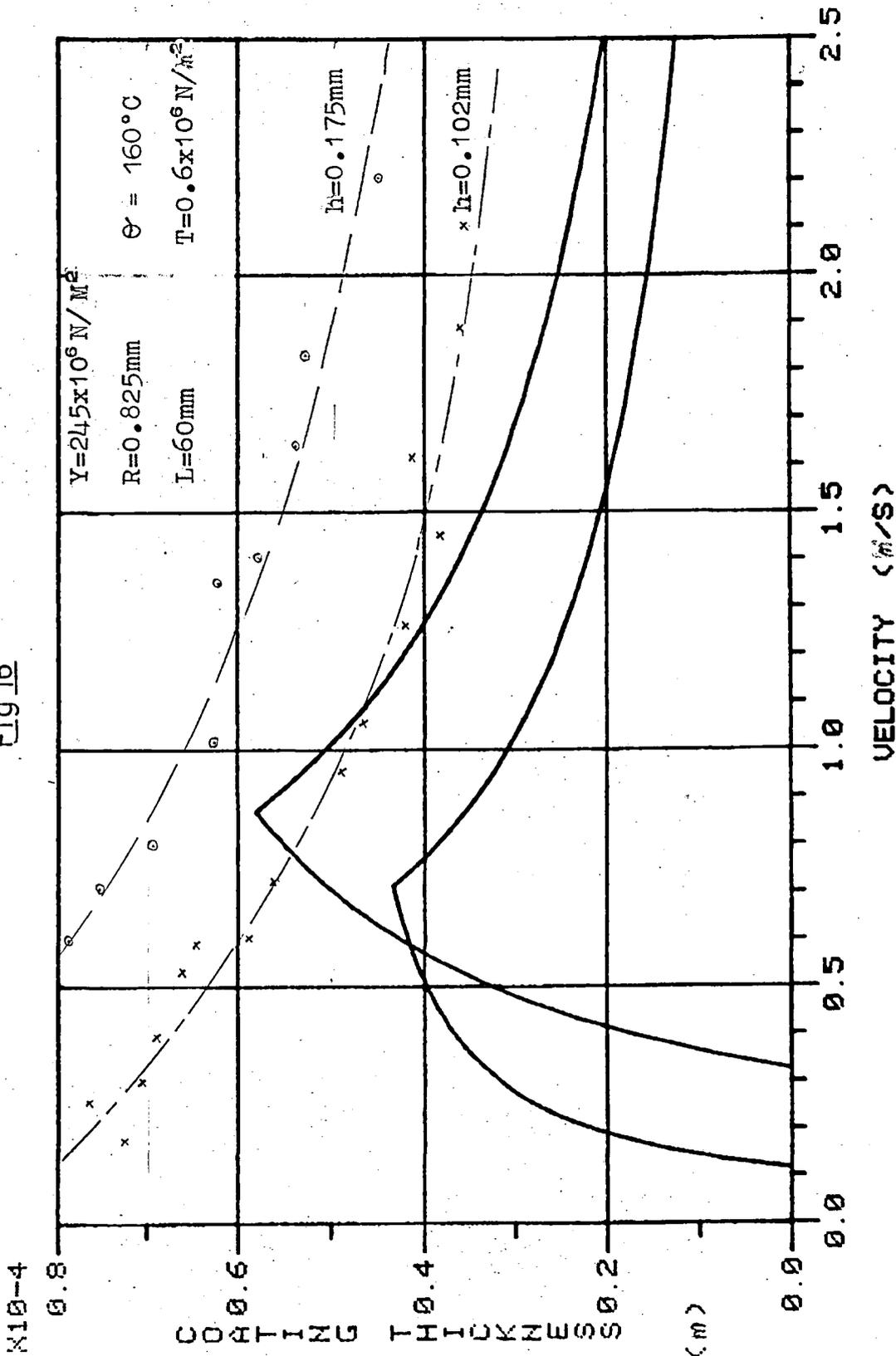
GRAPH SHOWING THE EFFECT ON COATING THICKNESS

OF CHANGING GAP

Fig 17
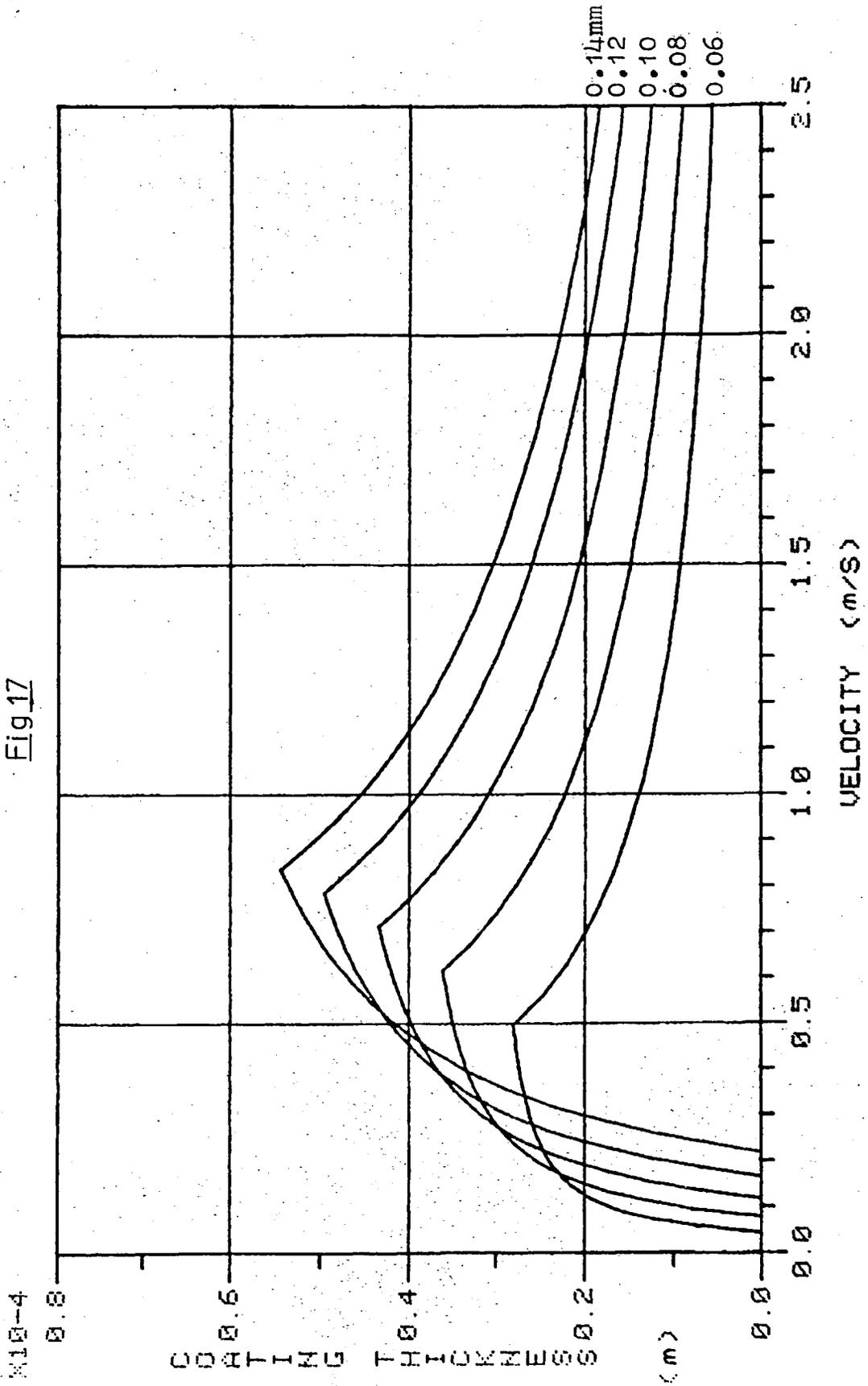
5.04 <u>The Effect on Coating Thickness of Changing Polymer Viscosity</u>

(Viscosity was assumed to be affected only by temperature when calculating the theoretical results but it is also affected by pressure and shear rate.)

The viscosity of a polymer is reduced as temperature rises and is described by the empirical formula

$$\eta = a\,e^{-b\,\theta}$$

where θ = absolute temperature

and a & b are material constants

For a polyethylene such as WVG 23 a rise in temperature of 80°C will reduce it's viscosity by 60%.

Viscosity increases with increasing pressure. For example Westover found that by raising the pressure of a polymer from 13 MN/m^2 to 172 MN/m^2, the viscosity of a polymer can be increased by a factor of between 5 and 100 depending on the molecular weight of the polymer. The higher the molecular weight, the greater the increase in viscosity. WVG 23, the polymer used in the tests, has a relatively low molecular weight, but the pressure developed was in the order of 600 MN/M^2 so the viscosity magnification factor was probably in the region of 20 - 30.

The effects of shear stress on viscosity can be seen in Fig. 8. High shear stresses greatly reduce the viscosity of a polymer, so much so that without the effect of pressure the viscosity of WVG 23 at the shear rates would be of the order of 2 Ns/m^2.

GRAPH SHOWING COATING THICKNESS v GAP

Fig 18
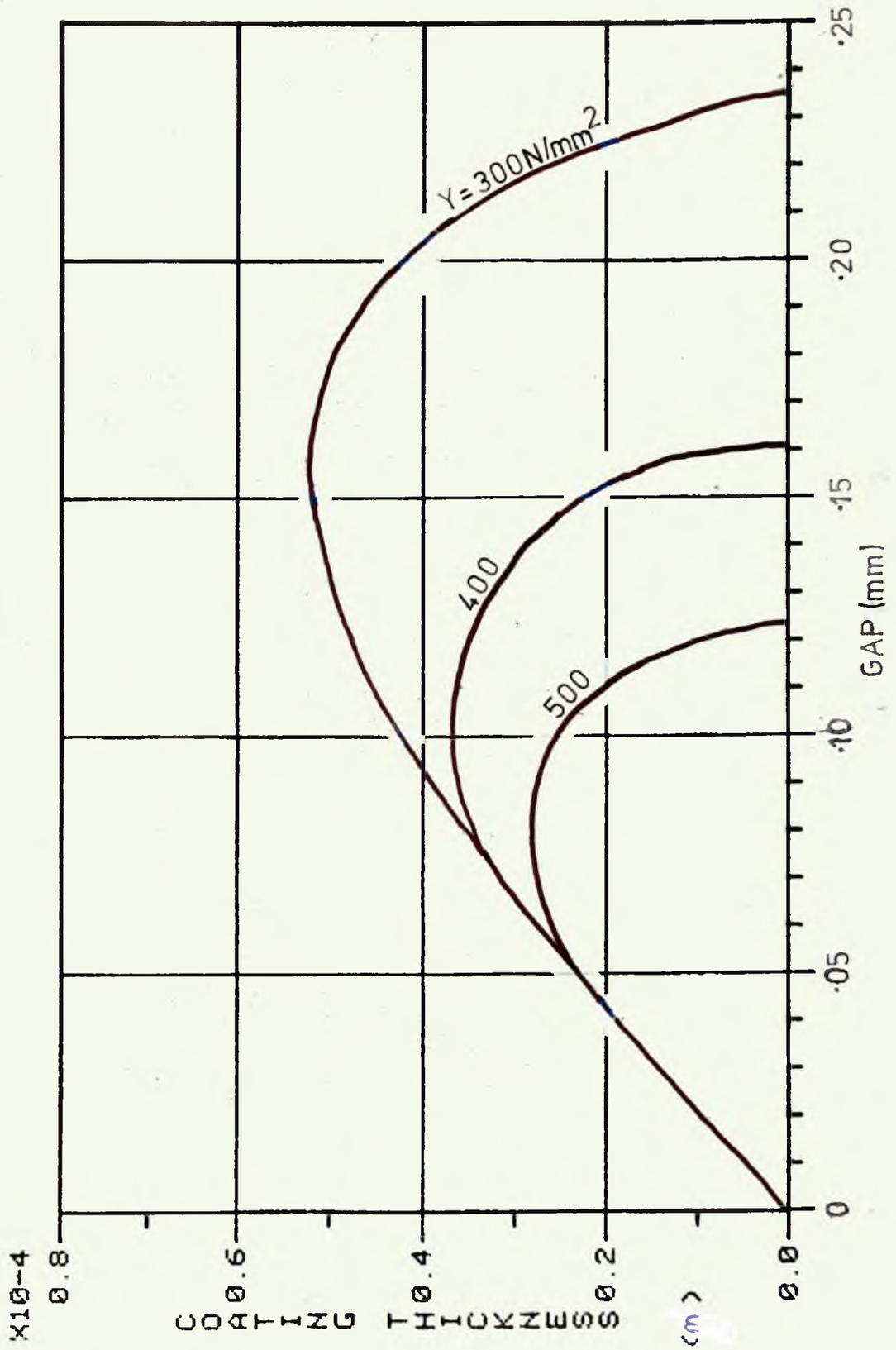
GRAPH SHOWING EXPERIMENTAL RESULTS FOR
CHANGING TEMPERATURE/VISCOSITY

Fig 19

$Y=245 \times 10^6 \, N/m^2$

$R=0.825mm$

$L=60.0mm$

$t \, °c$

135

160

180

VELOCITY (m/s)

COATING THICKNESS (m)
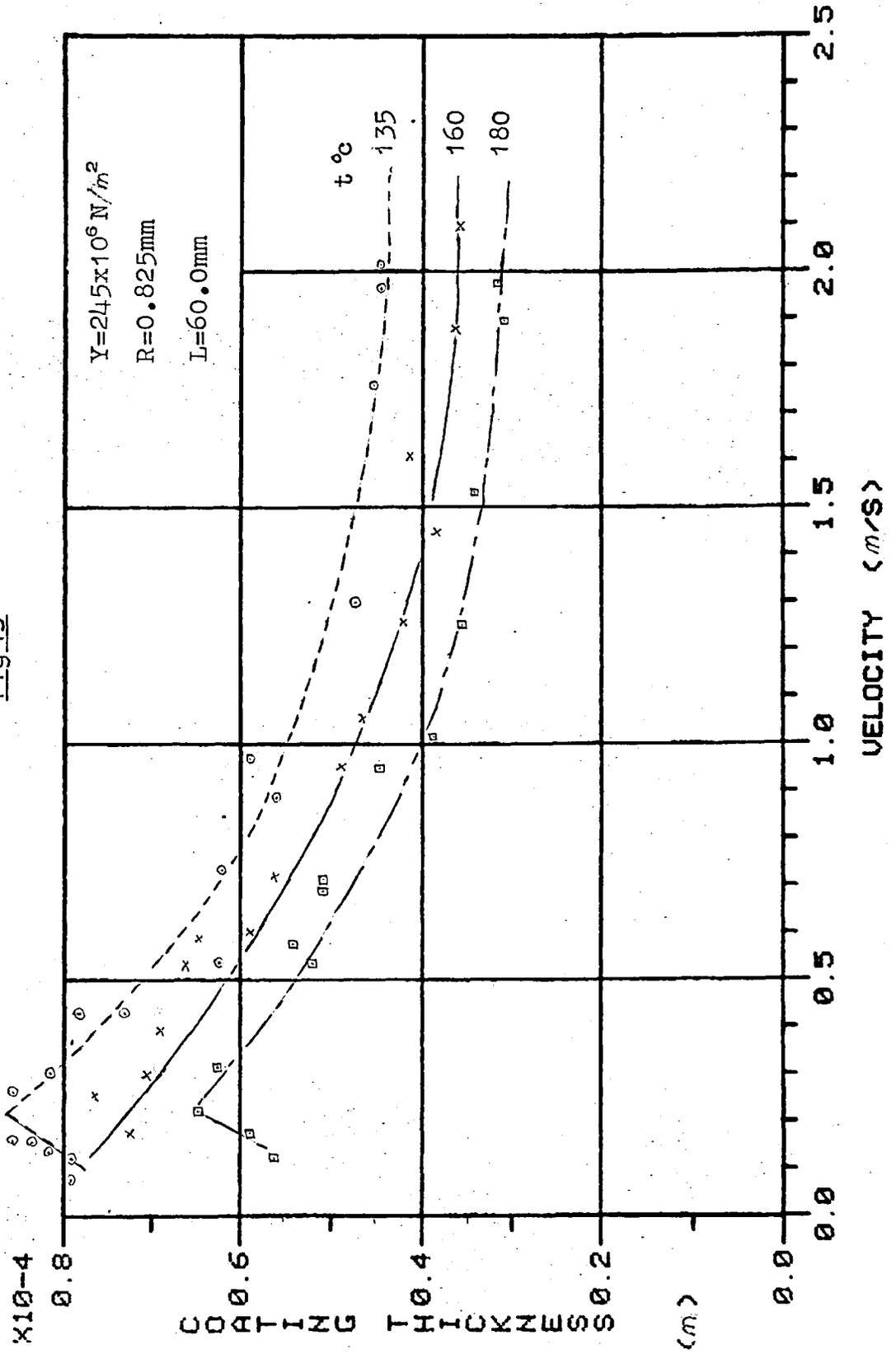
GRAPH SHOWING THE EFFECT ON COATING THICKNESS

OF CHANGING VISCOSITY

Fig 20
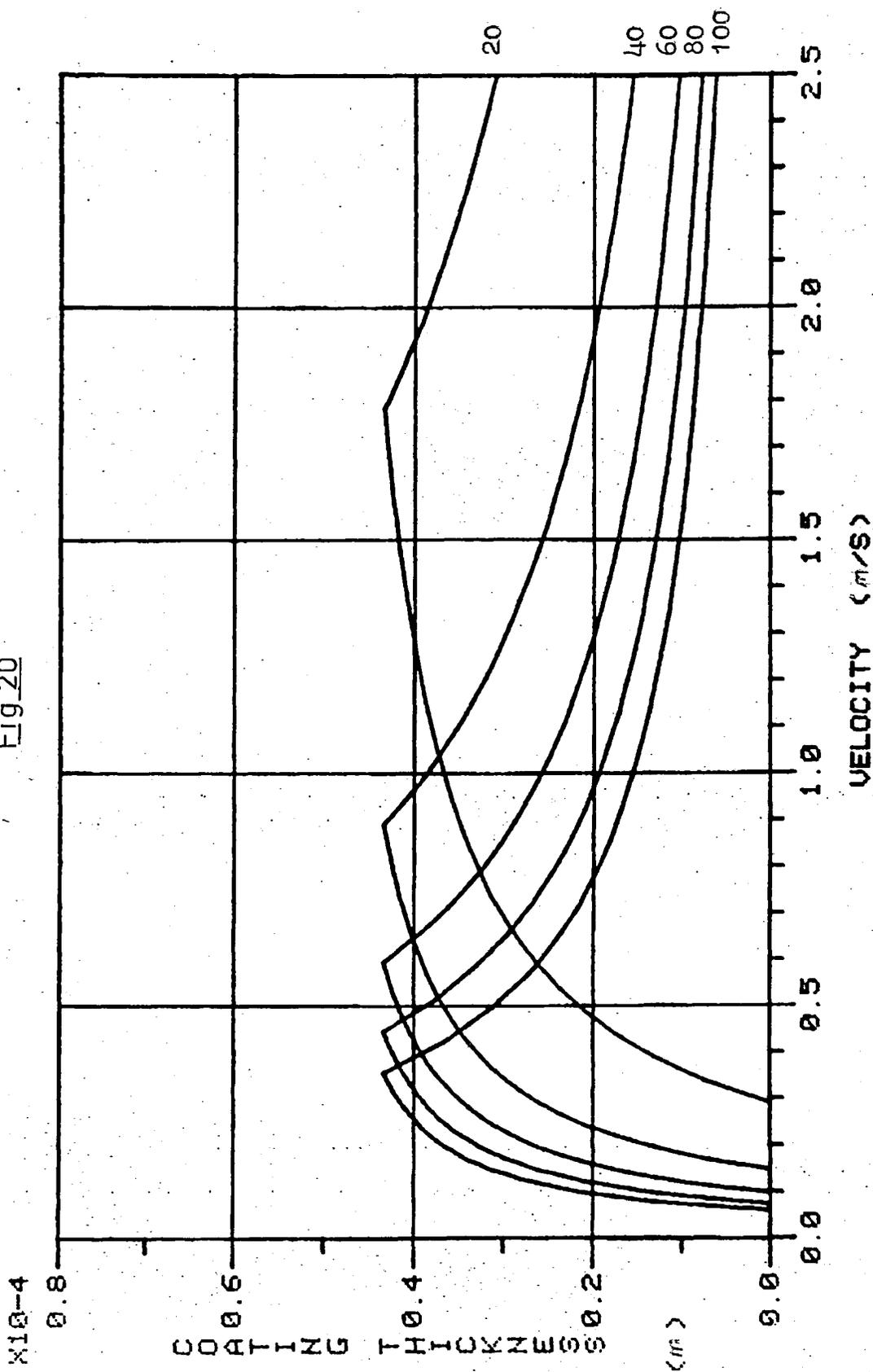
The effect of the three factors, described above, on the polymer used in the test cannot, therefore, be calculated accurately, but can only be estimated.

The theoretical predictions (Figs. 18 and 19) suggest that in the critical region of flow, the coating thickness should decrease as the viscosity of the polymer increases, but the experimental results appear to contradict this. However, the experimental results show only a small difference in coating thickness between 135°C and 180°C and considering the experimental error involved, approximately 13%, it is reasonable to suggest there was very little change. Theory predicts a small change in coating thickness with viscosity at high viscosities. As the pressure increases the viscosity by such a large factor, it is probable that the viscosity is much higher than the 50 Ns/m^2 used in the theoretical calculations and so would explain the apparent paradox. The hypothesis that the viscosity is much higher than assumed here is supported by the fact that the transition from no flow to critical flow is very rapid, which is predicted by the theory when the viscosity is high.

5.05 <u>The Effect on Coating Thickness of Changing Length</u>
<u>of Christopherson Tube</u>

Fig. 21 shows the effect of changing length of the Christopherson tube. It can be seen from a re-arrangement of equation 15 that for coating to occur

$$L = \frac{2\,h\,Y}{3\,Tc\,(1 + \frac{4}{3}\frac{h}{R})}$$

GRAPH SHOWING THE EFFECT ON COATING THICKNESS

OF CHANGING TUBE LENGTH

Fig 21
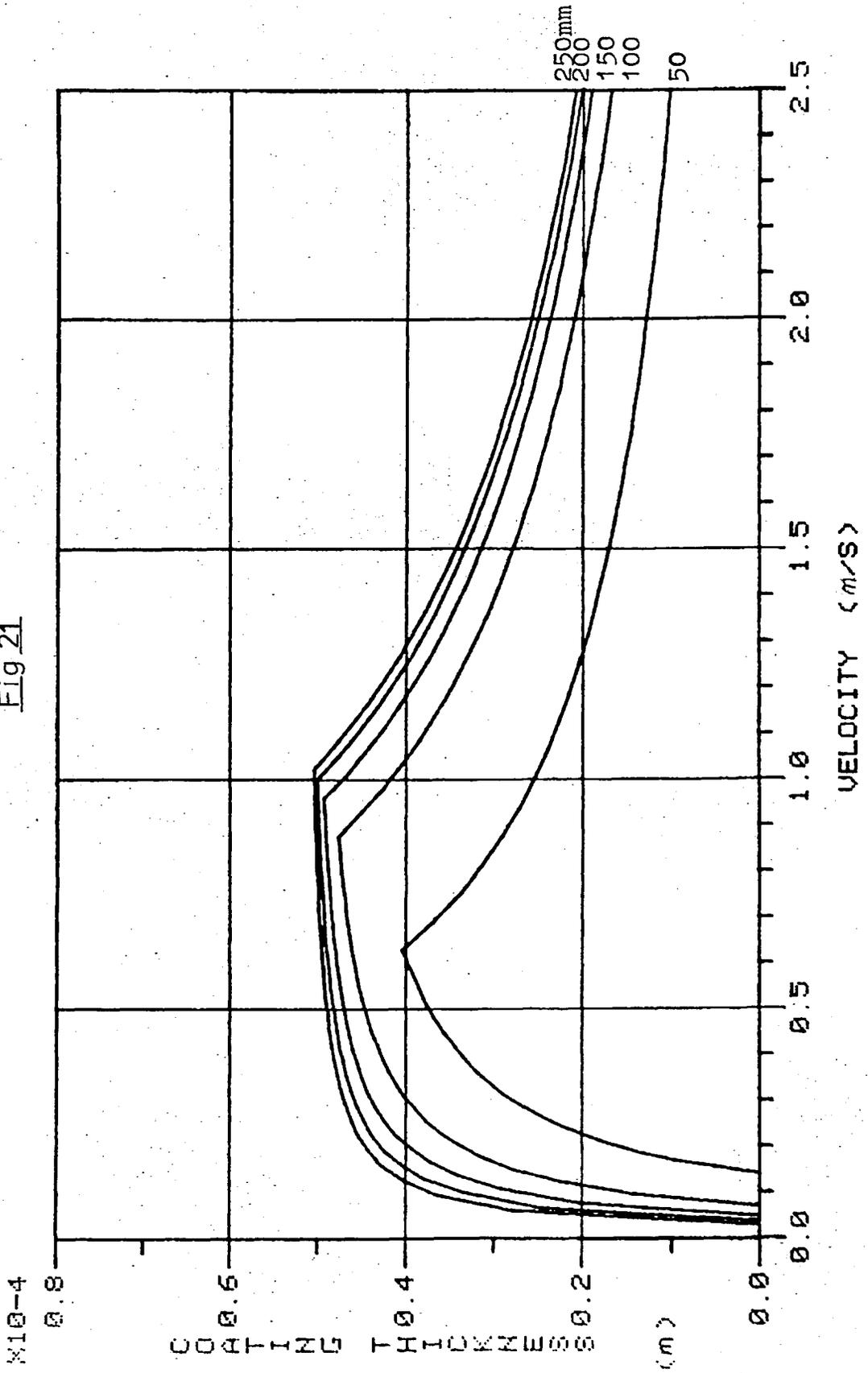
For the parameters used to produce Fig. 21 the minimum length required to produce a coating is 24 mm. Therefore the line showing the results when a 50 mm tube was used is approximately twice the minimum tube length required to allow coating. This length of tube generates an adequate coating but any further increase produces very little return in terms of an increase in coating thickness. For example a five fold increase in tube length only produces a 25% increase in coating thickness at the critical point. It would appear, therefore, that the optimum tube length is approximately twice the minimum length which will produce a coating. It should be noted at this point that the minimum, and hence the optimum tube length required, is increased as gap between the wire and the tube is increased. Therefore a balance must be struck between the gap size and the tube length. This will be discussed later when the design of Christopherson tubes is considered.

5.06 The Effect of Coating Thickness of Changing Critical
     Shear Stress of Polymer

Fig. 22 shows the effect on coat thickness of changing the critical shear stress of a polymer. Increasing the critical shear stress of the polymer has the effect of prolonging the sub-critical region, and so increases the coating thickness in the critical region. A polymer with a high critical shear stress allows wire of a high yield stress to be drawn, because this allows the greater flow stress to be achieved before slip occurs.

The critical shear stress is affected by the molecular weight of the polymer, as discussed in the introduction.

GRAPH SHOWING THE EFFECT ON COATING THICKNESS

OF CHANGING CRITICAL SHEAR STRESS

Fig 22
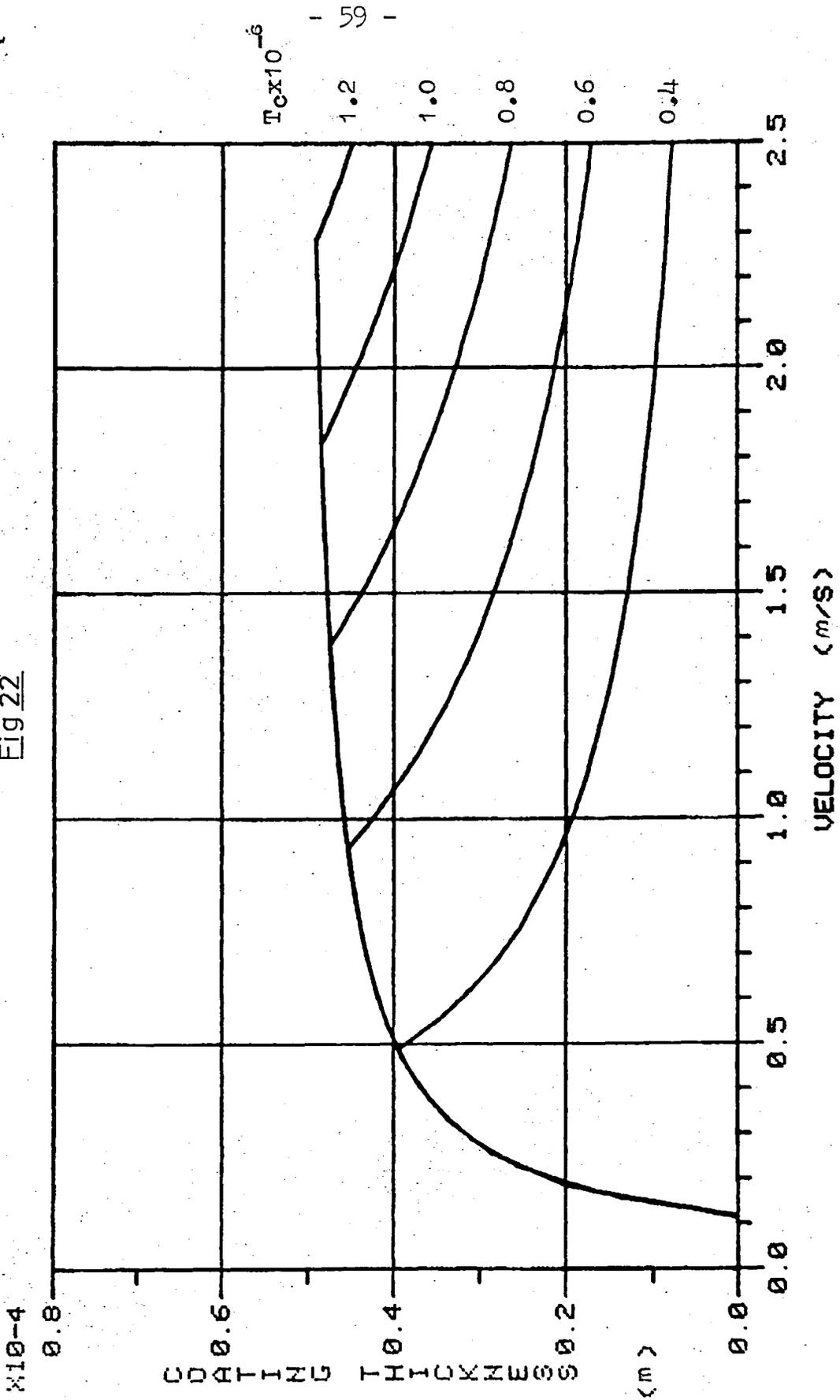
GRAPH SHOWING THE EFFECT ON COATING THICKNESS

OF CHANGING WIRE DIAMETER
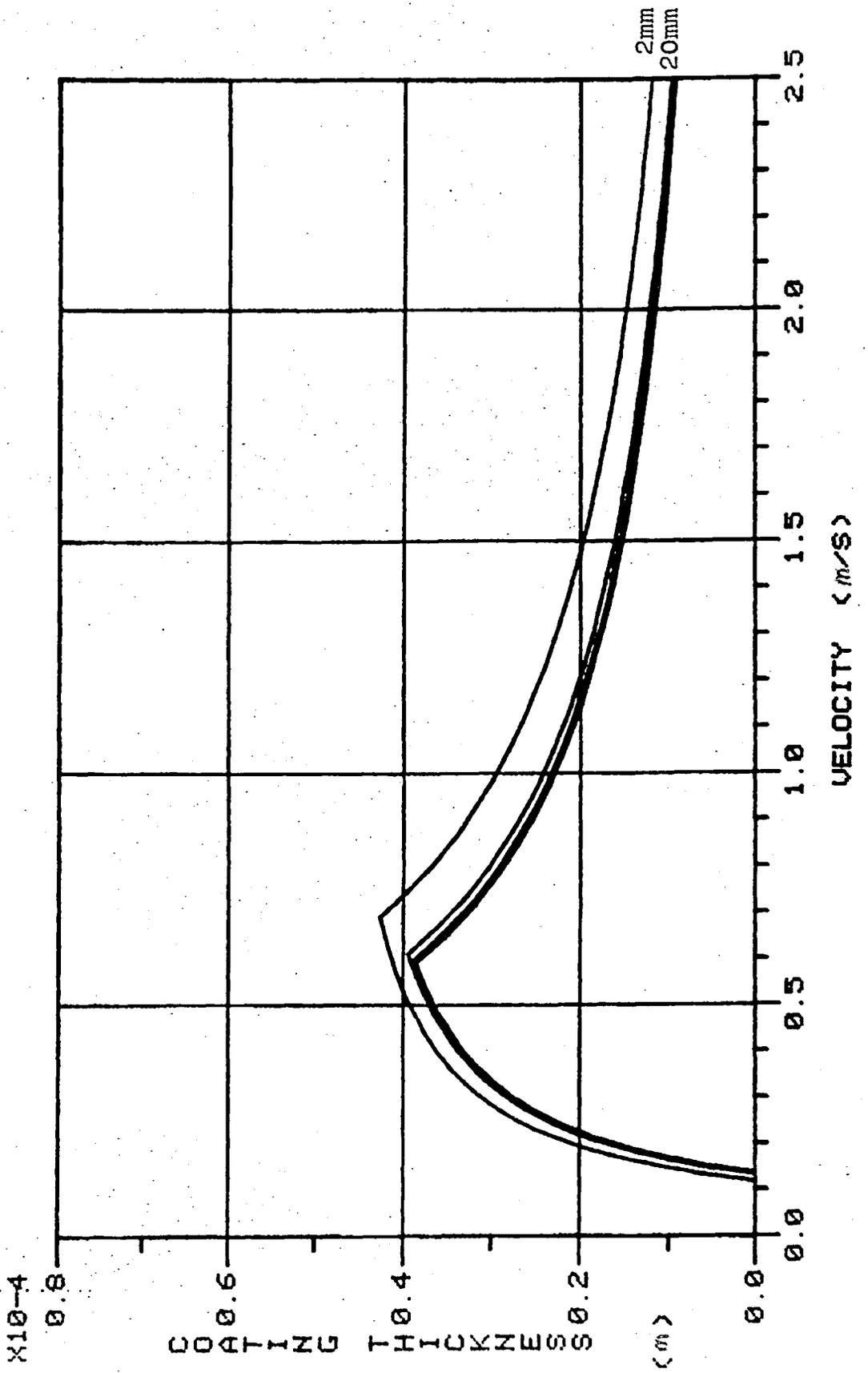
Fig 23

The higher the molecular weight of the polymer, the lower its critical shear stress. The critical shear stress for most polymers lie in the region of 0.4 to 1.0 x 10^6 N/m^2.

5.07 <u>The Effect on Coating Thickness of Changing Wire</u>

   <u>Diameter</u>

Fig. 23 shows the effect of changing the wire diameter was very small and so this process should be equally successful on wire of any diameter. The only limits on the diameter result from

a) The wider tolerances found on larger diameter wires

b) The length of tube which can be achieved when using small diameter wire because of the high depth to diameter ratio required in the Chrsitopherson tube.

CHAPTER VI

6. SUMMARY

6.01 Estimation of Errors

The experimental errors arise from the slight in-
accuracies in the measurement of the many variables upon
which the coating thickness is dependent. It will be shown
that the error in measuring the gap between the wire and the
Christopherson tube and the estimation of the critical
shear stress of the polymer are the dominant factors in the
overall error.

When calculating the experimental errors, 'typical
average' values of the variables will be used.

The tolerance of the wire diameter as given in BS
was $\pm$ 0.0125 mm (0.005") and a similar tolerance was assumed
for the bore of the Chrsitopherson tube giving an error of
8.7% on a nominal radial clearance of 0.1 mm.

The yield stress of the wire used was measured as
described earlier with an estimated error of $\pm$ 5 N/mm^2 or
approximately $\pm$ 2%.

The drawing speed was measured using a tachogenerator
and a digital voltmeter. From the suppliers specification
an error of $\pm$ 2% was estimated. The error in the measurement
of the length of the tube was very small, in the order of
0.1%.

The critical shear stress of the polymer used was
estimated, from the extrusion rheometer tests described
earlier, to be 0.6 x 10^6 N/m^2, $\pm$ 8%.

It was not possible to measure the viscosity of the
polymer at the pressures generated by the system. The value

used in the calculations was chosen arbiterily and so it is impossible to asign an error to this variable.

The equation predicting coating thickness has 3 terms

$$CT = \frac{hT}{2\eta V} - \frac{Yh^2}{3L} + \frac{2hT}{3Vr}$$

Let $A = \dfrac{hT}{2\eta V}$

then $\dfrac{\delta A}{A} = \dfrac{\delta h}{h} + \dfrac{\delta T}{T} - \dfrac{\delta \eta}{\eta} - \dfrac{\delta v}{V}$

hence percentage error = 12%

Let $B = \dfrac{Yh^2}{3L}$

$$\frac{\delta B}{B} = \frac{\delta Y}{Y} + \frac{2\delta h}{h} - \frac{\delta L}{L}$$

hence % error = 17.5%

Let $C = \dfrac{2h^2 T}{3nVR}$

$$\frac{\delta c}{c} = \frac{2\delta h}{h} + \frac{\delta T}{T} - \frac{\delta \eta}{\eta} - \frac{\delta v}{V} - \frac{\delta R}{R}$$

hence percentage error = 19.28%

To find total percentage error using 'typical average' values

$$E = \sqrt{(1 \times 12)^2 + (0.26 \times 17.5)^2 + (0.16 \times 19.28)^2}$$

$\therefore$ Total error $\pm 13\%$

It can be seen from the above calculations that the low degree of accuracy achieved in this experiment is due to the problems associated with maintaining the small gap between the wire and the Christopherson tube constant. It would however be difficult to improve on the accuracy as the gap is dependent on the wire diameter and the tube bore. The wire diameter is only limited to $\pm$ 0.0125 mm ($\pm$ .0005") and the hole drilled to create the Christopherson tube is 60 mm long and less than 2 mm diameter and so is difficult to control in manufacture.

6.02 <u>Rationalisation of Theoretical Equations to Facilitate</u>
<u>the Design of a Christopherson Tube</u>

Design of a Chrsitopherson Tube can be a long involved process because of the problems caused by parameters being interdependent. But, if certain simplifications are made then the design procedure can be shortened greatly. These simplifications are the result of the following observations:

1) The diameter of the wire has very little effect on the coating thickness and can be ignored. (See Fig. 23)

2) Provided the length of the tube is more than twice the minimum length required the actual magnitude does not greatly effect the coating thickness (See Fig. 21).

3) The optimum length is approximately equal to twice the minimum length. At this optimum length the gap can change slightly (i.e. due to a change in wire diameter) without a drastic change in coating thickness.

4) Most polymers have a critical shear stress in the order of 0.6×10^6 N/m^2. If a polymer has a significantly different critical shear stress, then this can be

accommodated by a simple multiplication factor when the
final length has been calculated. (A polymer with a
lower critical shear stress will require a longer tube).

5)   The minimum radial gap of practical use is 0.05 mm. If
a smaller gap is used the wire tolerance becomes signifi-
cant. Generally speaking a larger gap is preferred
provided the length of tube required can be accommodated.

6)   The length of tube is limited when drawing small diameter
wire by the ratio of tube length to diameter which can
be achieved when drilling the Christopherson tube.

Using the assumptions stated above and rearranging
equation 15 and substituting

$$L_{OPT} = 2 L_{MIN}$$

The quation becomes

$$L_{OPT} = \frac{4 h Y}{3 Tc \left(1 + \frac{4}{3} \frac{h}{R}\right)}$$

This is shown graphically in Fig. 24.

Suggested Design Procedure

1)   Estimate the maximum length of tube which can be used.
This is limited by

a) The space available in the die unit.

b) The length of hole which can be drilled at the diameter
required

2)   From Fig. 24 read off the gap required using the length
calculated in (1) and the yield stress of the wire to be
drawn.
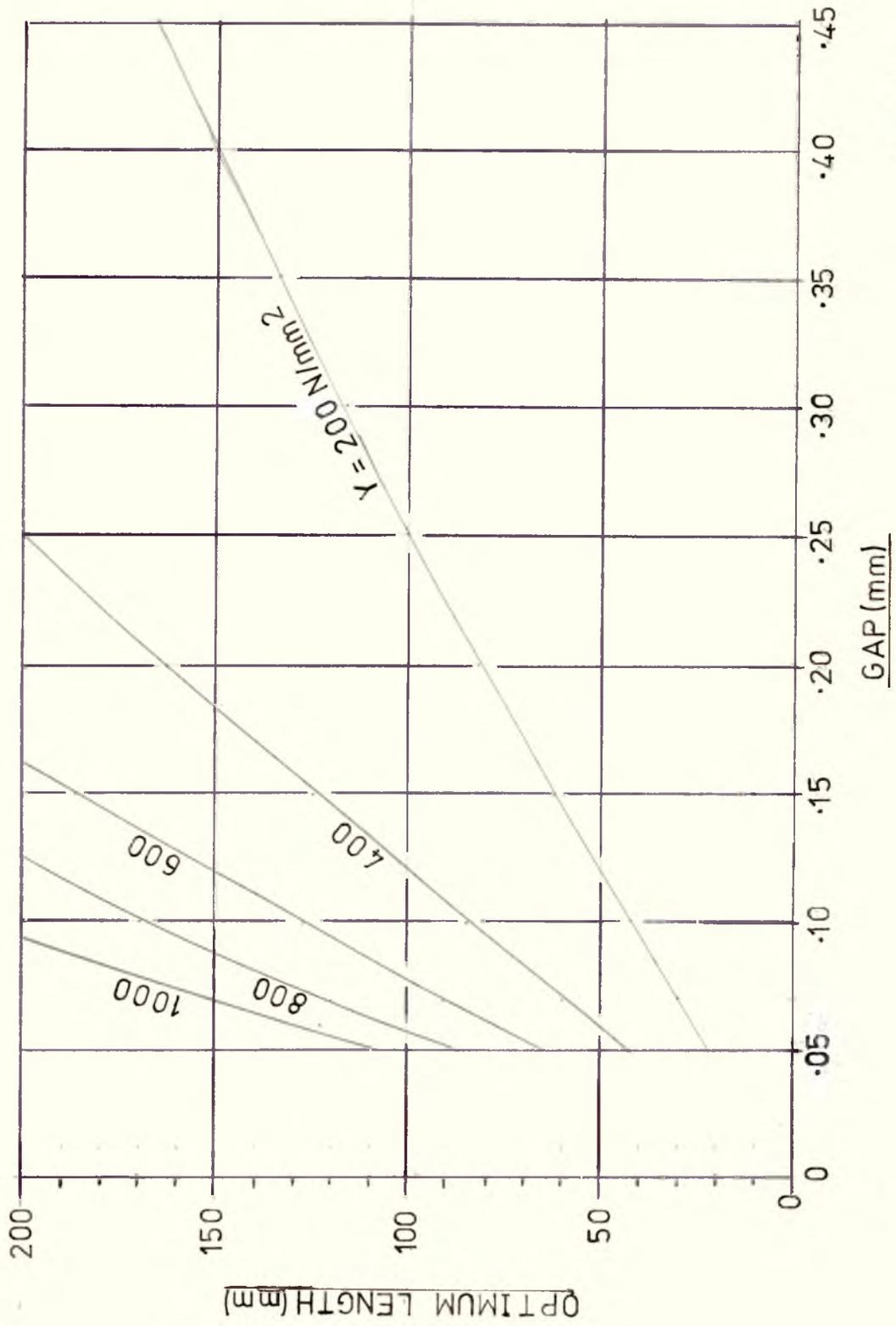
Fig 24

GRAPH SHOWING COATING THICKNESS v VELOCITY

CHOSEN DESIGN PARAMETERS
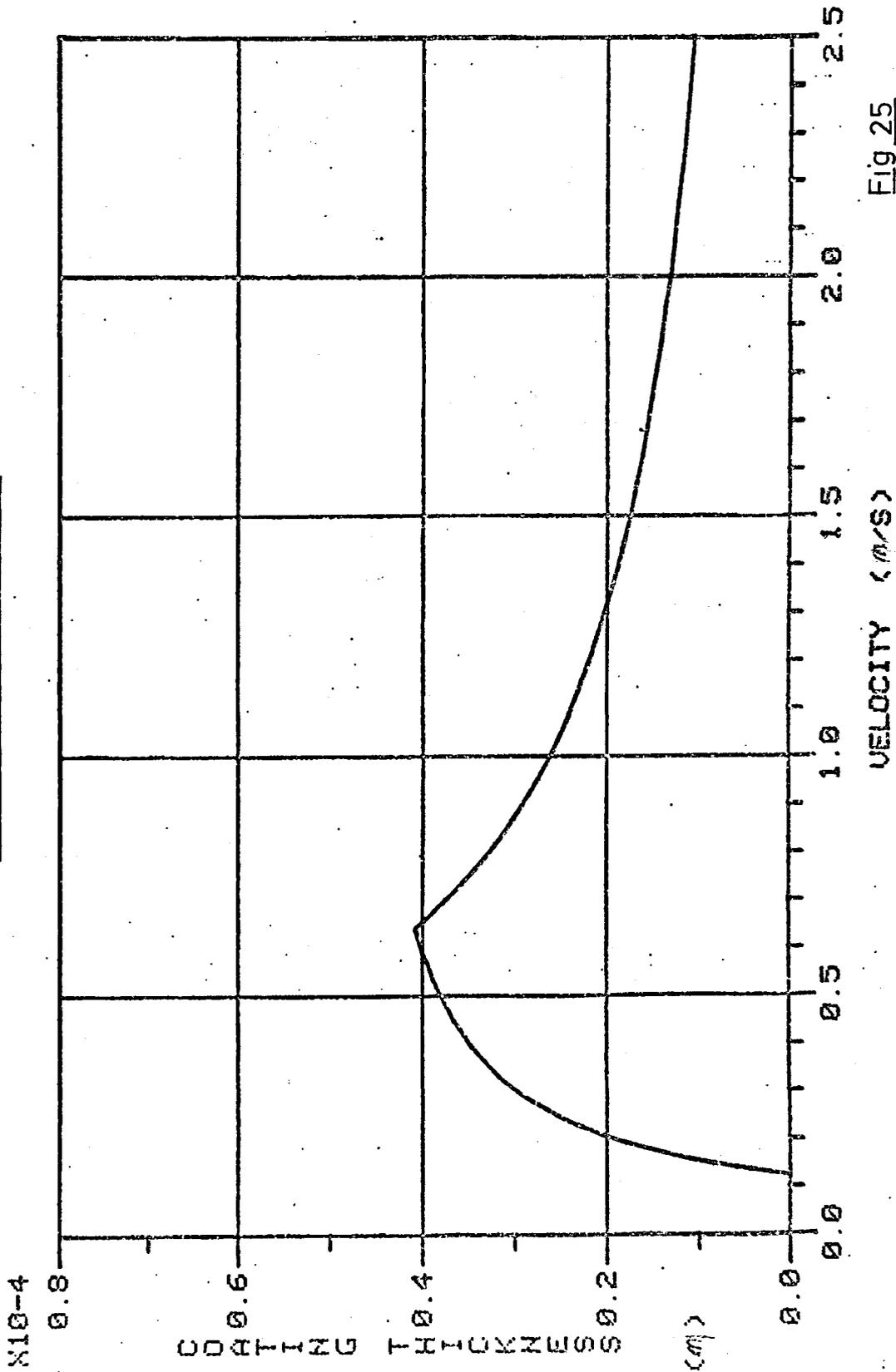
Fig 25

3)   Check the parameters chosen by plotting the coating
      thickness v velocity characteristics using Equation 16 -

<u>Example</u>

  Wire to be drawn

$$Y = 600 \text{ N/mm}^2$$

$$D = 6 \text{ mm}$$

Maximum $\dfrac{L}{D}$ 20:1

∴ 1) Maximum length = 120 mm (assuming no space
   restriction)

  2) From Fig. 24 gap required = 0.09 mm

  3) Fig. 25 shows plot of coat thickness v velocity
   for parameters chosen.

6.03 <u>Discussion</u>

After initial problems with sealing the Christopherson
tube to the die and attempting to draw wire with a yield stress
too high for the tube configuration used, the experimental
apparatus operated very successfully. It was found that the
heat treatment of the copper seal required for both complete
sealing and maximum life was dependent on the wire being drawn.
The harder the wire being drawn, the harder the seal needed
to be.

It can be seen from the discussion of experimental
errors, the greatest error arises from the estimation of the
gap between the wire and the Christopherson tube. As this
is dependent on the wire diameter, it is almost impossible to
estimate, unless wire with a very close tolerance is drawn
especially for the tests.

The other unknowns in the tests are the viscosity of the polymer, taking into account temperature, shear rate and the pressure generated at the end of the Christopherson tube.

The pressure can be measured when the material being drawn has a relatively low yield stress, such as copper, but when higher yield stress material is drawn then it is not possible to obtain a transducer to withstand such a pressure.

The effect on viscosity of changing temperature and shear rate was measured, see Fig. 8, although this was not used when calculating the theoretical prediction. If this were to be included, it would have the effect of reducing the range of the sub-critical flow because of the much higher viscosities at the lower shear rates, which the practical results suggest.

Experimental work on the viscosity of polymers suggest that the extremely high pressure developed in the tube is the dominant factor in determining the viscosity of the polymer, although to check this would require the use of a double piston rheometer (Westover 13).

Although the tests show it to be possible to lubricate and coat the wire, the coating produced was poorly adhered to the wire. The adherence was improved slightly when the wire was heated before drawing, but this reduced the coating thickness. Heating the wire would not be acceptable in industry where research is directed towards keeping the wire cool. The only way open appears to be investigation into the possibilities of applying a 'keying' agent in the same way as soap is 'keyed' to the wire. As the critical shear stress of the polymer/wire boundary is affected by the surface properties

of the wire, it is possible that such a coating could increase the critical shear stress and so make the system more versatile.

The theoretical predictions in general, underestimate the coating thickness by about 20%, this can be partly explained by the experimental error. The remainder is probably due to the arbitary choice of a fixed value for the polymer viscosity, when in fact the viscosity changes constantly as described earlier.

The 'fishscale' coating is an interesting phenomena which can only be partially explained. The effects are caused by the pulsating flow of the melt through the die, induced by stick-slip motion of the melt in the Christopherson tube. This is probably caused by a periodic variation on the degree of slip, (melt fracture) initiated at the inlet to the Christopherson tube. It is not possible to determine if this is the case, but from the similarity in appearance of the defective coat to defects occurring in other polymer melt processes, see Ref. 13, melt fracture appears to be the likely cause. When the defect occurs a corresponding variation in the wire diameter is observed, particularly with the softer copper wire (see Fig. 11).

At higher drawing speeds the coating becomes smooth again. A similar effect was noted by Du Ponts but no explanation was offered. This effect could be caused by the polymer slipping completely at the higher shear rate.

The lengths of wire drawn in these tests were very short by industrial standards and so it was not possible to check the thermal stability of the system. If long runs are to be tested,

then improvements must be made to the polymer feed system and methods used in the injection moulding industry should be considered.

6.04 Conclusions

The work undertaken has demonstrated that it is possible to lubricate and coat wire using a polymer melt during drawing. The limits of the relevant parameters have been defined.

The polymer coatings were not sufficiently well adhered to lubricate a further reduction of the wire

A theory has been developed to predict the coating thickness of the polymer on the wire incorporating the phenomenon of critical shear stress and assuming a constant polymer viscosity.

The theory underestimates the coating thickness which is produced but, nevertheless, provides a method of optimising the Christopherson tube dimensions.

The polymer coating is uneven at speeds slightly above the critical speed. This 'bambooing' or fishscaling is probably due to melt fracture of the polymer.

6.05 Further Work

Although it has been shown that wire can be lubricated and coated during the drawing process and the theory outlined in this study gives a reasonable estimate of the coating thickness achieved both the theory and the practical problems require further development.

The polym   coatings obtained have not been well adhered to the wire sufficiently to lubricate   Further reduction of the wire.

The present theory assumes a constant viscosity whereas in practice this is affected by shear rate, temperature and pressure. Refinements of the theory in these areas should be useful.

From the practical application side of the research, the biggest problem appears to be lack of bonding between the polymer and the wire and a study of the mechanism of bonding between metals and polymers should be made.

If polymer lubrication is to be used commercially, the feed mechanism of the polymer will have to be developed, possibly employing the screw system, at present used on injection moulding machines. In an industrial situation, the thermal stability of the system will become important and must be understood. If these problems can be overcome the polymer lubrication of wire drawing could become commercially viable.

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COMPUTER PROGRAM TO GENERATE THEORETICAL PREDICTIONS

Fig 26

```
/LOAD VSBASIC
10 PRINT 'GAP','WIRE RAD','YIELD'
20 INPUT H,R,Y
30 PRINT 'LENGTH','TORR CRIT','VISCOSITY'
40 INPUT L,T2,N
50 T1=(2*H*Y)/(3*L*(1+(4*H)/(3*R)))
60 IF T1>T2 GOTO 500
70 V1=(2*L*H*T1*(1+H/R)-H**2*Y)/(2*N*L)
90 V2=(2*L*H*T2*(1+H/R)-H**2*Y)/(2*N*L)
100 PRINT'V FLOW','V CRIT'
110 PRINT V1,V2
120 PRINT 'VELOCITY','COAT THICKNESS','TORR'
130 V=V1
140 V=V+(V2-V1)/5.0
150 T=(H**2*Y+2*N*V*L)/(2*L*H*(1+H/R))
160 C=(H**2/(N*V))*(T/2-(Y*H)/(3*L)+(2*H*T)/(3*R))
170 PRINT V,C,T
180 IF V<(V2-0.001)GOTO 140
190 T=T2
200 V=V+0.2
210 IF V<(V2*3) GOTO 160
220 GOTO 999
490 PRINT T1
500 PRINT 'NO COATING POSSIBLE'
999 END
*END
```

COMPUTER PROGRAM TO GENERATE DATA

FOR GRAPHICAL DISPLAY

Fig 27

```
//LIST OPEN
*TO PROGRESS
/SYS TIME=40X
/FILE ITSK=(1,C305SZ%%,REC=11),FSIZ=234,VOL=405ICS,IISP=(NEW,KEEP)
//DAT FORTO1
      DEFINE FILE 1(11,280,L,I1)
      CALL XGCON
      REAL LVAR
      DIMENSION KEND(5)
      COMMON
     1/DATLET/G,D,R,T,Y,V,E
     1/VARLE/VEL(70),COAT(70)
     1/DATIN/GVAR,LVAR,RVAR,TVAR,YVAR,VVAR
     1/VMISC/KFIN,T1,IERR
      READ(5,19) G,D,R,T,Y,V,E
      JFIN=0
      WRITE(6,20)
100   JFIN=JFIN+1
      DO 21 J=1,6
      READ(9,22) VAR,VARNUM
22    FORMAT(A1,G12.0)
      CALL SELEC1(VAR,VARNUM)
      IF(IERR.EQ.1) J=J-1
      IF(JFIN.EQ.1) GO TO 21
      IF(VAR.EQ.E) J=6
21    CONTINUE
      WRITE(6,23) GVAR,LVAR,RVAR,TVAR,YVAR,VVAR
      CALL DATGEN
      IF(T1.GT.TVAR) GO TO 501
      KPFIN=3*((KFIN-1)/3)
      WRITE(6,11) (VEL(I),I=1,KPFIN,3)
      WRITE(6,11) (COAT(I),I=1,KPFIN,3)
      WRITE(6,41)
      READ(9,40) IGO
      IF(IGO.EQ.1) GO TO 500
      JFIN2=JFIN*2
      JFN2P1=JFIN2+1
      WRITE(1'JFIN2) (VEL(I),I=1,KFIN)
      WRITE(1'JFN2P1) (COAT(I),I=1,KFIN)
      KEND(JFIN)=KFIN
      IF(JFIN.LT.5) GO TO 501
      WRITE(6,301)
      GO TO 999
500   JFIN=JFIN-1
501   WRITE(6,302)
      READ(9,40) IAG
      IF(IAG.EQ.0) GO TO 999
      WRITE(6,300)
      GO TO 100
999   CONTINUE
      WRITE(1'1) JFIN,(KEND(I),I=1,JFIN)
      STOP
```

Fig 27 cont

```
C       FORMAT STATEMENTS
  20 FORMAT(23X,'PARAMETER IDENTIFIERS'/10X,'GAP',
     114X,'G',12X,'LENGTH',11X,'L',/10X,'WIRE RADIUS',
     2/6X,'R',12X,'TORR CRIT',3X,'T'/10X,'YIELD',
     312X,'Y',12X,'VISCOSITY',3X,'V'///' TO INPUT ',
     4'TYPE THE PARAMETER IDENTIFIER FOLLOWED BY ',
     5'THE VALUE.'/' A TYPICAL INPUT IS AS FOLLOWS:'
     6/' ?'/' L   0.6E-1'/' ?'/' G0.102E-4'/' (',
     7'INPUT IS IN FREE-FORMAT)'//' INPUT VALUES'/)
  11 FORMAT(1PE12.4)
 301 FORMAT(' YOUR DATA FILE IS FULL! EXECUTION ENDS')
 302 FORMAT(' TYPE 0 TO END DATA GENERATION. TYPE 1 TO CONTINUE')
 300 FORMAT(' INPUT YOUR VARIABLES. TO END TYPE ''E''.')
  41 FORMAT(//' IF YOU WANT THIS DATA SET STORED TYPE 0'/
     1' TYPE 1 TO CHANGE PARAMETERS AND RECALCULATE (DATA NOT',
     2' STORED)'/' CLEAR THE SCREEN IF ON GRAPHICS TERMINAL')
  19 FORMAT(7A1)
  23 FORMAT(//21X,'GAP =',10X,1PE12.6/21X,
     1'LENGTH =',7X,1PE12.6/21X,'WIRE RADIUS',
     2' =',8X,1PE12.6/21X,'TORR CRIT =',4X,
     31PE12.6/21X,'YIELD =',8X,1PE12.6/21X,'VISCOSITY',
     4' =',4X,1PE12.6//)
  40 FORMAT(I1)
     END



     SUBROUTINE DATGEN
     REAL LVAR
     COMMON
     1/VARTB/VEL(70),COAT(70)
     1/DATTN/GVAR,LVAR,RVAR,TVAR,YVAR,VVAR
     1/VMISC/KPTN,T1,IFRE
     T1=(2.*GVAR*YVAR)/(3.*LVAR*(1.+(4.*GVAR)/
     1(3.*RVAR)))
     IF(T1.GT.TVAR) GO TO 50
     V1=(2.*LVAR*GVAR*T1*(1.+GVAR/RVAR)-GVAR*GVAR*YVAR)
     1/(2.*VVAR*LVAR)
     V2=(2.*LVAR*GVAR*TVAR*(1.+GVAR/RVAR)-
     1GVAR*GVAR*YVAR)/(2.*VVAR*LVAR)
     WRITE(6,24) V1,V2
     I=1
     VEL(I)=V1
     COAT(I)=0.0
     UINC=(V2-V1)/30.0
 140 I=I+1
     VEL(I)=VEL(I-1)+UINC
     TORR=(GVAR*GVAR*YVAR+2.*VEL(I)*VVAR*LVAR)/
     2(2.*LVAR*GVAR*(1.+GVAR/RVAR))
     COAT(I)=(GVAR*GVAR/(VVAR*VEL(I)))*(TORR/2.-
     1(YVAR*GVAR)/(3.*LVAR)+(2.*GVAR*TORR)/(3.*LVAR))
     IF((V2-VEL(I)).GT.0.0001) GO TO 140
     TORR=TVAR
     INTI=I
     KK=INTI
     VINC=(2.5-VEL(INTI))/30.0
 160 KK=KK+1
     VEL(KK)=VEL(KK-1)+VINC
     COAT(KK)=(GVAR*GVAR/(VVAR*VEL(KK)))*(TORR/2.
     1-(YVAR*GVAR)/(3.*LVAR)+(2.*GVAR*TORR)/
```

Fig 27 cont

```
      CON.RETADD
      IF(VEL(KK).LT.F.5) GO TO 140
      KFIN=KK
      GO TO 100
 50   WRITE(6,25) T1
 25   FORMAT('   NO COATING POSSIBLE!'/'  T1 =',
     11PE12.6)
 24   FORMAT(10X,'VFLOC =',1PE12.6,10X,'V CRIT =',
     11PE12.6//)
100   CONTINUE
      RETURN
      END


      SUBROUTINE SELECT(ALET,ALETNO)
      REAL LVAR
      COMMON
     1/DATLET/G,D,R,T,Y,V,E
     1/DATIN/GVAR,LVAR,RVAR,TVAR,YVAR,VVAR
     1/VMISC/KFIN,T1,IERR
      IERR=0
      IF(ALET.EQ.G) GVAR=ALETNO
      IF(ALET.EQ.R) RVAR=ALETNO
      IF(ALET.EQ.T) TVAR=ALETNO
      IF(ALET.EQ.Y) YVAR=ALETNO
      IF(ALET.EQ.V) VVAR=ALETNO
      IF(ALET.EQ.D) LVAR=ALETNO
      IF(ALET.NE.G.AND.ALET.NE.R.AND.ALET.NE.T.AND.ALET.NE.Y
     1.AND.ALET.NE.V.AND.ALET.NE.R.AND.ALET.NE.D) GO TO 6
      GO TO 7
 6    WRITE(6,5)
 5    FORMAT(' YOU HAVE MIS-INPUT! TRY AGAIN!!')
      IERR=1
 7    CONTINUE
      RETURN
      END

/DATA
GETIVE
*END

*GO
```

```fortran
      DEFINE FILE 1(11,280,L,I1)
      DIMENSION LAB1(23),LAB2(15),VEL(70),COAT(70),LAB3(3),KEND(5)
      DATA LAB1/67,79,65,84,73,78,71,32,84,72,73,67,75,
     178,69,83,83/
      DATA LAB2/86,69,76,79,67,73,84,89,32,32,40,100,
     147,115,41/
      DATA LAB3/40,109,41/
      READ(1'1) JFIN,(KEND(I),I=1,JFIN)
      KEN=KEND(1)
      READ(1'2) (VEL(I),I=1,KEN)
      READ(1'3) (COAT(I),I=1,KEN)
      CALL INITT(120)
      CALL FINITT
      CALL SLIMX(100,1000)
      CALL SLIMY(125,740)
      CALL DLIMX(0.0,2.5)
      CALL DLIMY(0.0,8.0E-5)
      CALL NOTATE(450,40,15,LAB2)
     .CALL NOTATE(1,199,3,LAB3)
      CALL MOVABS(13,620)
      CALL VLABEL(17,LAB1)
      CALL NPTS(KEN)
      CALL CHECK(VEL,COAT)
      CALL DSPLAY(VEL,COAT)
      DO 20 J=2,JFIN
      JFIN2=2*J
      JFIN2P1=JFIN2+1
      IFIN=KEND(J)
      CALL ANMODE
      READ(1'JFIN2) (VEL(I),I=1,IFIN)
      READ(1'JFIN2P1) (COAT(I),I=1,IFIN)
      CALL NPTS(IFIN)
      CALL CPLOT(VEL,COAT)
   20 CONTINUE
      CALL TINPUT(II)
      CALL FINITT(0,700)
  500 CONTINUE
      STOP
      END
```

COMPUTER PROGRAM TO GENERATE GRAPHICAL DISPLAY

Fig 28

COMPUTER PROGRAM TO GENERATE GRAPHICAL DISPLAY

RESULTS OF VISCOSITY V SHEAR STRESS

FOR POLYMER WVG23 AT 230°C

Shear Stress $(N/m^2 \times 10^{+3})$	Viscosity (Ns/m^2)
2.21	8.51
2.53	8.47
3.04	8.63
3.82	8.38
4.72	8.42
5.80	8.59
9.35	8.46
12.00	8.54
18.30	8.43
21.70	8.29
28.50	7.68
36.40	7.31
51.00	6.87
62.30	6.53
68.60	6.08
72.10	5.54
91.30	4.82
105.00	4.71
120.00	4.50
129.00	4.06
141.00	3.78
152.00	3.83

RESULTS OF VISCOSITY V SHEAR STRESS

FOR POLYMER WVG23 AT 130°C

Shear Stress $(N/m^2 \times 10^3)$	Viscosity (Ns/m^2)
4.5	97.1
6.1	93.7
1.10	89.3
1.31	90.8
15.5	83.7
17.6	82.6
20.9	78.2
29.0	71.8
36.1	64.7
41.5	59.3
55.3	54.2
76.0	47.1
92.0	37.9
110.0	33.5
130.0	28.4
160.0	22.6
180.0	19.8
220.0	17.3
240.0	15.7
310.0	12.8
330.0	8.01
370.0	7.63

RESULTS OF STRESS/STRAIN COMPRESSION TEST

COPPER

Strain	Stress N/mm2
0.015	100
0.025	110
0.040	130
0.040	150
0.060	155
0.070	165
0.070	185
0.090	190
0.105	205
0.125	210
0.135	230
0.165	230
0.185	245
0.210	265
0.235	260
0.255	260
0.255	280
0.275	275
0.290	280
0.305	290
0.320	295
0.340	290
0.370	300
0.395	315
0.415	310
0.435	320
0.470	315
0.480	325
0.500	330
0.530	335

RESULTS OF STRESS/STRAIN COMPRESSION TEST

STEEL

Strain	Stress N/mm^2
0.010	169
0.015	220
0.030	280
0.020	320
0.035	365
0.060	440
0.085	479
0.085	475
0.110	500
0.110	530
0.130	550
0.150	585
0.175	625
0.210	705
0.240	710
0.270	790
0.310	810
0.350	840
0.389	885
0.445	920
0.495	950
0.535	985

RESULTS OF CHANGING YIELD STRESS ON COAT THICKNESS

$h = 0.102$ mm

$R = 0.825$ mm

$L = 60.00$ mm

$n = 50$ Ns/m^2

$T = 0.6 \times 10^6$ N/m^2

When $Y = 245 \times 10^6$ N/m^2

Velocity m/s	Coating Thickness mm
0.05	0.000
0.08	0.080
0.15	0.082
0.17	0.084
0.17	0.085
0.25	0.085
0.33	0.083
0.35	0.079
0.40	0.078
0.41	0.073
0.55	0.062
0.67	0.061
0.85	0.062
0.97	0.058
1.28	0.046
1.75	0.044
1.95	0.044
2.03	0.044
2.33	0.041

When $Y = 551 \times 10^6$ N/m^2

Velocity m/s	Coating Thickness mm
0.20	0.010
0.20	0.013
0.28	0.009
0.33	0.018
0.40	0.032
0.45	0.030
0.45	0.024
0.55	0.010
0.60	0.011
0.65	0.011
0.73	0.010
0.93	0.012
1.58	0.011
1.67	0.011
1.77	0.010
1.98	0.011
2.18	0.009
2.40	0.009

RESULTS OF CHANGING GAP ON COATING THICKNESS

$Y = 245 \times 10^6 \ N/m^2$ $0 = 160°C$

$R = 0.825 \ mm$ $T = 0.6 \times 10^6 \ N/m^2$

$L = 60.0 \ mm$

Gap = 0.102 mm

Velocity m/s	Coating Thickness mm
0.15	0.073
0.25	0.077
0.29	0.071
0.38	0.069
0.52	0.066
0.60	0.065
0.61	0.059
0.73	0.057
0.95	0.049
1.05	0.047
1.25	0.042
1.43	0.038
1.63	0.041
1.90	0.036
2.12	0.036

Gap = 0.175 mm

0.61	0.079
0.73	0.076
0.80	0.070
1.02	0.063
1.37	0.062
1.42	0.058
1.64	0.054
1.83	0.053
2.20	0.044

LIST OF COURSES ATTENDED

1)   Final year lectures in Metal Forming, Sheffield City
     Polytechnic.   October 1975 - March 1976

2)   Basic Lubrication Theory and Application,
     Imperial College, London.   June 1st to 5th, 1976

AJS/LB