

**PLASTO-HYDRODYNAMIC PRESSURE IN A SIMPLE TAPERED
AND COMBINED GEOMETRY UNITS FOR DRAWING
AND COATING OF WIRES**

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This thesis is submitted to Dublin City University in
fulfilment of the requirement for the award of Degree of

Doctor of Philosophy

School of Mechanical & Manufacturing Engineering
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*Dedicated to My Parents,
and My Wife*

DECLARATION

I hereby certify that this material, which is on this programme of study leading to the award of Doctor of Philosophy, is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

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Date:

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Finally, the support and the encouragement of my wife and family deserve greater acknowledgements than words can express.

ABSTRACT

Plasto-hydrodynamic Pressure in a Simple Tapered and Combined Geometry Unit for Drawing and Coating of Wires

By

Mohamed Abubaker Nwir B.Eng.

In plasto-hydrodynamic die-less wire drawing process, the conventional reduction die is replaced by a pressure unit of certain internal geometry. The deformation is induced by the combined effect of hydro-dynamic pressure and stress generated in the unit due to the motion of the wire and the viscous action of the polymer melt. The dimensions of the unit are such that the smallest bore size is greater than the incoming wire diameter. In this system, larger magnitude of the hydro-dynamic pressure is advantageous in obtaining greater deformation. In the present study, theoretical models have been developed for both the combined parallel and tapered geometry and simple taper bore pressure units, assuming non-Newtonian characteristics of the pressure medium, which enabled prediction of the maximum pressure and drawing stress, which gives better indication about the unit and its performance. The pressure and the viscosity coefficients were derived from the available data in the literature. Experimental work was undertaken with borosiloxane polymer at 110 °C melt temperature and using combined geometry and simple tapered bore pressure units. A number of parameters in terms of gap ratios and wire materials were changed for drawing speed of up to 0.7 m/sec.

The whole work was mainly devoted to assessing the performance of the unit and to establish the way it is affected by the unit geometry, the drawing speed, the working temperature. The optimum working dimensions were investigated and the theoretical results seem to be reasonably close to the experimental ones.

NOMENCLATURE

- B slope of the deformation profile within Δx .
D wire diameter.
S strain-hardening constant.
 K_0 dynamic/static stress ratio.
Q flow of polymer.
Y flow stress of the wire material.
a viscosity constant.
b pressure constant.
h radial gap ratio.
k non-Newtonian constant.
l length of the section of the unit.
n strain hardening constant.
p radial pressure in the unit.
 dP/dx pressure gradient in the unit.
u velocity of the polymer melt in the unit.
v velocity of the wire.
 x_a yielding position in the first part of the unit.
 α semi-angle of the effective die within Δx .
 $\dot{\nu}$ apparent shear rate in the unit.
 μ_0 reference viscosity of polymer melt.
 σ_x axial stress in the wire.
 τ shear stress of the polymer melt in the unit.
 τ_{c1} shear stress on the wire surface in the unit.

subscripts

- 1 stepped part of the unit.
2 tapered part of the unit.
i deformation zone in the stepped part.
j deformation zone in the tapered part.
r denotes radial direction.
x denotes axial direction.

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CHAPTER- ONE

INTRODUCTION

1.1- *Hydrodynamic phenomenon*

Hydro-dynamic means dynamics of fluid and under certain flow conditions. The hydro-dynamic action generates very high pressure inside the passage through which the fluid is flowing. A common situation is when the fluid is flowing through a converging surface (like a journal bearing). The magnitude of this hydro-dynamic pressure is dependent on the viscosity of the fluid, the geometrical configuration of the confined passage and the relative speed of the surfaces. The effect of such action is less apparent for thin oil type fluids. However, for plastics processing and food and mineral processing industries the pressure generation due to hydro-dynamic phenomenon could be a significant design factor for the processing equipment and pipe work. It has been observed experimentally that when a solid rod is pulled through a stepped or conical bore passage which is filled with a viscous fluid (like polymer melt) then the pressure generated is so high that the outer casing may rupture if the wall thickness is not large enough. Furthermore, if the casing is very strong, the rod may suffer permanent deformation if it is not made of a very hard material. A number of studies have been carried out applying this phenomenon to plastically reduce the diameter of steel, copper and aluminum wires and tubes when pulled through a strong cylindrical unit of stepped or tapered bore geometry. In these processes no contact takes place between the cylindrical unit and the wire or tube. The deformation is caused partly by the fluid pressure generated through hydro-dynamic action.

1.2- Fundamentals of wire drawing process

Conventional wire drawing process involves pulling a length of metal wire (usually circular in cross section) through a converging die, as shown in Figure 1.1, in order to obtain a reduced wire diameter of specific size while improving surface quality, obtaining the desired metallurgical properties and maintaining a high reproducibility of the product. This process has evolved through experience rather than by the application of scientific principles. The first theoretical analysis [1] of the process appeared in 1922. The pull and the nip of the die together stress the metal sufficiently for it to deform plastically within the confine of the die. However the reduction in size attainable thereby is limited by the pull that the wire can sustain without breaking, so that the operation has to be repeated usually a great many times [2].

Such process is usually carried out employing tungsten carbide dies , whereas diamond dies are used especially for finer wires. When the wire is drawn cold, the deformation of metal produces a very high drawing load which makes the presence of lubricant essential. Traditionally two principal methods of drawing were used "wet" and "dry" which differ as regards preparation of the wire, lubrication, and design of machine. In wet drawing the entire drawing apparatus is usually submerged in a bath of liquid which allows the wire to slip on the drawing capstans and it is usually used for drawing fine wires of less than 0.5 mm diameter. In dry drawing, soap powders picked up by the moving wire from a container placed ahead of the die are commonly employed as lubricants and the capstans are lapped by the wire a sufficient number of times to ensure that a tangential slip does occur [3] and such method is employed for wire of more than 0.5 mm diameter.

Friction between the wire and the die is of a boundary type where metal to metal contact takes place inspite of the presence of a lubricant resulting in die wear. The high rate of die

wear and the importance of getting acceptable metallurgical, physical and mechanical properties of the wire, has given impetus to consideration of the possibility of maintaining full film of lubricant so that no metal to metal contact takes place.

To create such regime, certain wire speed and lubricant pressure must be reached and maintained in order to keep the surfaces continuously apart. Prior to hydro-dynamic lubrication, boundary lubrication is the dominant regime, the film thickness produced in dry drawing is greater than that in boundary lubrication but less than that in hydrodynamic lubrication [4,5,6].

1.3- Background literature of hydro-dynamic phenomenon in drawing process

In as much as die wear is a destructive process, it is natural to expect that the rate of wear and it's progress will vary substantially with conditions of drawing and material of the die and the wire. When lubrication is good and all conditions are carefully controlled, the rate of wear of any one die may remain constant for relatively long periods of time [7].

The functions of lubrication are very complex in wire drawing, it is variously relied upon to minimize friction, keep the temperature down, prolong die life, impart lustre to the wire, endow it with a slippery surface for subsequent forming processes, protect it from rusting in storage, and so forth. Some of their tasks are mutually exclusive, so that different methods need to be employed depending on which are the principal requirements. When drawing for surface finish the role of the lubricant film is essentially to prevent scuffing of the wire and the die.

This consideration apart, the film should be thin so as not to interfere with the burnishing action of the die. Ideally solid friction or boundary lubrication seems to be the method best suited for this purpose. In dry drawing the speed dependence of coefficient of friction [8,9], and of amount of lubricant passing through the die at industrial speed [10,11] have

undermined the original view that even in dry drawing only boundary lubrication prevails. More experiments have been conducted studying the lubricant and its amount passing through [10] and its effect [12,13].

Based on the results of the previous investigations it was suggested in reference [11] that a rapid sequence of formation and collapse of hydrodynamic films gives rise to the regime which is intermediate between the boundary and hydrodynamic states which may be termed to as "quasi-hydrodynamic".

In contrast, when the function of drawing is merely to reduce the size of the wire, a thick film of lubricant is required with low friction and large heat capacity so that the job may be done in the least number of passes at the highest speed and with minimum wear of dies, in this case it seems logical to strive for hydro-dynamic lubrication.

The existence of quasi-hydrodynamic state in dry drawing naturally leads one to speculate about the possibility of achieving true hydro-dynamic lubrication in which the wire and die would be completely and permanently separated throughout the running period. For this to occur, it is necessary to feed the lubricant into the die /wire interface at the pressure which prevails [16].

CHRISTOPHERSON [14] invented a technique which owes its inspiration to a process [15] which consists of passing the wire through a tube with a small clearance, firmly attached to the die which acts as a constriction to the free flow of fluid fed to the tube entrance and causes pressure to built-up in it Figure 1.2. While conducting experiments using this technique deformation of soft copper wire half way down the tube was observed.

A theory of pressure tube has been worked out by CHRISTOPHERSON and NAYLOR [16] for a fluid with constant viscosity, or with a viscosity increasing exponentially with pressure. The principal features of the theory are that the pressure generated for a particular flow of

oil through the die is proportional to oil viscosity, wire speed, tube length, and the reciprocal of the square of the clearance. The back pull generated by the viscous drag is proportional to the viscosity, speed, length of the tube, wire diameter and the reciprocal of the clearance. WISTREICH [24] conducted experimental work on the forced lubrication based on a pressure tube system. Soap powder was used as the lubricant in a short nozzle (2 inch. length) which was attached to the entry side of the die. The experimental results showed that the speed, temperature and the tube gap had direct effect on the property of the film thickness produced. He also showed that when the soap powder was replaced by oil, an increase rather than the decline of the film thickness was observed.

TATTERSALL [17] published a detailed analysis of plasto hydrodynamic lubrication in conventional wire drawing taking some rheological and metallurgical properties of the process into account. Results from experiments and theory showed that these were in reasonable agreement. Subsequently BEDI [18] introduced his analysis for wire drawing assuming complete hydro-dynamic lubrication. Thereafter, CHU [19] using the work of TATTERSALL presented charts for inlet tube design.

Studies of the lubricant film thickness which would be developed under practical drawing conditions have been presented in references [20,21,22]. MIDDLEMISS [23] improved the previously used drawing unit by using externally pressurized lubrication system. The unit consisted of two dies separated by a narrow tube which was connected to a hydraulic pump to pressurize the lubricant in order to assist the formation of hydrodynamic film at the beginning of the drawing process. The wire first passed through an ironing die which acted as a seal and then through the reduction die, Figure 1.3. This pre-pressurized lubrication method was reported to work successfully for the reduction die but the ironing die was worn severely due to lack of lubrication. More improvement to the system was done by replacing

the ironing die by a short pressure tube with a very fine clearance, the system was still provided with pressurized lubricant and the function of the tube was to reduce the oil leakage [24].

ORLOV et al [25] has done further improvements, Figure 1.4, to the system changing the design of the unit thus eliminating the need for the hydraulic pump; the motion of the wire could perform the same work.

1.4- Background literature of polymer melt as lubricant and pressure fluid in drawing process

The difficulties associated with the use of oil or soap as the lubricant prompted for more research to overcome these problems. Although successful attempts were made to introduce hydrodynamic lubrication, still some areas of inconvenience exists such as the need for leader wire, start up problems in which the wire may snap and the die wear before reaching hydrodynamic lubrication. A number of investigators [26,27,79] have carried out research using polymer melt as lubricant and pressure medium in the pressure tube unit. Their work led them to the conclusion that the polymer coating thickness on the wire reduced as the wire speed increased and at certain speeds "bamboo" effect was observed with subsequent necking of the wire.

A careful study of previous works was undertaken to develop a system in order to eliminate the difficulties inherent in wire drawing process. CRAMPTON [76,77] using the setup shown in Figure 1.5 showed that during drawing deformation of wire took place before the die entrance due to the high pressure generated within the pressure tube. This led to the idea that under certain geometrical configuration of the unit it might be possible to remove the reduction die and still generate necessary pressure by the polymer melt to reduce the wire diameter.

The feasibility study showed that in the absence of the die, die-less pressure units, capable of deforming the wire, could be used to a certain degree of success. Hence stepped and tapered bore reduction units (Figures 1.6 & 1.7) have been designed and their dimensions have been chosen in a way that a narrow gap be present between the wire and the smallest diameter of the units. This prevented metal to metal contact and eliminated die wear and there was no need for the leader wire. Tests have been carried out to assess the performance, of the unit; the results obtained confirmed the successful achievements in the die-less wire drawing. However, there still remained one serious limitation, the fact that at increasing drawing speeds the performance of both units in terms of the obtainable reduction in area decreased.

Since the design and manufacture of the stepped bore reduction unit proved simpler. An extensive experimental and theoretical work was carried out for that unit by PARVINMEHR [61], who developed a theoretical analysis based on Newtonian and non-Newtonian fluids. Considering the rheological and metallurgical properties of the polymer and the wire materials, he concluded that the amount of deformation was much higher at slower drawing speeds, and the performance of the unit was partially improved at higher speeds by employing a high viscosity polymer melt.

HASHMI and SYMMONS [62] developed a numerical solution for a conical tubular orifice through which a continuum is drawn. A very well agreement between the theoretically and experimental results was observed at low drawing speed, whereas, for higher drawing speeds the agreement between the predicted and the actual percentage reduction in area was very poor.

Further investigation was carried out by AL-NATOUR [71] using a combined geometry (parallel and tapered bore) plasto-hydrodynamic pressure unit in conjunction with a polymer

melt. He developed a theoretical analysis assuming Newtonian pressure medium. Some limited experiments were conducted in which the effect of the dimensions of the unit on the maximum pressure generated was studied.

1.5- Rheology of polymer melts¹

Rheology can be defined as the science of the flow and deformation of materials. In this work, however, the meaning of rheology will be restricted to the polymer melts. Polymers generally consist of very long molecular chains for thermo-setting polymers. The bonding between the molecules is achieved by cross-linking. The forces of attraction between the molecules is the van der Waals forces and polymers with this type of bonding are commonly called thermo-plastic polymers. A useful image of the structure is a mass of randomly distributed long strands of sticky wool. When the polymers are heated the inter-molecular forces are weakened so that they become soft and flexible and eventually, at high temperatures, it becomes a viscous melt. If the stress applied together with a temperature increase is high enough to overcome the van der waals forces, a relative molecular motion takes place causing the polymer to flow. The type of flow will depend on the mobility of the molecular chains and the forces holding them together. In thermo-plastic polymers long molecules take up a non-random configuration under the stress which would be partially recoverable, causing the polymer to act elastically. The break of the bonds enable flow to occur. The thermo-setting polymers show distinct brittle behaviour. The flow characteristics of polymer melts are very different to those of conventional lubricants such as oil. In this chapter, discussions are made of flow characteristics of polymer melts, which are influenced by many factors in relation to the present work.

¹ *Even though in this work only borosiloxane was used for the experiments, the rheological properties of a number of other polymers are given here for illustration purposes. These polymers have been used by previous workers and may also be used for this work with modification of the rig.*

1.5.1- Temperature effect on viscosity

An increase in temperature generally decreases the viscosity of the fluids. This effect vastly differs for different types of polymer. Figure 1.9 shows typical changes in viscosity against temperature at zero shear rates. The slope of each line measures the activation energy for each polymer. Temperature increase in polymers with higher activation energies has more deterioration effect on viscosity compared to those of lower activation energies. This energy is a function of polarity in polymers and the most non-polar polymers such as polyethylene with very small inter-molecular forces have low activation energy.

DIENES [28] believed that as the temperature increases the molecular arrangements within the polymer change more towards random configuration, therefore, it becomes easier for the polymer to flow at higher temperatures. BRYDSON [29] explained that the variation of viscosity with temperature is a function of the difference between the melt temperature and the glass transition temperature of the polymer.

PAMWHER [66] has carried out experiments on (ALKATHENE WVG23), (POLYPROPYLENE KM61), RIGIDEX and POLYSTERENE polymers in order to study the effect of temperature on viscosity of these polymers. Figures (1.9-1.10) shows the variation of viscosity versus temperature for these polymers at zero shear rate. These graphs do not represent the complete behaviour since viscosity measurements are affected by pressure, shear rate, temperature etc. and it is necessary to include these effects on viscosity of polymer melts.

1.5.2- Shear stress and shear strain effect on viscosity

Newtonian fluids under shear stress condition exhibit linear relationship with shear rate where the slope of the line represents the viscosity, whereas, it is widely accepted that polymer melts exhibit non-Newtonian flow characteristics in which as the applied stress is

increased the viscosity of most polymers is decreased. Figures 1.11-1.14 show the effect of shear rate on viscosity where the influence of temperature may be noticed. These curves were produced in reference [30] by extruding polymer melt "ALKATHENE WVG23" and "POLYPROPYLENE KM61" through an extrusion rheometer at different temperatures. A non-linear relationship seems to exist between shear stress and shear rate whereas for a Newtonian fluid it would be a straight line passing through zero. The viscosity of the melt can be obtained from the tangent to the curve at any point. Figures 1.15-1.18 show that the viscosity could be read directly. For Newtonian fluids straight horizontal line would be produced.

Certain polymer melts are known to have flow discontinuities at higher shear rates and "critical" shear stress value for polymer may be defined as the one after which flow tends to be irregular.

1.5.3- *Flow instabilities*

Polymer melt flow through capillaries produce smooth strands at low shear rate, but at higher shear rates certain kinds of flow instabilities can develop in which the surface of the extruded strand becomes rough or non-uniform in cross-section, and the rate of flow is no longer steady but pulsating [31-36],[42-53]. The flow irregularities were shown to take the form spiral, bamboo, zigzag for different types of polymers. The terms melt fracture, elastic turbulence and flow distortion have been used to describe this effect. This phenomena have been investigated [37-41], and there is a general agreement on the following points;

- 1- The critical shear stress is independent of the die length and diameter.
- 2- The critical shear stress is in the region of $0.1 - 1.0 \text{ MNm}^{-2}$ for most polymers.
- 3- The critical shear stress does vary widely with temperature.
- 4- A discontinuity in the slope of viscosity - shear stress occurs.

5- The flow defect always took place when non-Newtonian fluids were involved.

6- The flow defect is often associated with die entrance and the surface finish.

1.5.4- Pressure affect on viscosity

The effect of hydro-static pressure on the apparent viscosity and other flow properties of polymer melts is not as well understood as the effect of temperature and shear rate. MAXWELL and JUNG [54], and CHOI [55] demonstrated that the effect of hydro-static pressure on the apparent viscosity of branched POLYETHYLENE and POLYSTYRENE at constant shear stress and temperature are appreciable and should not be neglected. WESTOVER [56] was able to measure the apparent viscosity of several polymeric materials between atmospheric pressure and that of 172 MNm^{-2} at fixed temperature and shear stress. He showed, for example, that the apparent viscosity of POLYETHYLENE increased by a factor of five when the hydrostatic pressure was changed from 13 to 172 MNm^{-2} . COGSWELL [57] suggested that the effect of an increase in pressure may be linked to that due to a drop in temperature. He observed that for low density POLYETHYLENE, an increase in pressure of 1000 bar had the same effect on viscosity as that due to a drop in temperature of 53°C within the melt range. It had been noted that at very high pressure (above 140 MNm^{-2}) the melt tended to recrystallise and in consequence, the melt acted like a solid plug [58]. For this reason, pressure - viscosity measurements are often conducted at relatively high temperature. Most of the experimental work carried out by WESTOVER [53] was on a branched 0.92 density polyethylene with pressure varying from 14 MN/m^2 to 170 MN/m^2 . Figure 1.19 shows the effect of pressure alone on viscosity, where as in Figure 1.20 the change in shear stress with shear rate is illustrated.

1.5.5- Effect of the polymer flow characteristics

In the present work polymer melt is subjected to very high shear rates and pressures,

much greater than those capable of being investigated in any extrusion rheometer. CRAMPTON [77] concluded that the decrease in coating thickness was due to the presence of the critical shear stress at low shear rates. However, it is also believed that, the poor performance of the units at higher drawing speeds is related to a combination of factors such as melt flow instability, partial crystallization, compressibility, etc. and not the critical shear stress alone. The formation of shark skin is thought to take place at the exit end of the unit, therefore it's effect on the performance of the unit is negligible. The high pressures generated are believed to have the effect of increasing the melt viscosity in the unit. Temperature was maintained at a steady value when the tests were conducted, minimising the effects inherent with changing temperature. However, more investigation is needed to understand these effects fully.

1.6- *Present work and its aim*

It is evident from the foregoing section that considerable work was carried out studying the hydro-dynamic action in drawing process using a stepped or a tapered bore pressure unit. The aim of these researchers was to reduce the diameter of the material to a specific size with an acceptable surface finish and to generate sufficient pressure to ensure a hydro-dynamic film which would prevent excessive friction between the die and the material. This would result in no metal to metal contact and would reduce the die wear. A thick hydro-dynamic film can be generated by high viscosity lubricants.

Generation of very high hydro-dynamic pressure is one way to ensure a continuous film between the wire and the die. In die-less wire drawing higher pressure should produce continuous film over a wider range of drawing speeds. The principal aim of the present investigation is to develop a combined parallel and tapered bore geometry pressure unit for generating greater hydro-dynamic pressure for die-less wire drawing or coating of wires.

The objectives of the present project are

- (i) Experimentally, to optimise the performance of the combined geometry and simple tapered pressure units in relation to a stepped parallel bore unit.
- (ii) Theoretically, to develop mathematical models for the prediction of results for hydro-dynamic pressures for these pressure units.
- (iii) To examine the correlation between the experimental results and the theoretical predictions.

The details and background of the investigation are presented in this thesis as following.

In chapter one, a background literature of the hydro-dynamic phenomenon and it's presence in wire drawing process as well as literature review into the rheology of polymer melts and the affect of pressure and the temperature on the viscosity of molten polymers.

The aim of the research was included in the first chapter too.

A discussion on the equipments and the materials used during the course of the tests is given in the second chapter, the design of the pressure units and the modification of the rig used is discussed in details in this chapter, whereas, the theoretical analysis for both the pressure units (combined and the simple tapered) is given in chapter three.

The theoretical predictions and the experimental results of the combined unit is given in chapter four. The effect of some parameters on the performance of the unit was discussed and a comparison between all the units performance is given in this chapter.

Theoretical predictions and experimental results of the tapered unit is given in chapter 5.

The discrepancy between the theoretical predictions and experimental results is discussed in chapter 6 and suggestions as to reason for these discrepancy was given.

Finally, chapter seven states some conclusion remarks and gives suggestions for further work both theoretically and experimentally for both of the pressure units.

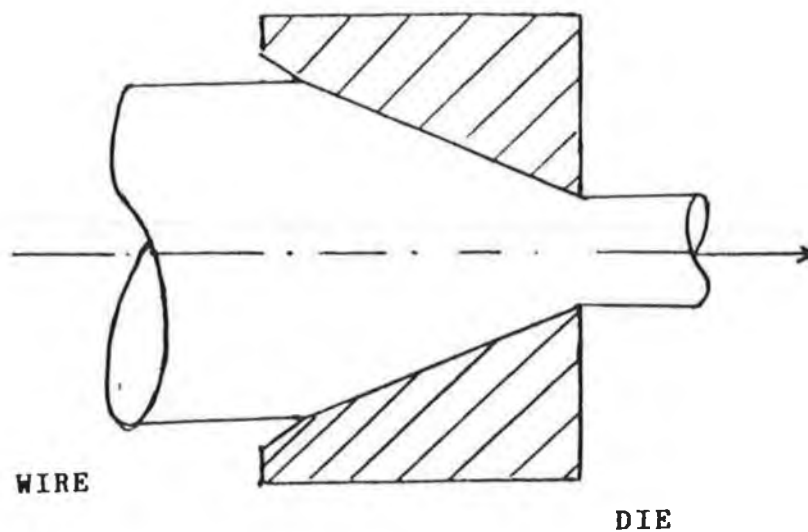


Fig 1.1 WIRE THROUGH CONICAL DIE

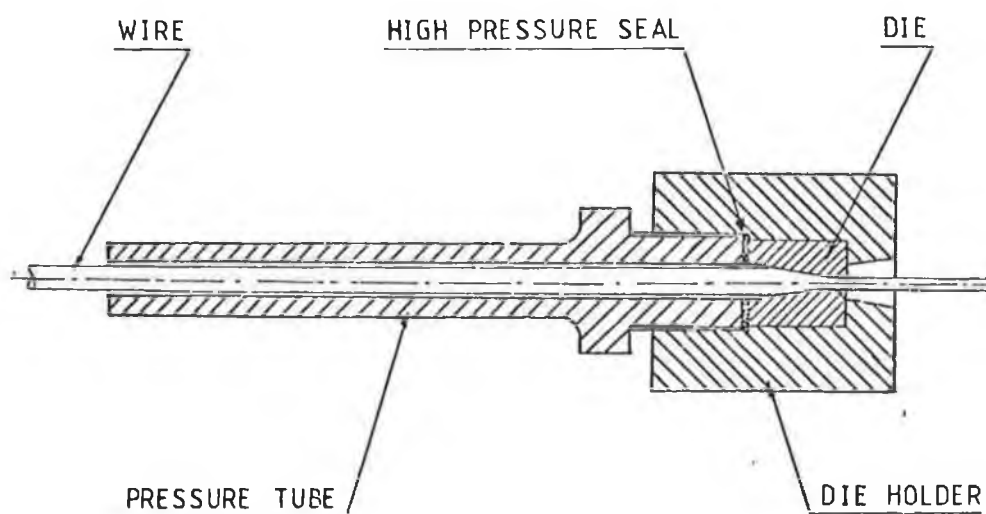


Fig 1.2 TYPICAL CHRISTOPHERSON TUBE ASSEMBLY

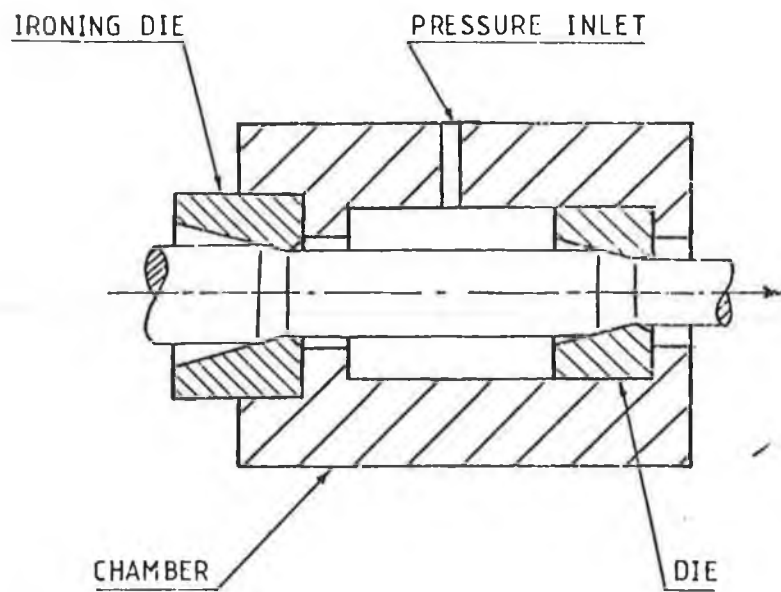


Fig 1.3 *PRESSURIZED CHAMBER*

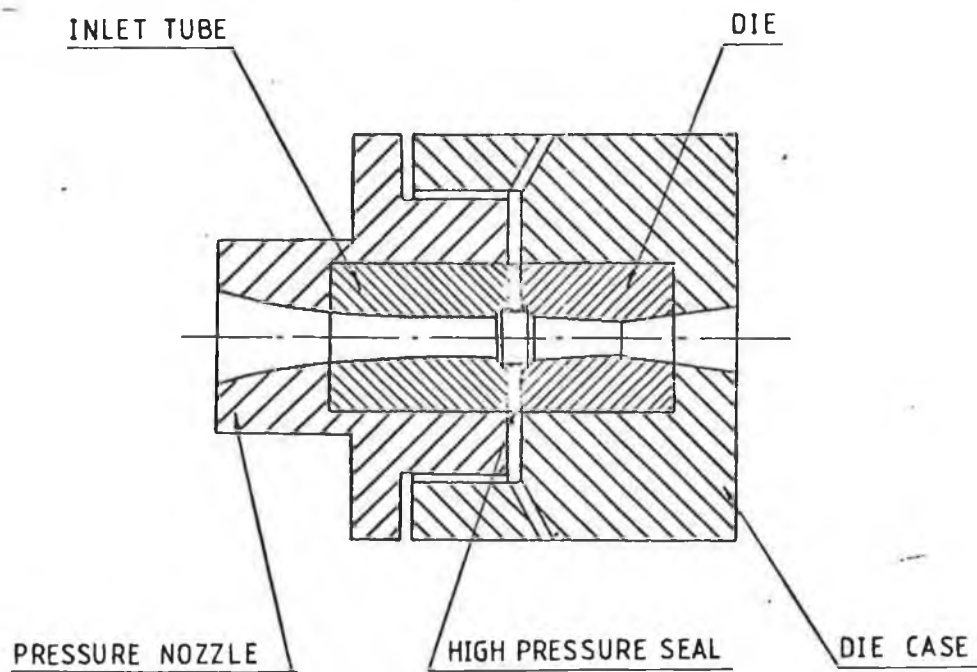


Fig 1.4 *NOZZLE - DIE UNIT*

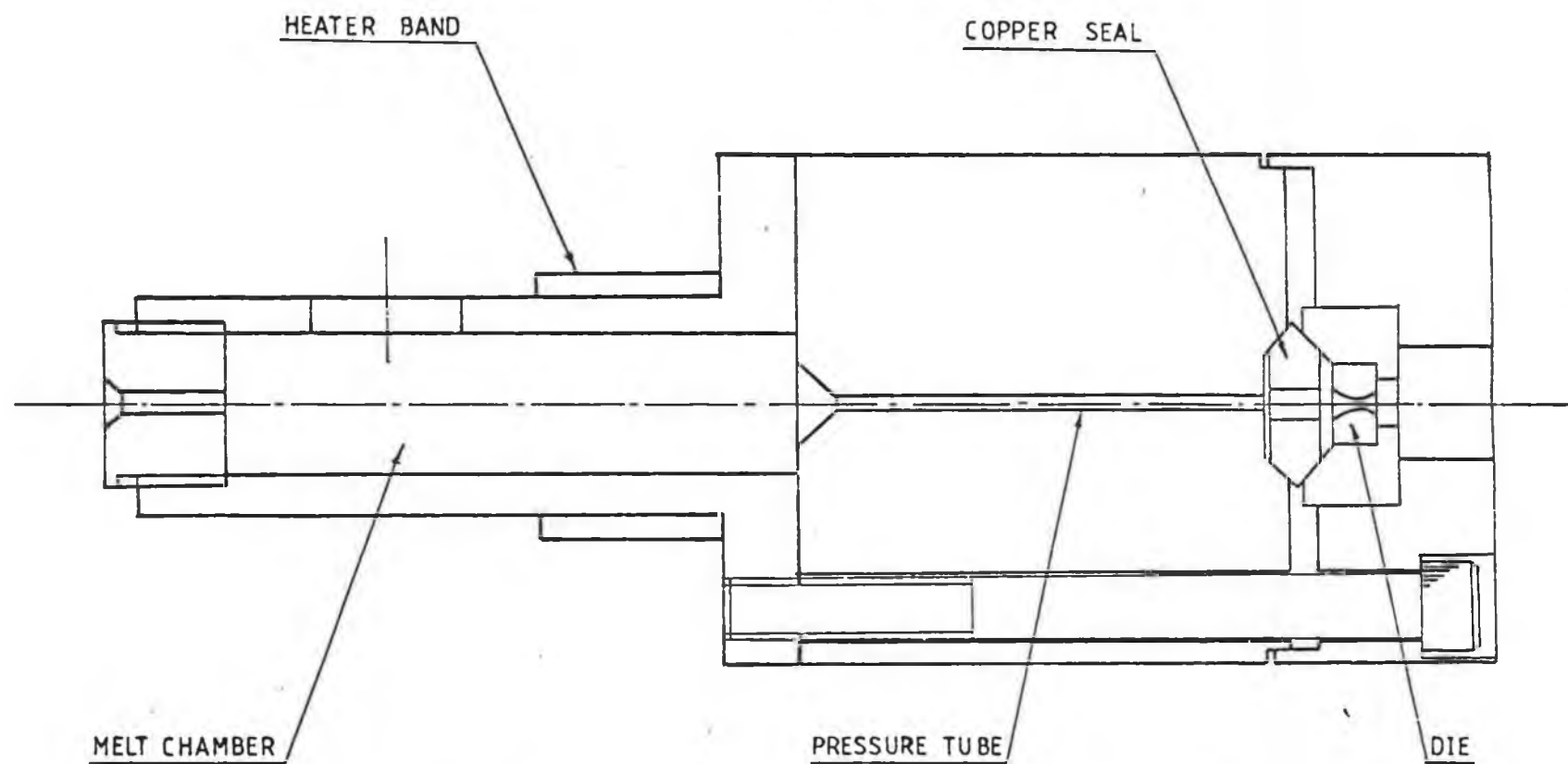


Fig 1.5 : PRESSURE TUBE - DIE ARRANGEMENT

Fig 1.6 STEPPED BORE REDUCTION UNIT

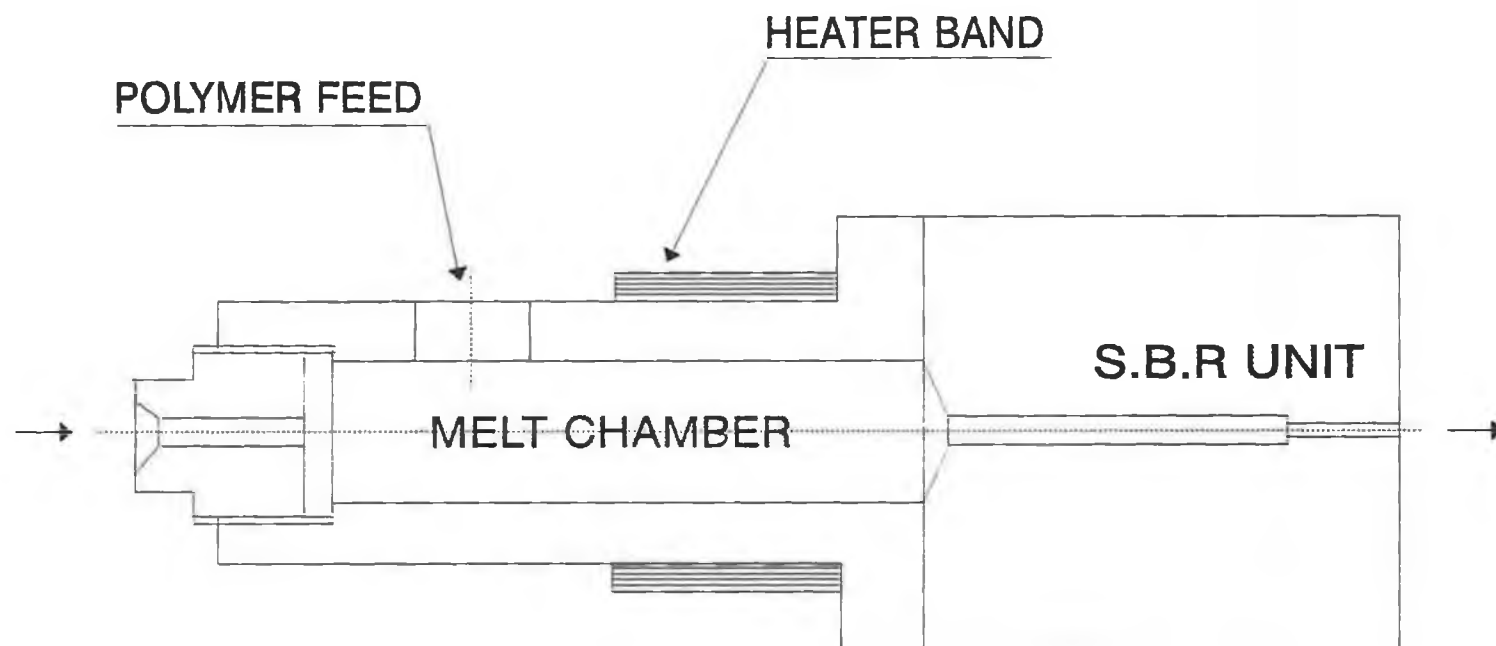


Fig 1.7 TAPERED BORE REDUCTION UNIT

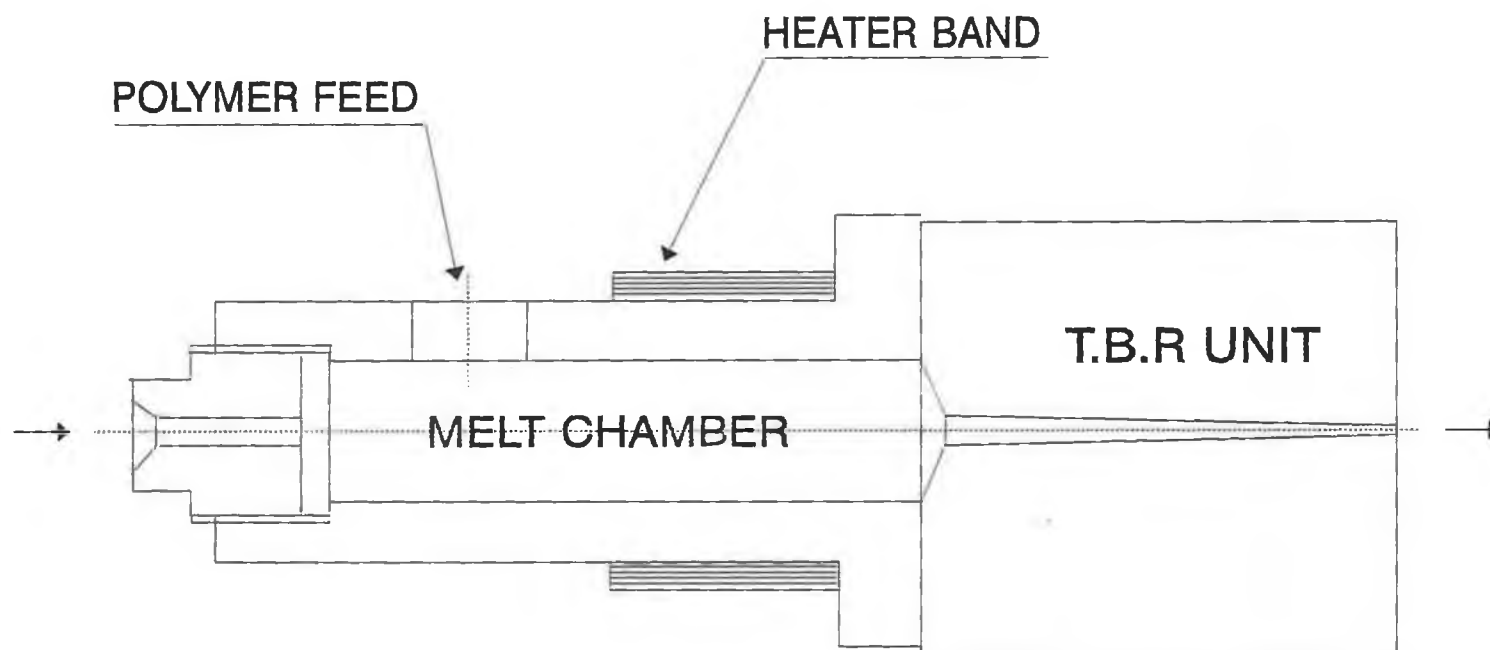
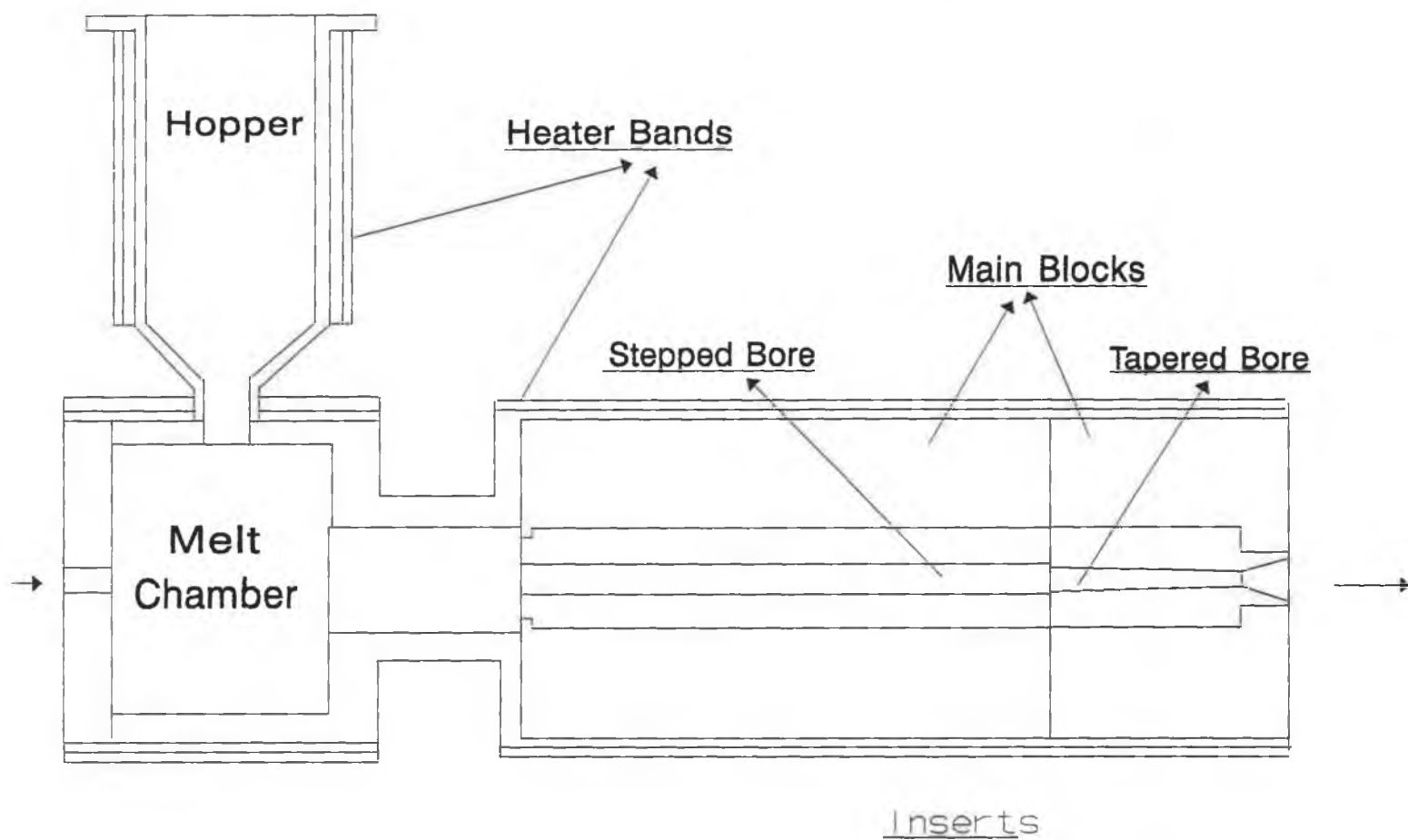


Fig 1.8 Combined Geometry Pressure Unit



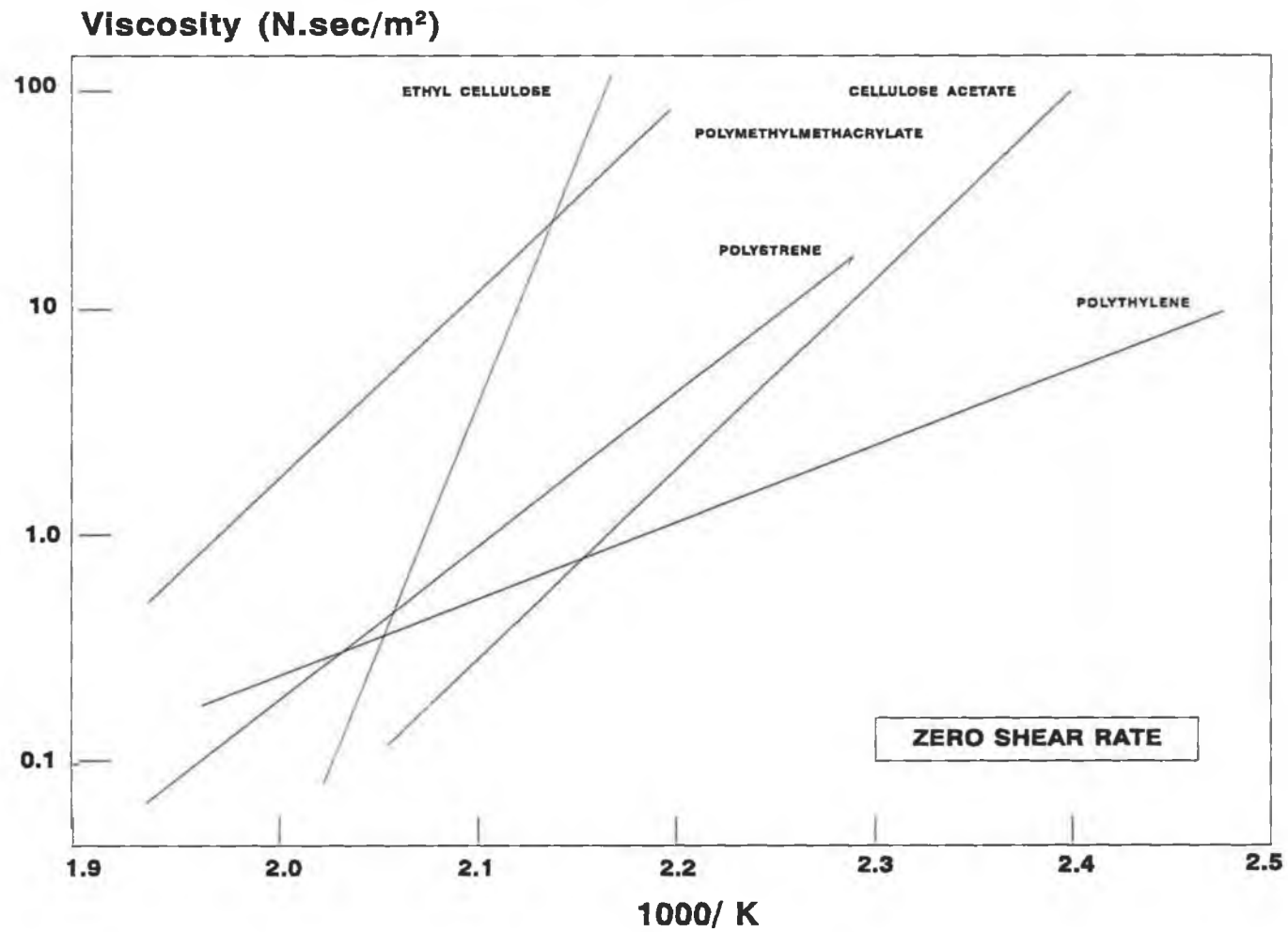


Fig 1.9 Effect of temperature on viscosity of polymer

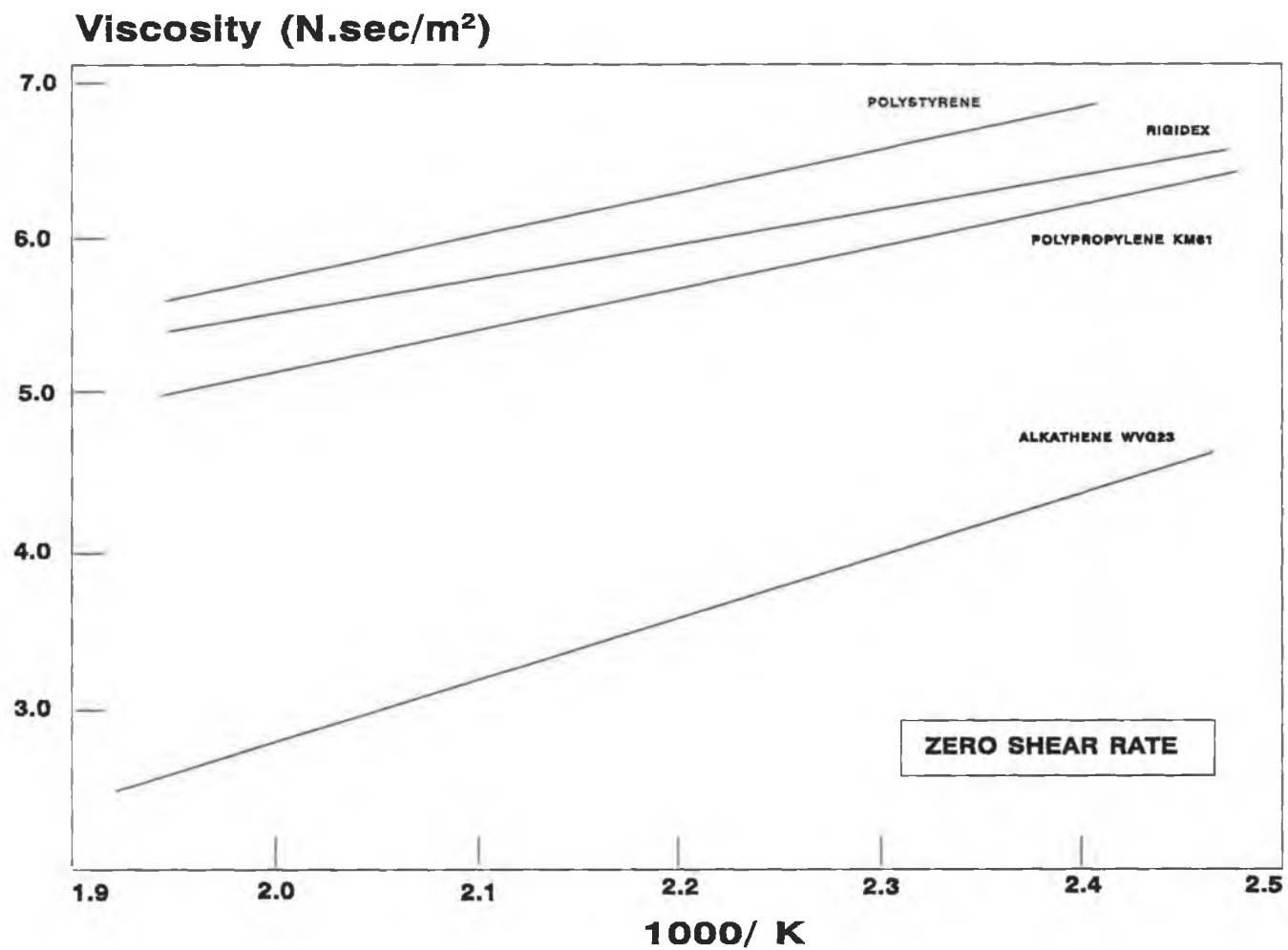


Fig 1.10 Effect of temperature on viscosity of WVG23
KM61, RIGIDEX and POLYSTYRENE

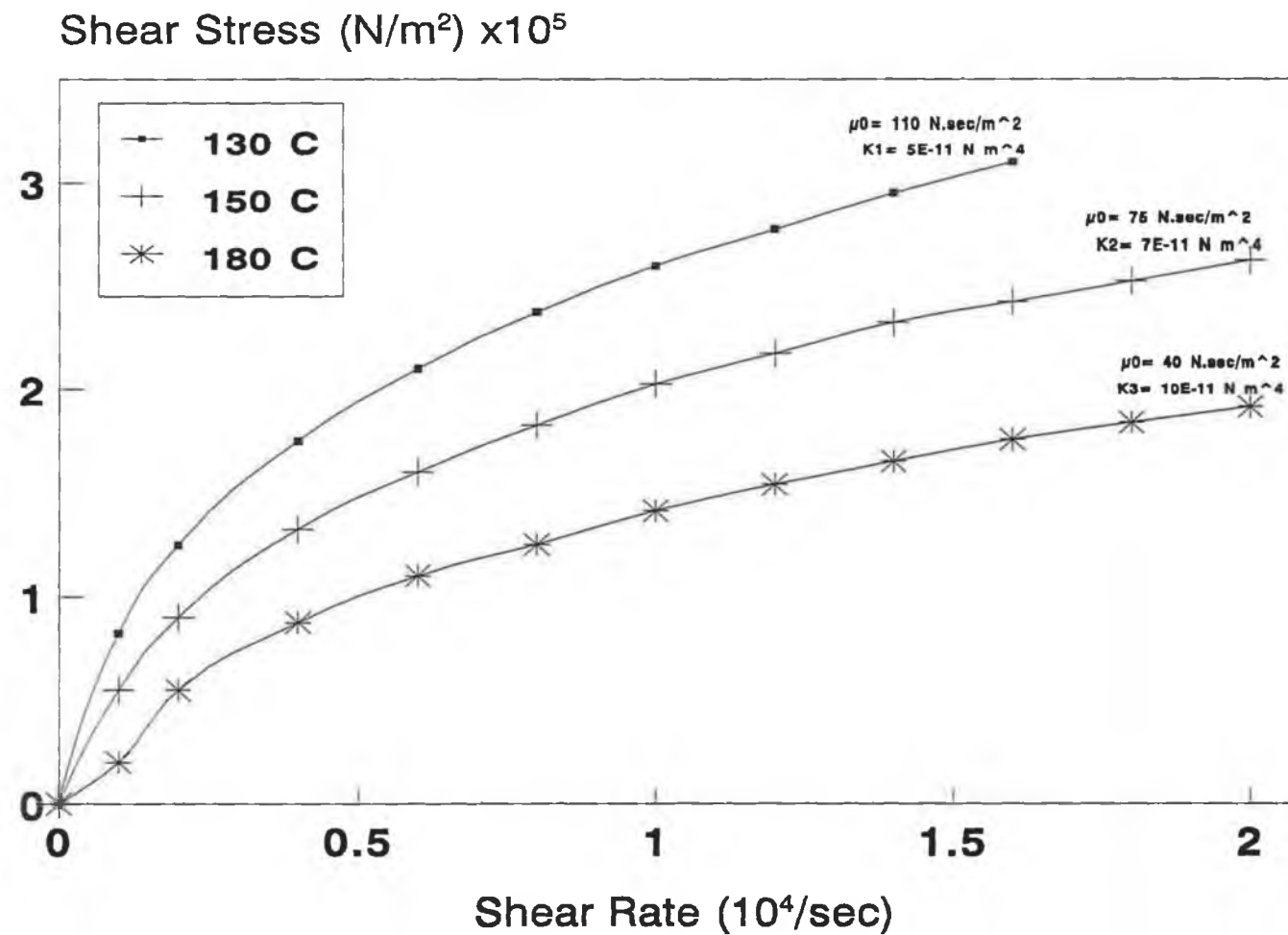


Fig 1.11 Flow curves for ALKATHENE WVG23

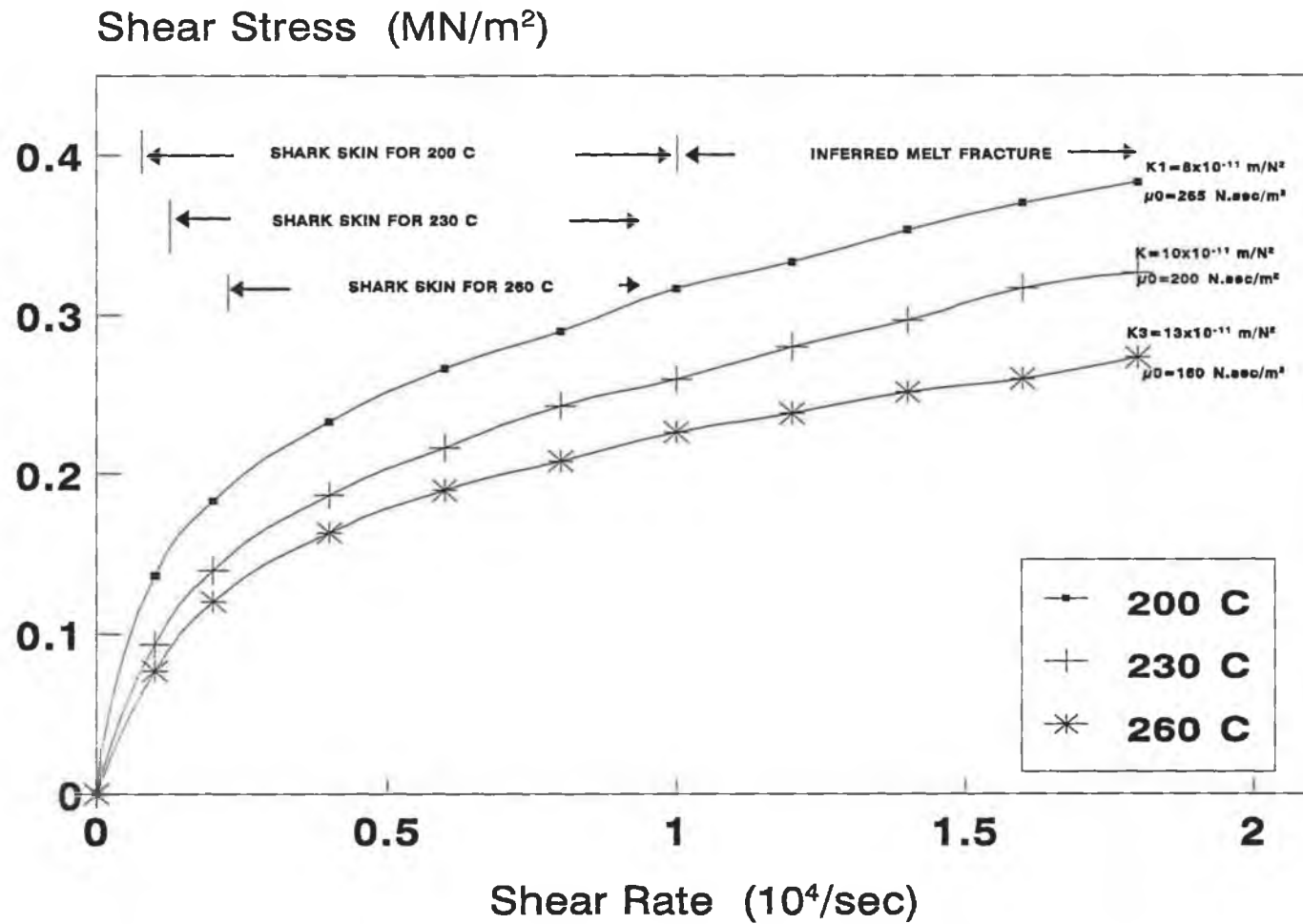


Fig 1.12 Flow curves for POLYPROPYLENE KM61

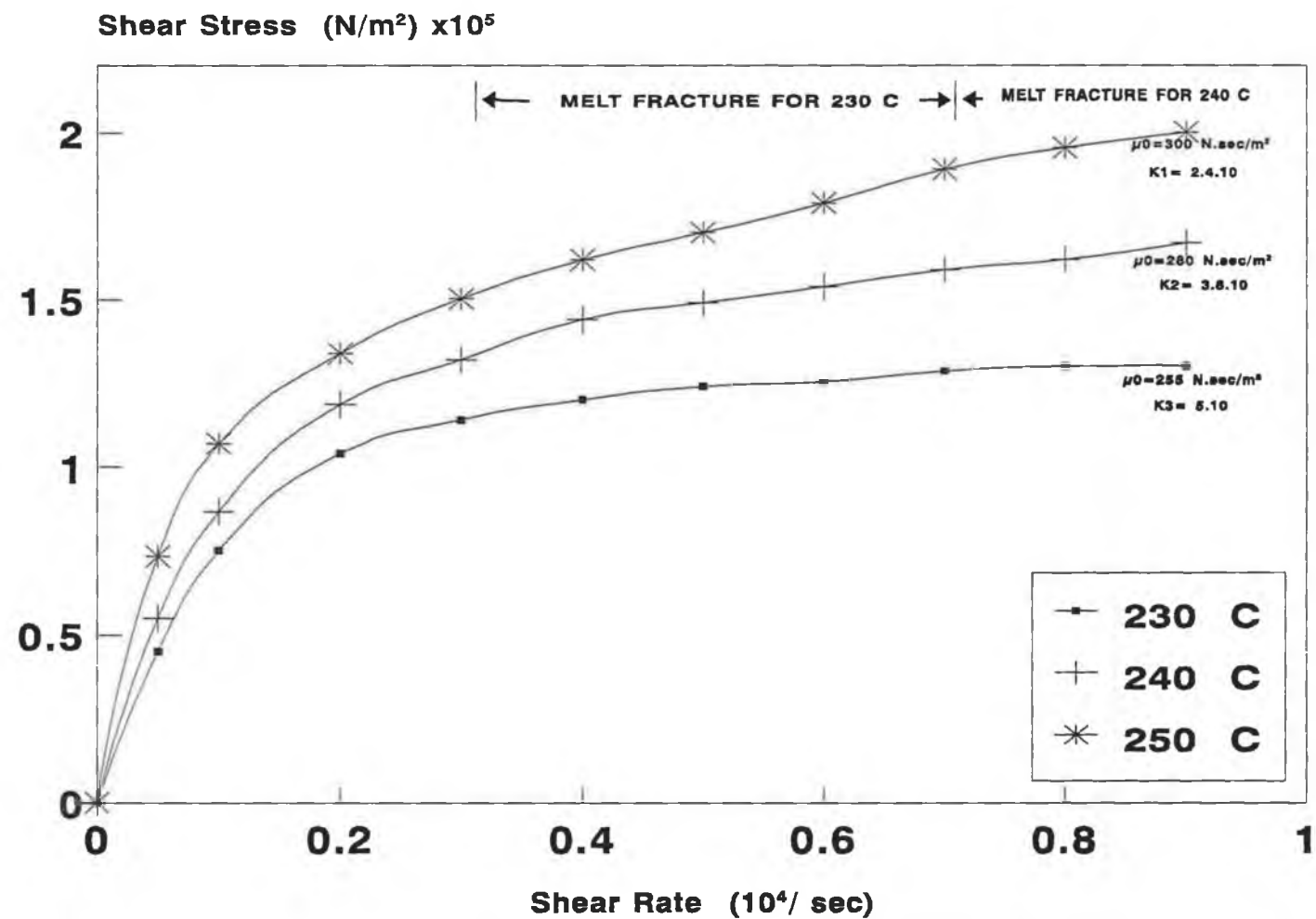


Fig 1.13 Flow curves for POLYSTYRENE

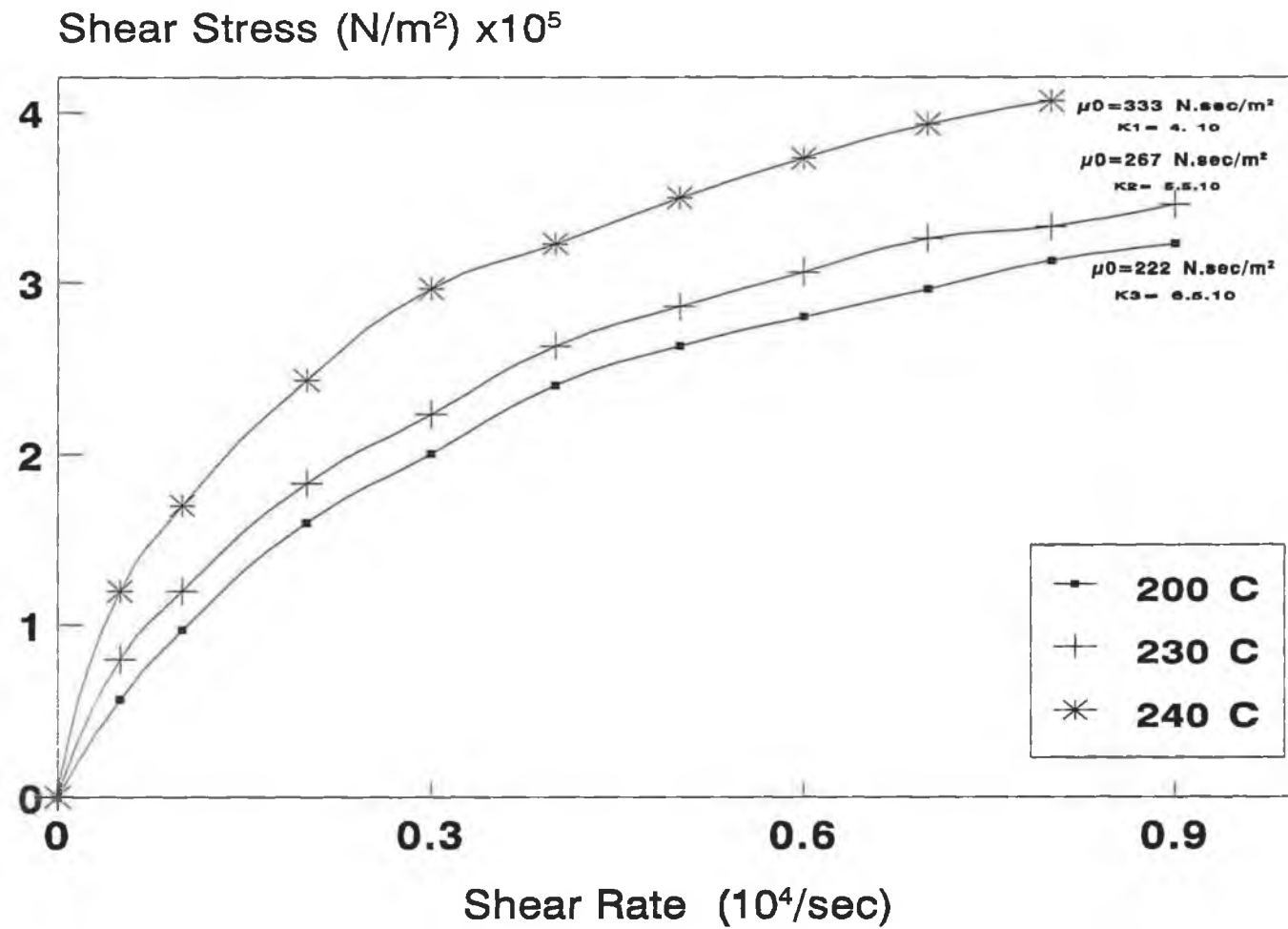


Fig 1.14 Flow curves for RIGIDIX

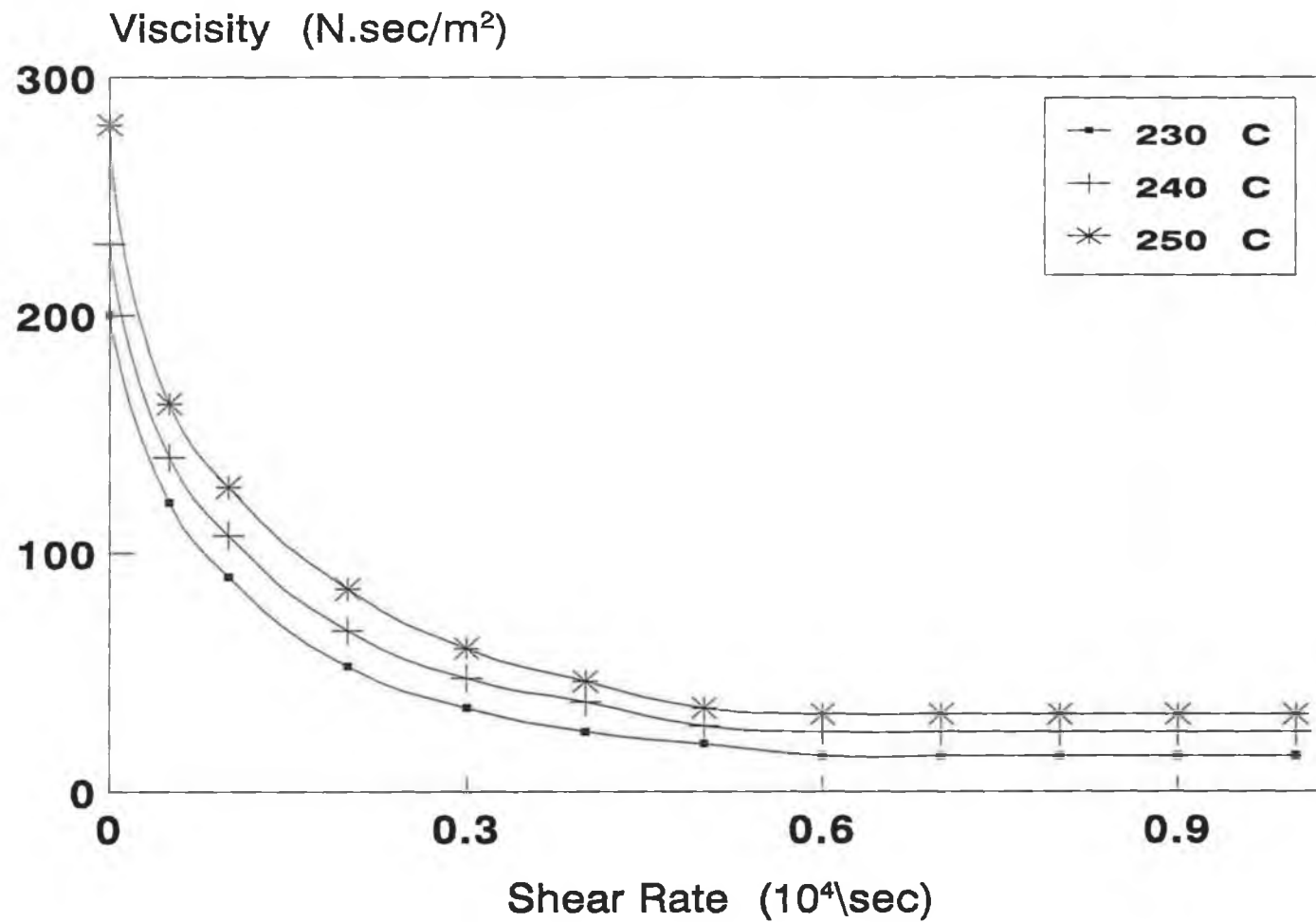


Fig 1.15 Effect of shear rate on viscosity of POLYSTYRENE

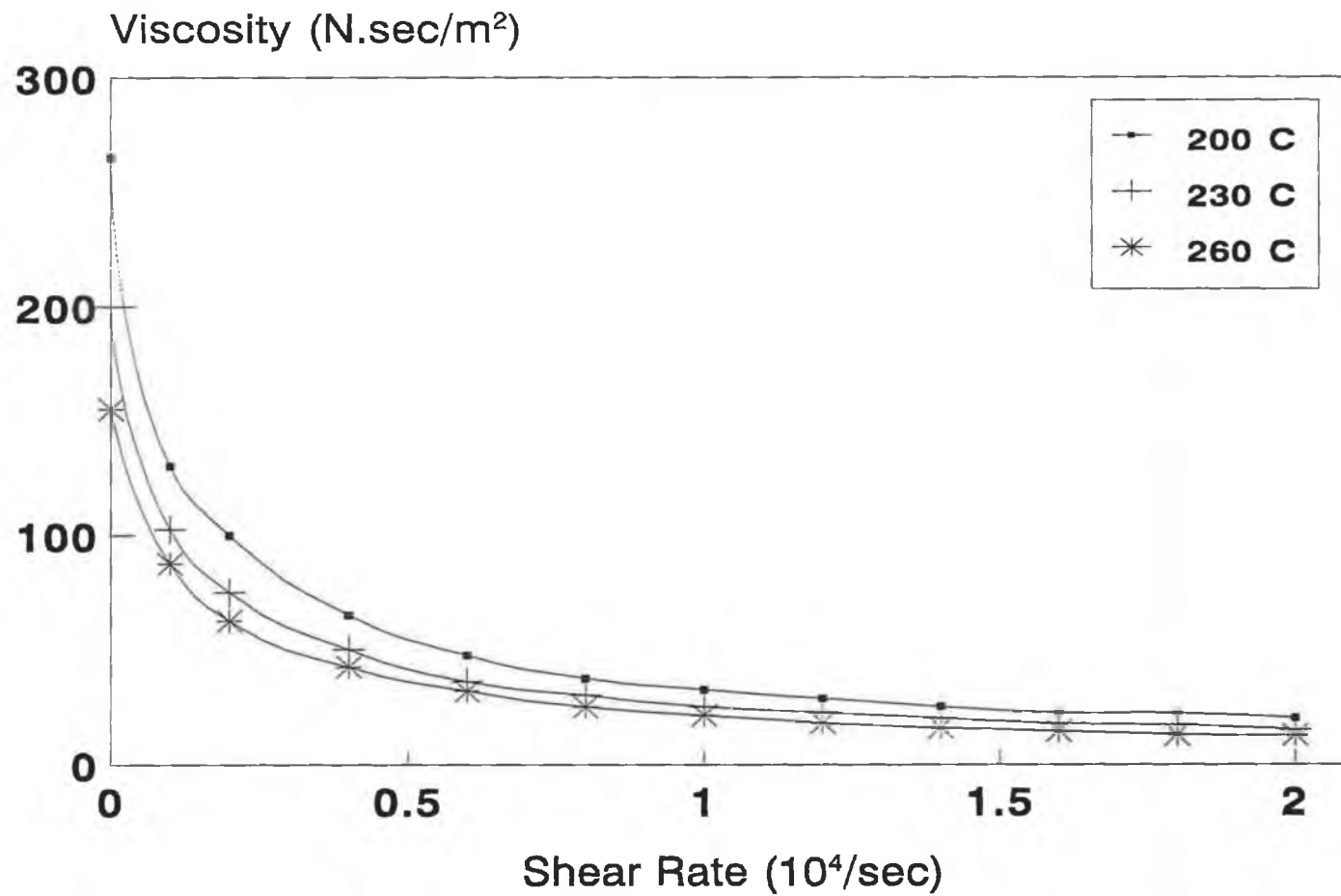


Fig 1.16 Effect of shear rate on viscosity of
POLYPROPYLENE KM61

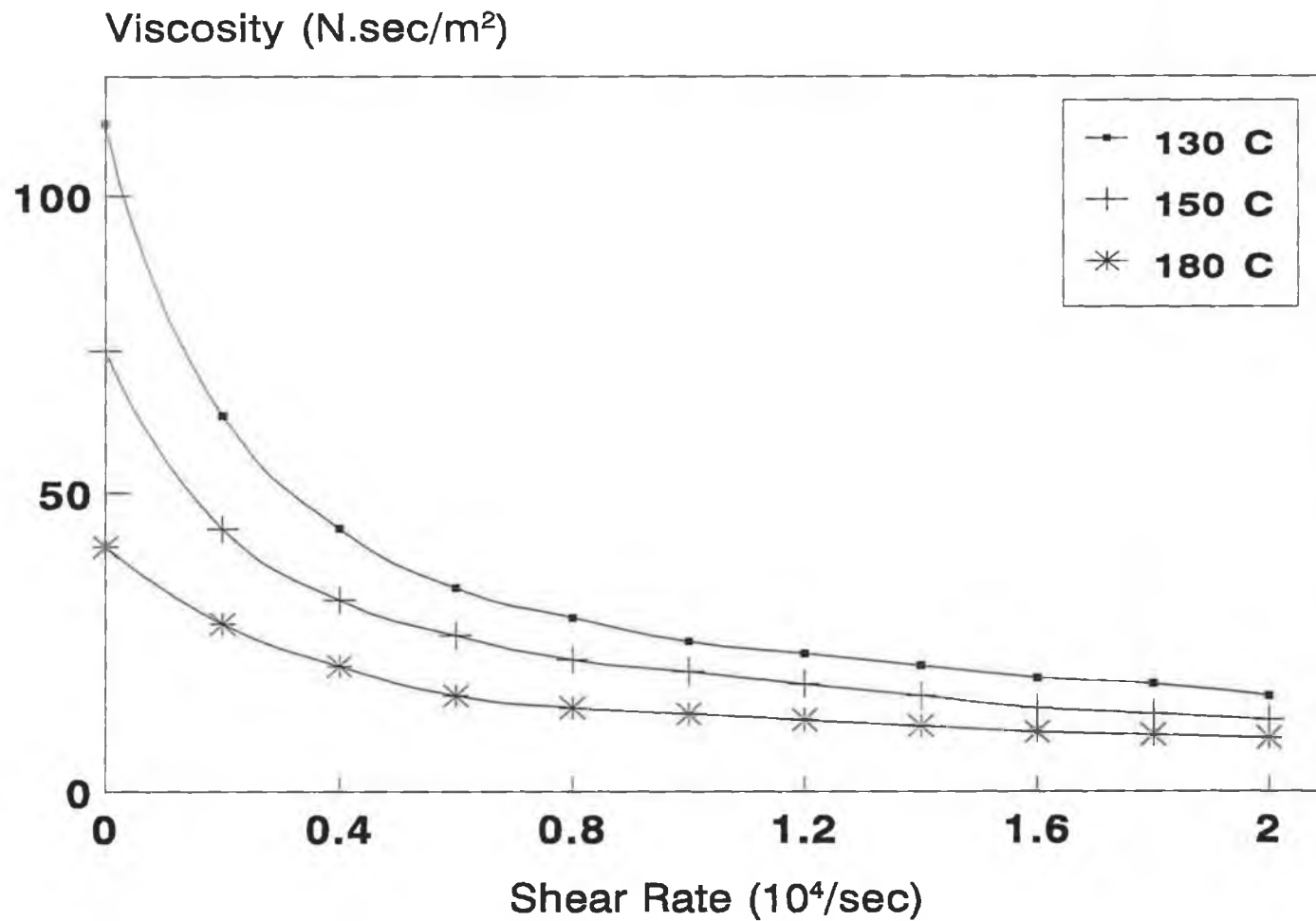


Fig 1.17 Effect of shear rate on viscosity of ALKATHENE WVG23

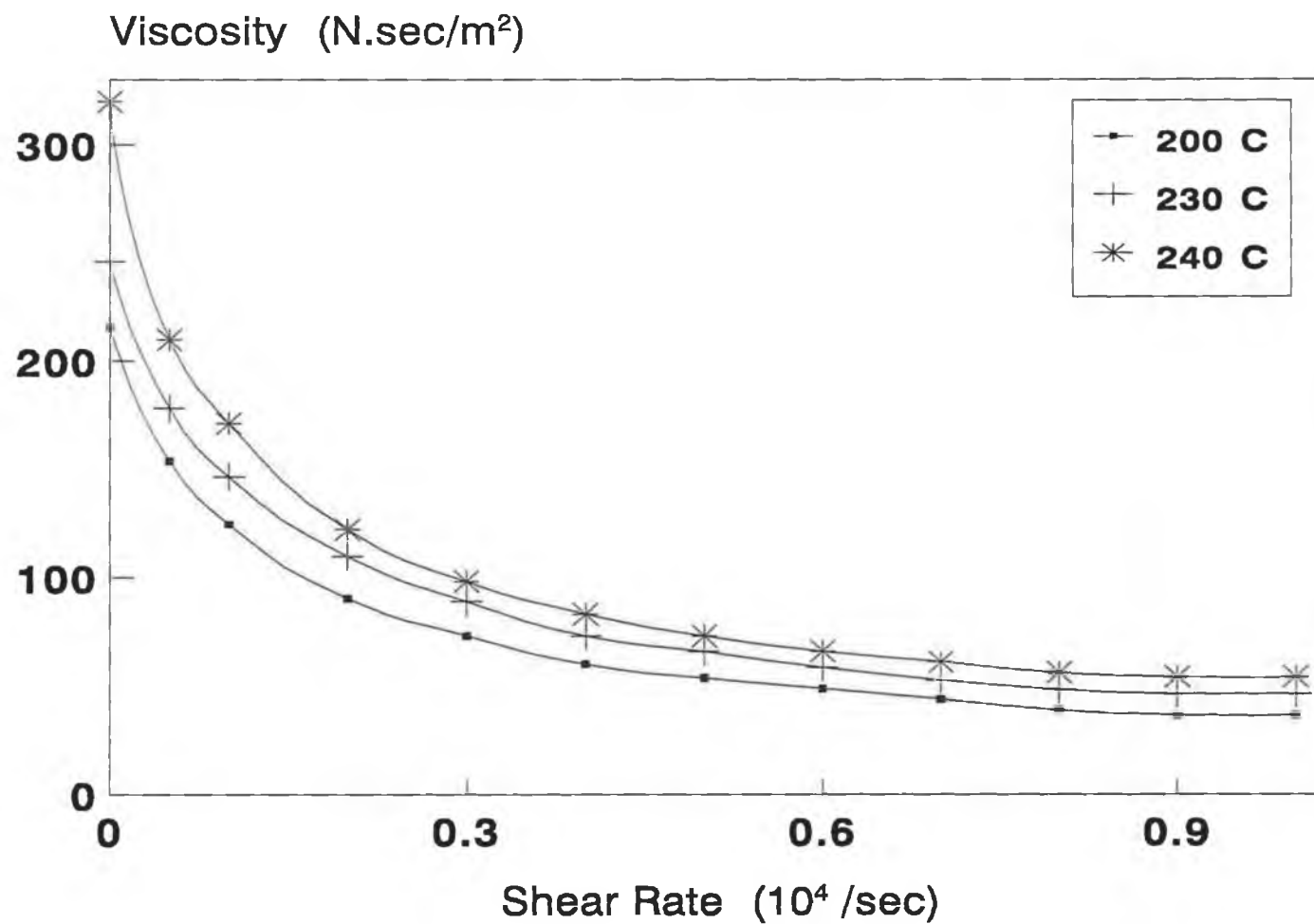


Fig 1.18 Effect of shear rate on viscosity of RIGIDEX

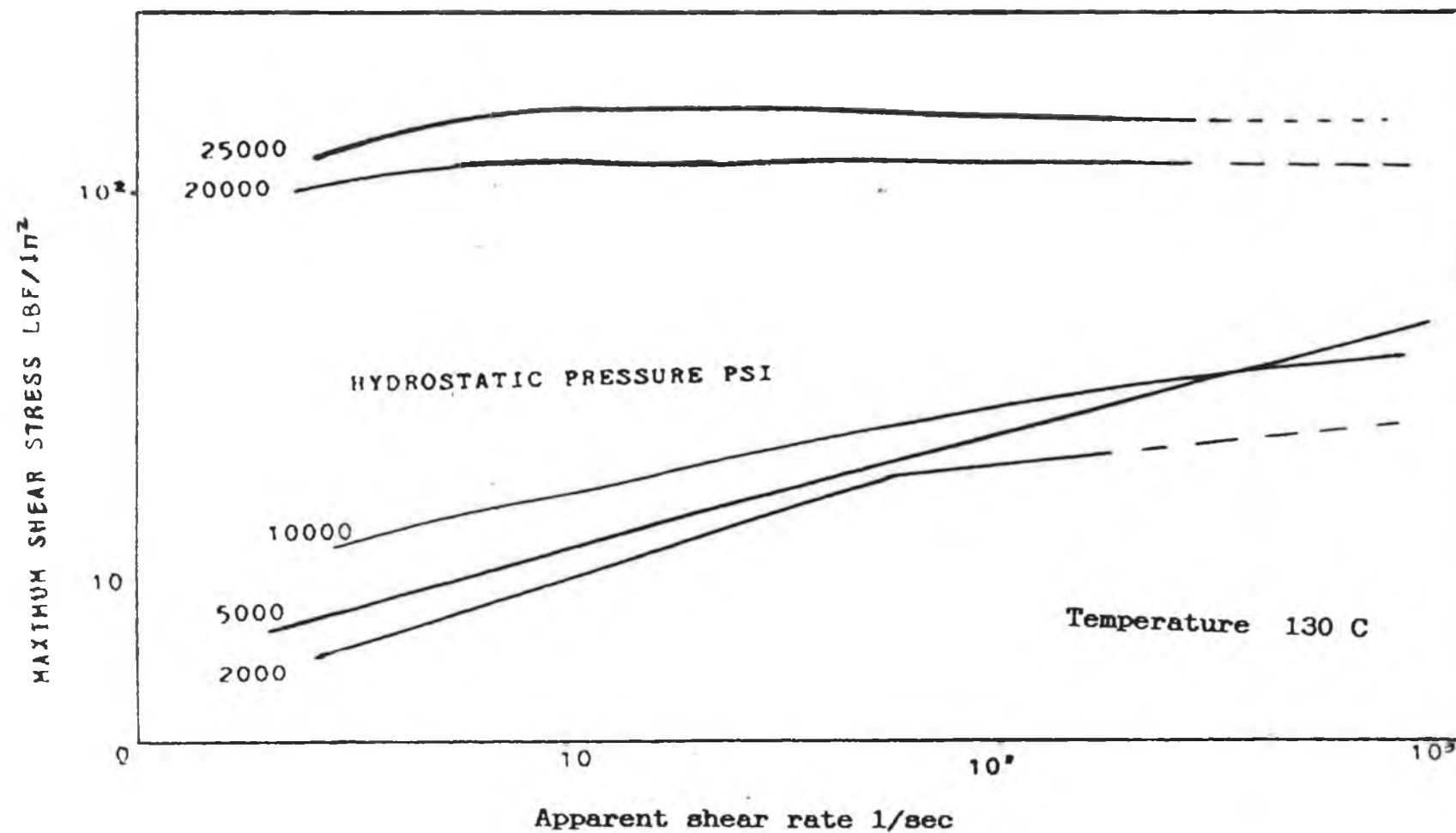


Fig 1.19 Flow curves for
POLYETHYLENE

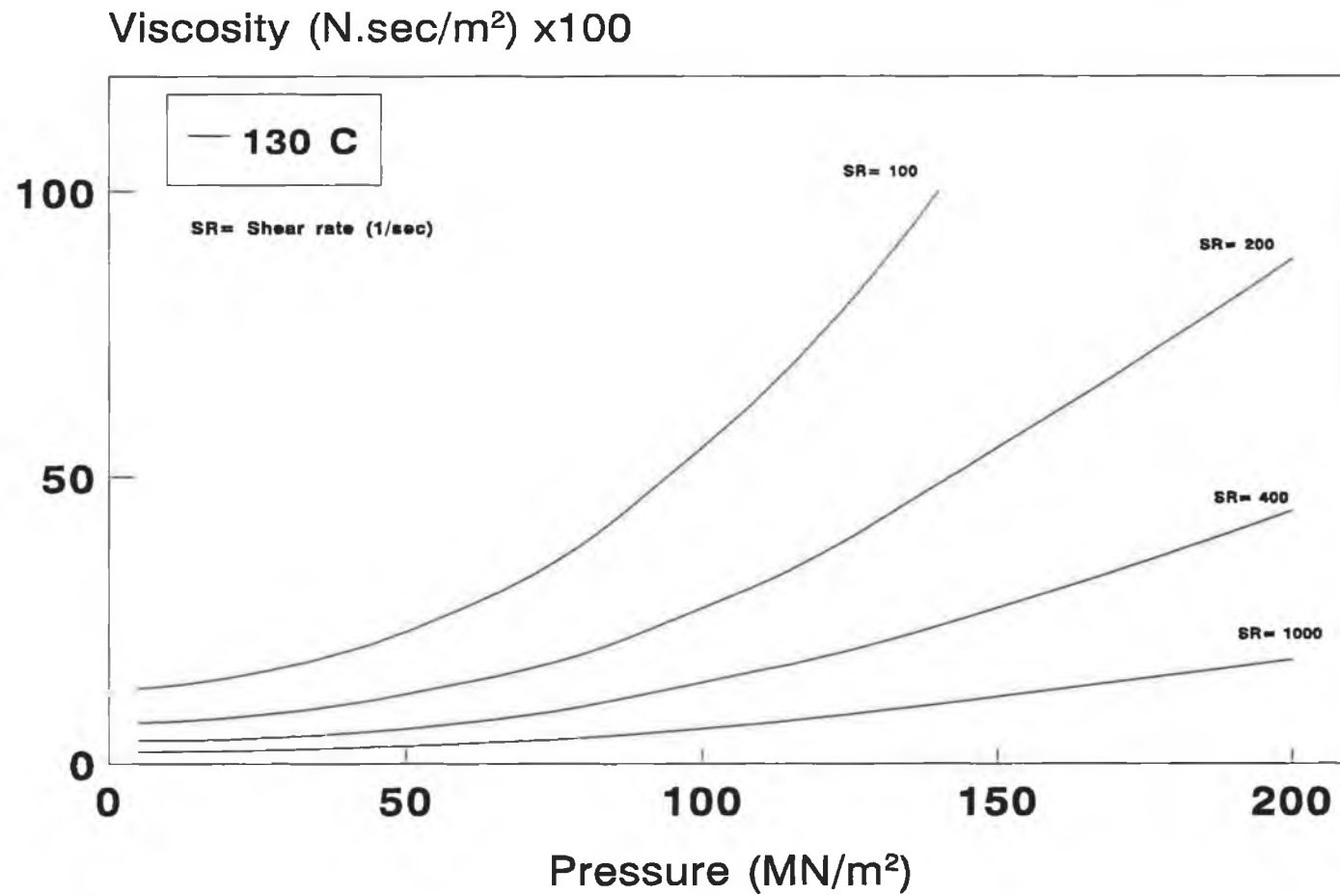


Fig 1.20 Viscosity versus pressure for different shear rates 0.92 POLYETHYLENE

CHAPTER- TWO

EXPERIMENTAL EQUIPMENTS, MATERIALS AND TEST PROCEDURES

2.1- General Description

Experiments were carried out using a general purpose drawing bench which has been adapted and modified. The general view of the drawing bench is shown in plate (4) and Figure 2.2. The total length of the drawing bench is approximately 2 m. The machine is driven by means of an electric motor, squirrel cage 3 kW, 380 volt, 3 phase power supply. The power is transmitted from the motor to the bull block via a coupling type RM 12 F/F fenner coupling with taper lock bushing with an integral speed reduction worm gear box, David Brown type A237 10/1 L position 1 shown in plate (3), using another coupling, fenner type RM 12 with taper lock bushing. The build up of speed is determined by the accelerator set on the frequency inverter which varies the motor speed settings. Actual motor speed in RPM is obtained using a remote hand held digital tachometer- SHIMPO type DT-205 which measures the speed of a rotating mark on the motor output shaft. The above arrangement facilitated drawing speeds infinitely variable between 0.05 and 2.01 m/sec. The accelerator set and the remote hand held digital tachometer are shown in plate (5). The polymer was heated by means of an electric heater band and the temperature was controlled thermostatically within ± 5 °C of the pre-set temperature using a temperature regulator. The temperature was monitored continuously by means of thermo-couples. Two strain gauge based pressure transducers were mounted at different locations in turn on the pressure unit, which enabled the pressure variation along the unit to be measured. The drawing force was measured by means of a piezo-electric load cell, the output from the load cell was fed into

a chart recorder via a charge amplifier, while the output of the pressure transducers was displayed through two recording and display units which provided with the required excitation voltage.

2.2- Modification to the existing rig

To accommodate the load cell, a new housing was designed and fabricated. It consists of a rectangular plate accommodating the load cell at its top end as shown in plate (4). The rectangular plate was provided with a web to minimise any bending deflection.

2.3- Instrumentation

In order to determine the feasibility of the system and the correlation between the theoretical and experimental results, a number of equipments and devices were used to monitor, control display and record various parameters during the drawing tests. These included heater bands, temperature controllers, thermocouple, pressure transducers, charge amplifier, load cell, recording and display units, and the chart recorder, see plate (4).

2.3.1- Pressure transducers

Two "ENTRAN XT21" pressure transducers were used which are made with a bonded strain gauge system making them robust transducers of high accuracy and suitable for both static and dynamic pressure measurements. The maximum working pressure limit of 2000 bar with pressure overload of 750 bar and with a maximum excitation voltage of 20 volts d.c or a.c rms.

2.3.2- Load cell

A quartz load washer (KISTLER type 9001 S.N 330425) which consists of one or two cylinders of quartz crystal, an electrode and a housing with a plug as shown in Figure 2.3 was used. The force to be measured must act uniformly on the annular surface. Owing to the mechanical compressive stress an electrical charge is developed which is proportional to the

change in the force applied and does not depend on the dimensions of the quartz discs (longitudinal piezo-electric effect). The charge produced is picked up by the electrode and transferred to the plug connection. The polarity is arranged so that a compressive force produces a negative charge which is then converted into a positive voltage in the charge amplifier, when the load washer is unloaded, a positive charge results provided that the negative charge generated previously under load is dissipated by shorting on the plug. The maximum load capacity of the load cell is 750 N.

2.3.3- Heater bands

Hollow cartridge heater bands "clampable type" were used to heat the hopper, pressure unit, and the melt chamber. The dimensions are given as follows:

The Pressure unit heater band

Type	I.D mm	Length mm	Volts	Watts
Clampable	66	190	240	1000

The Hopper heater band

Type	I.D mm	Length mm	Volts	Watts
Clampable	48	70	240	1000

The melt chamber heater band

Type	I.D mm	Length mm	Volts	Watts
Clampable	50	60	240	1000

2.3.4- Chart Recorder

The output from the piezo electric load cell was fed into a chart recorder via a charge amplifier. This recorder is made by LINSEIS (Type L 6514-4) and the charge amplifier is supplied by FYLDE (Type FE-128-CA). Plate (4) shows the arrangements for the chart recorder and the charge amplifier.

2.3.5- Temperature Controller

An electronic ON-OFF temperature relay "Type West 3300" was used to control the pre-set temperature. The controller (plate 4) was designed to be used with thermo-couples "type J, K and T" to monitor the temperature. A relay change over contact within the controller operates at a pre-determined temperature previously set by a panel mounted digital temperature indicator model "RS 258-186". The operating temperature range for type J thermo-couple is -25°C to $+625^{\circ}\text{C}$.

2.3.6- Thermo-couples

To monitor the temperature continuously, J type thermo-couples "fibre glass insulated with 2 mm insulation diameter" were used to carry out the experiments. Their working temperature range is 0 to $+450^{\circ}\text{C}$. These are shown in plate (1).

2.4- Design of the pressure units

It was extremely difficult to machine a combined geometry pressure unit (parallel cylindrical hole and a tapered hole at the end of a solid piece of material). Therefore it was necessary to manufacture the unit in two parts, the parallel bore tube before the step and the tapered bore orifice after the step. Because of the need to have variable dimensions it was more practical to make two main blocks as housings to accommodate two separate inserts machined to the required geometrical configuration as shown in Figures 2.5 & 2.6 and plate (1). These two main blocks are bolted together. As the pressure generated is of high

magnitude, the major problem was one of sealing at the edge of the mating parts in order to prevent any leakage during drawing, this design allowed variation in geometrical configuration easier by making modification to the inserts only.

All the parts of the unit were made from orvar supreme steel "tool steel" by machining and drilling operations. Initially the housing cylinders were machined to a rough size close to the final dimensions and finally ground precisely to the required dimensions with a tolerance of 0.015 mm. The inserts were made to press fit in the housing and in the first instance copper seals were used between the inner mating surfaces of the main cylinders to prevent leakage that might occur when a high pressure is generated. Provisions were made in the unit to fit four pressure transducers, two at the tapered bore and the other two on the parallel bore tubes to record the generated hydro-dynamic pressure. Additional holes were also drilled for inserting thermocouples to monitor the temperature of the unit. A heater band was clamped to the unit to heat it to a pre-set temperature.

The simple taper unit was made in a different way, a main block as housing to accommodate the inserts which are made of two parts welded together. This is because it was not possible to drill the tapered passage along the whole length of the insert, provisions were made in the unit to fit three pressure transducers, Figure 2.4, plate (2) shows the tapered bore unit.

2.5- Melt chamber and the hopper

To carry sufficient quantity of polymer melt for a full set of tests, a melt chamber and hopper was designed as shown in plate (4). The hopper facilitated feeding of polymer into the melt chamber and acted as a reservoir. Heater bands were used for heating the melt chamber and the hopper, the temperature was controlled thermo-statically. The melt chamber was bolted to the entrance face of the unit.

2.6- *The pressure fluid*

Polymer melts have been used in die-less drawing process by previous workers because of inherent high viscosity, which permitted reduction of the length of the required reduction unit, offered the flexibility and the provision of a coating of the product for several industrial applications . Several types of polymer melts have previously been tested to meet various industrial requirements in which a melt chamber heated to temperatures suitable for the particular polymer has been used at the entry position of the reduction unit. The thermal conditions of the melt can promote degradation problems of the polymer resulting in the loss of performance of the deformation process.

The present experimental investigation concentrates on the performance of the unit using copper and stainless steel wires and using borosiloxane as pressure fluid.

Borosiloxane polymers have constitutive elements of boron, silicon, oxygen with phenyl or methyl groups. The structure is organised around an Si, O, B chain with either the phenyl or the methyl groups linked to the silicon atoms. The physical characteristics and the properties of the phenyl based and the methyl based borosiloxanes differ. The phenyl based borosiloxanes are used as heat and fire resistant materials while the methyl based borosiloxanes are used for abrasive flow machining where silicon carbides are added to the media to produce the debarring process. The methyl based borosiloxanes have been used in the present investigation. The rheological properties are similar to "bouncing putty" in which the properties are affected by additives such as fillers, pigments and oils. Extrudehone supplies three grades of these borosiloxanes, blue, yellow and red where the resistance to flow is least with the red. The medium range yellow was used in the tests, which has the properties similar to bouncing putty. It is known for it's unusual properties, readily mouldable, easily drawn into threads, rebounds as much as 80% and when struck with a

hammer it will shatter into small pieces [72]. It's cold flow ability and high elastic property makes this type of borosiloxane particularly useful in die-less wire drawing.

$$\mu = \mu_R \exp[- b_T (T - T_R)] \quad (1)$$

The reference viscosity used in the analysis is taken from equation (1) which is derived from Figure 2.1 [81]. This equation is valid for temperature of up to 70 °C at atmospheric pressure. In the present study the maximum pressure within the unit was up to 2000 bar. The reference viscosity was taken to be 50 N.sec/m² based on Figure 2.1. In the absence of any viscosity data at high pressure, this available data at low pressure was used for the theoretical results. Thus, it is likely that some error will be introduced in the magnitudes of the predicted pressure. Although the trends should be predicted reasonably accurately.

2.7- Test procedure

Experimental work was carried out using a purpose built drawing bench instrumented to measure the drawing speed, drawing load and the hydro-dynamic pressure distribution within the combined unit. The schematic diagram of the drawing bench is shown in Figure 2.2. The drawing bench consists of a motorised bull-block for winding the wire, the composite hopper, melt chamber and the pressure unit assembly together with the sliding support. The bench is instrumented to facilitate continuous monitoring and recording of the pressure with the use of strain gauge based pressure transducers which were mounted on the pressure unit at different points to measure the pressure. The drawing force was measured by a piezo-electric load cell connected to a chart recorder via a charge amplifier and the drawing speed was measured using a hand held digital tachometer. Electrical heater bands were used to heat the unit and to melt the polymer. Thermo-couples were used to monitor

and control the temperature through a temperature controller to ensure a constant temperature during the test.

In carrying out the drawing tests, the following procedure was followed.

Before switching "on" the rig, the wire is guided through the met chamber into the pressure unit, over the pulley and then connected to the bull-block and then checked for satisfactory drawing process. The hopper and the melt chamber are filled with enough polymer for a complete test programme. Thermo-couples are attached at appropriate positions so that the temperature can be monitored, controlled thermostatically and maintained at the pre-set level. Pressure transducers are connected to the recording and display units, the load cell is connected to the charge amplifier and then the rig is switched "on" and left for half an hour to reach the steady state temperature level. During the drawing process, the drawing load is noted from the chart recorder and the drawing speed is monitored by a hand held digital tachometer. The diameter of the uncoated wire was measured by a micrometer before starting the test. At the end of each test, the motor, the chart recorder and the recording and display units are switched back to their original positions, test number is recorded on the data sheet and all the parameters are recorded for subsequent collection and analysis

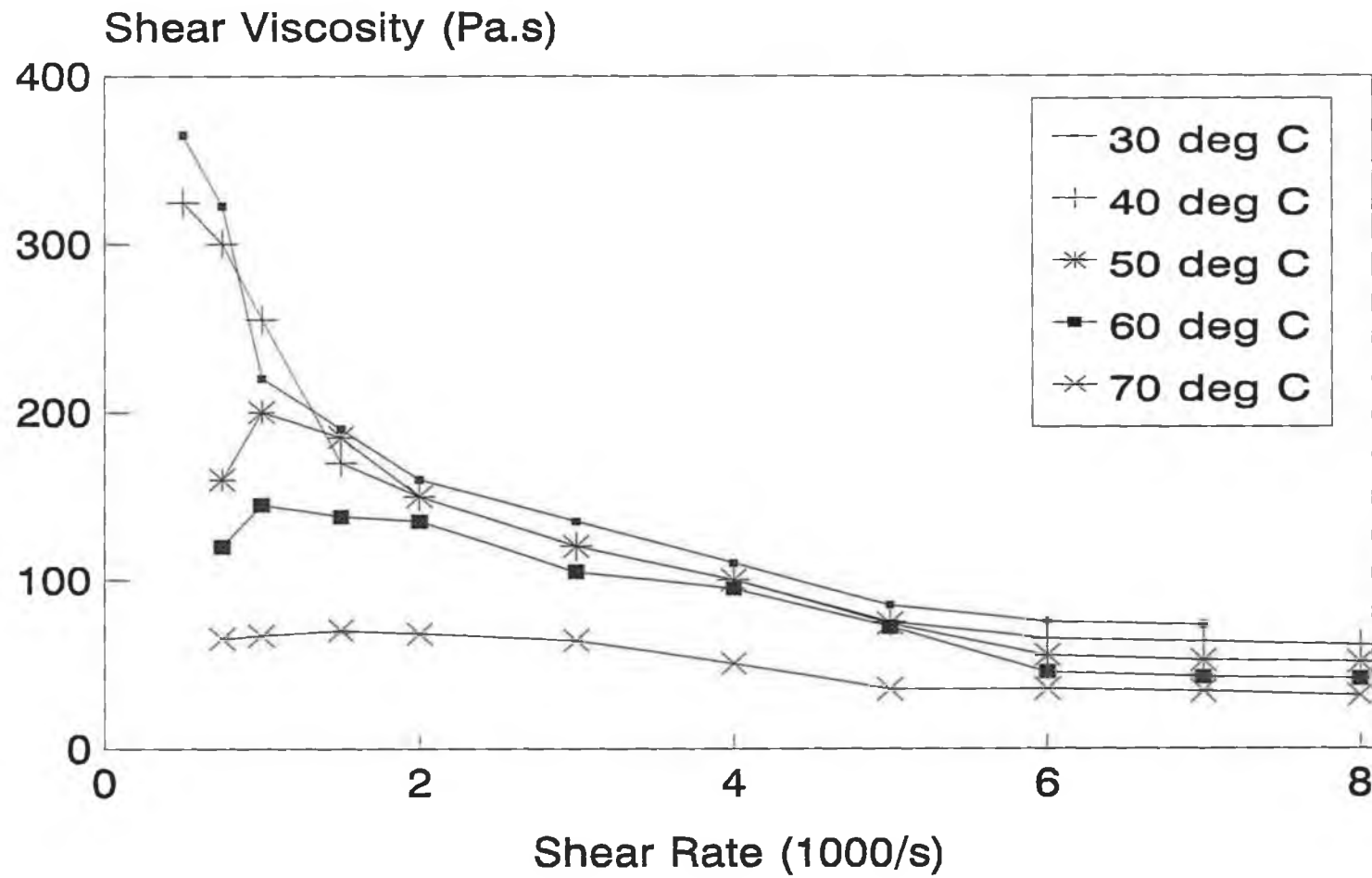


Fig 2.1 Effect of temperature on shear viscosity / shear rate

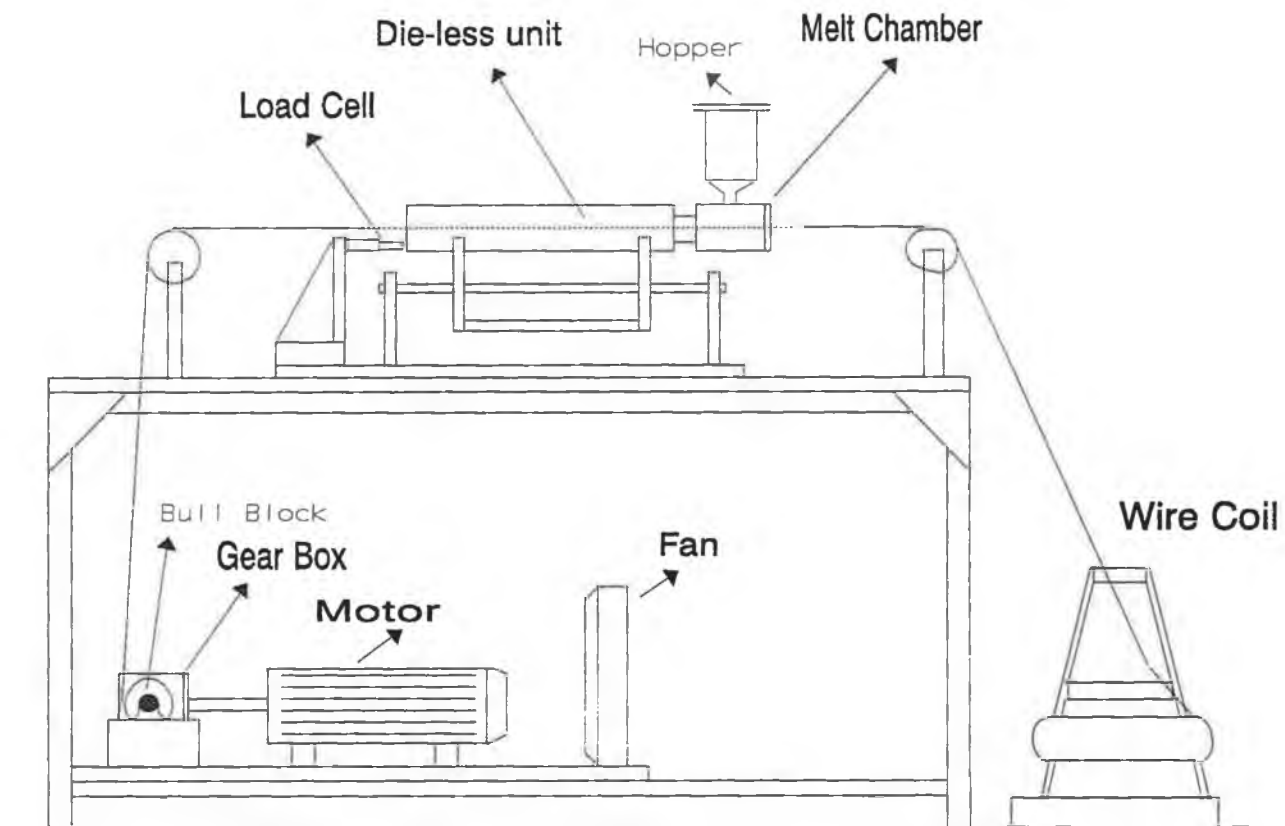
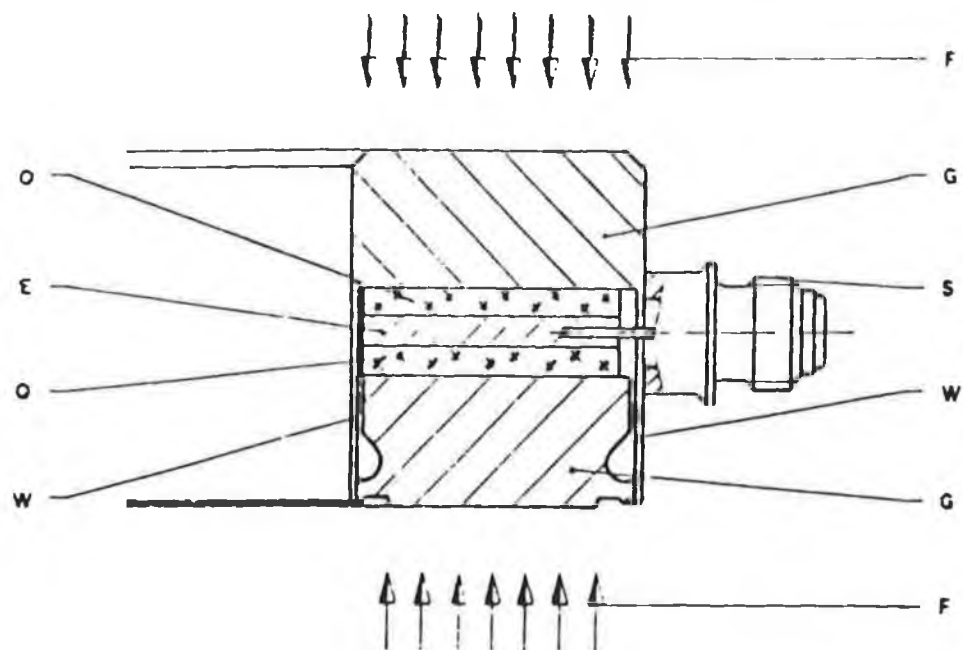


Fig 2.2 General view



- Q = quartz disk
- E = electrode
- W = elastic wall
- G = housing
- S = plug

Fig 2.3 Schematic section through a quartz load cell

Fig 2.4 The Simple Taper Pressure Unit

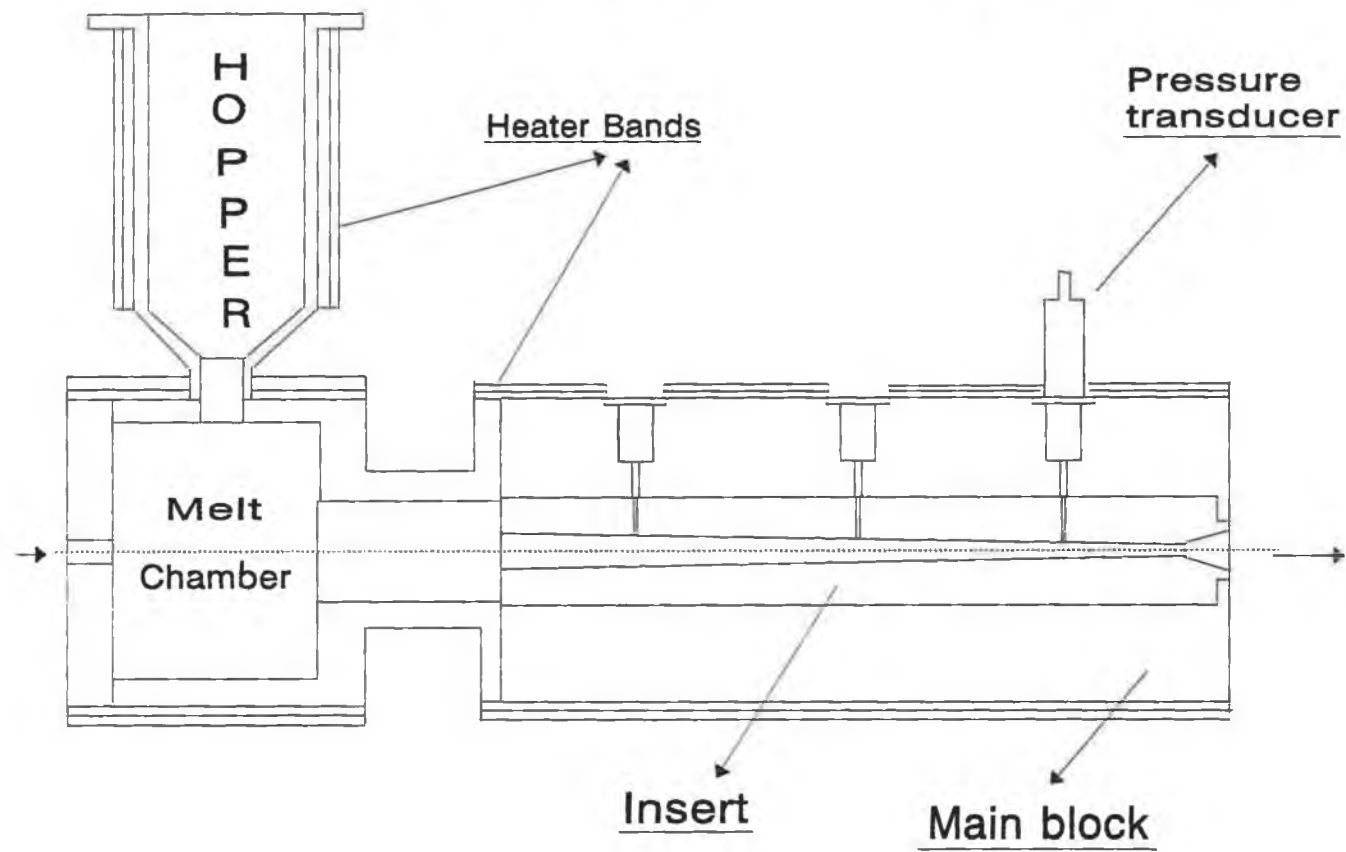


Fig 2.5 Combined Pressure Unit

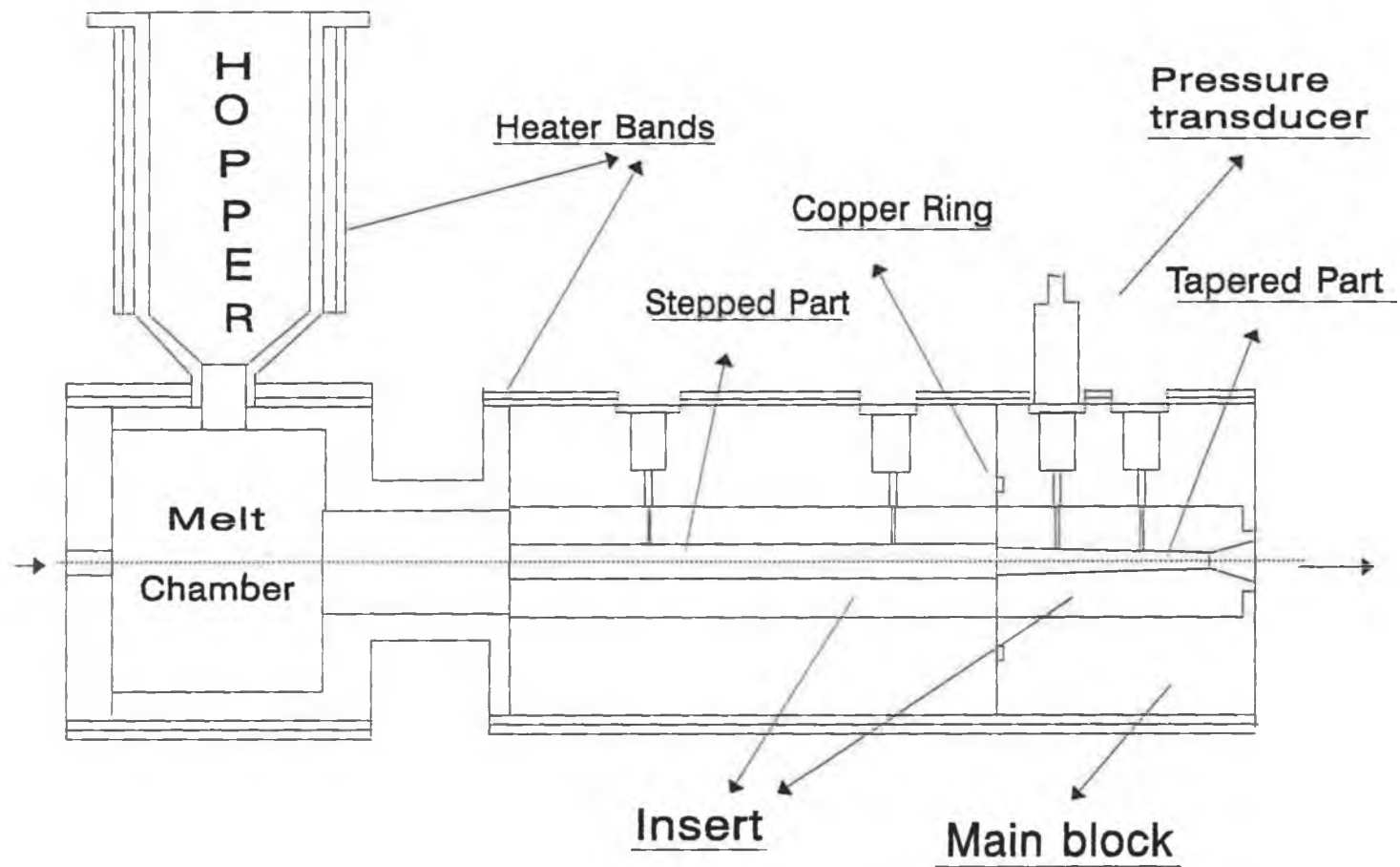
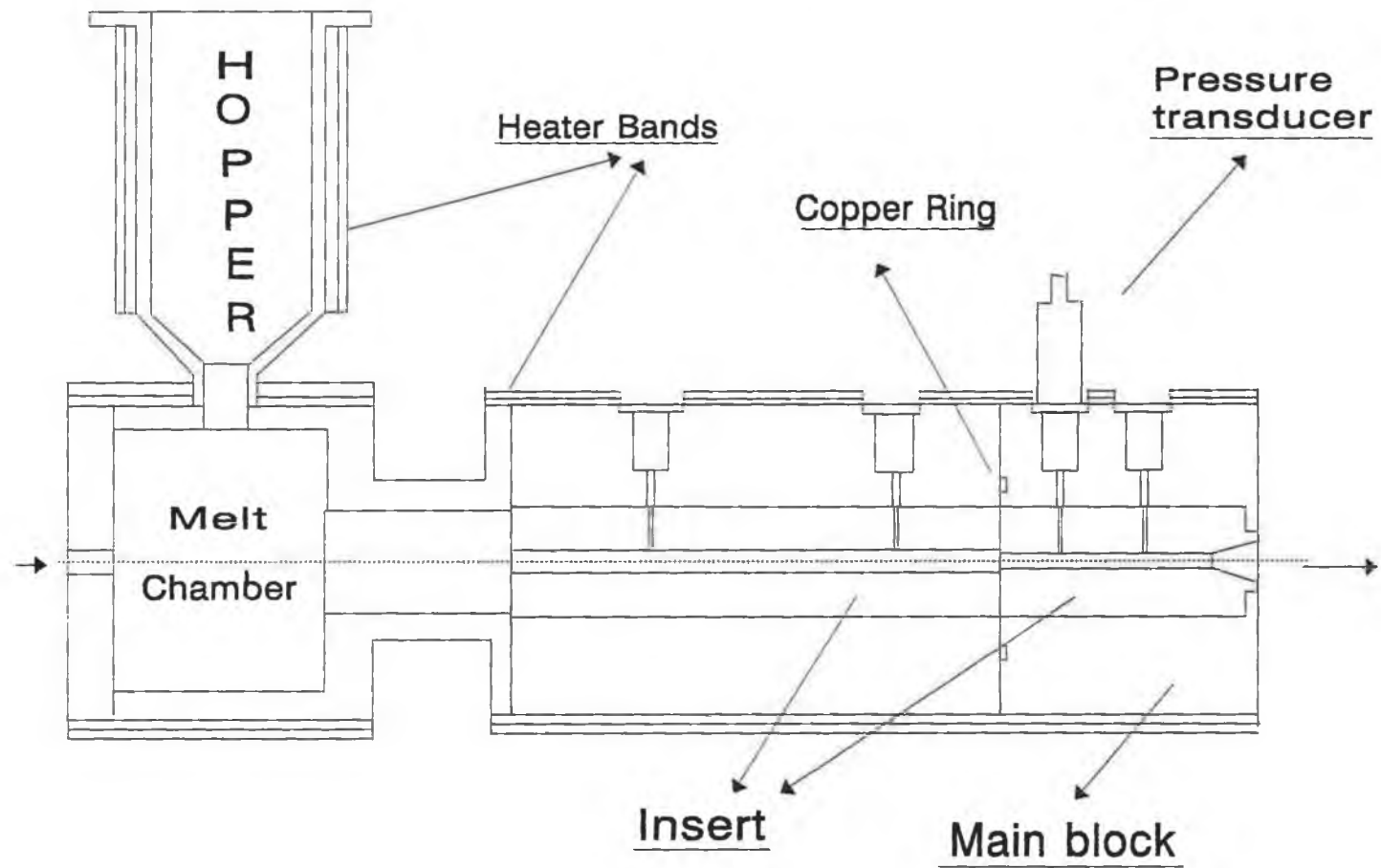


Fig 2.6 The Stepped Bore Unit



Main Blocks

Inserts



Plate No 1. *Combined Pressure Unit Assembly*

Inserts

Pressure Transducers locations

Main Block



Plate No 2. *Simple Taper Pressure Unit*

Pressure Unit

Thermocouple

Pressure Transducer

Load Cell

Hopper

Heater Band

Melt Chamber

Wire

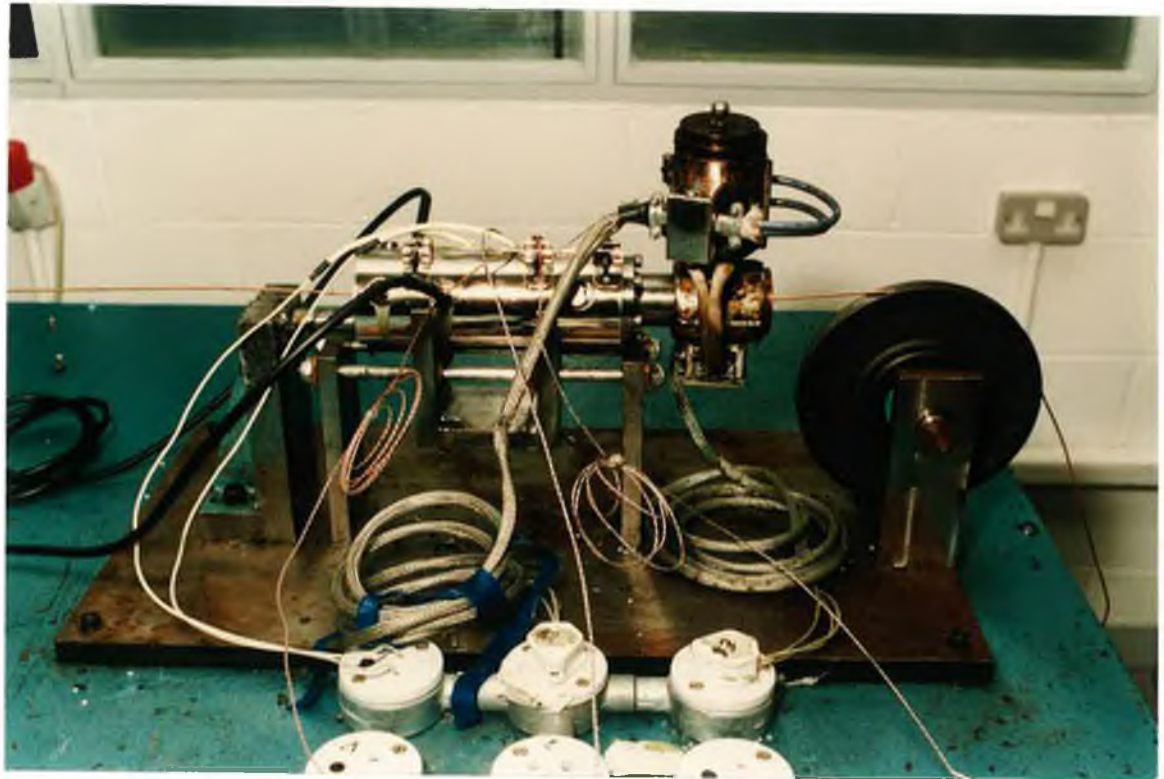


Plate No 3. *General View of pressure unit*

Wire

Bull Block

Motor

Gear Box

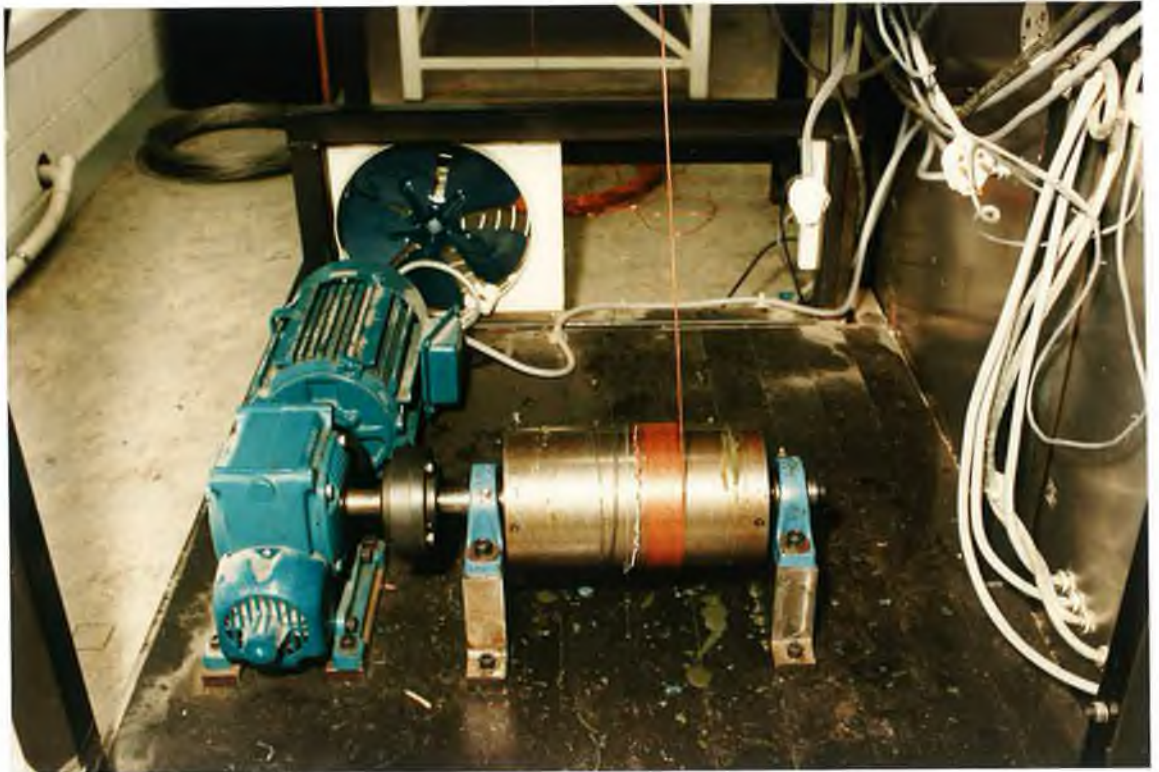


Plate No 4. Power Train

Pressure Unit

Chart Recorder

Temperature Controller



Plate No 5. *General View of the Test Rig*

Amplifier

R.D. Units

M.S. Controller

Tachometer

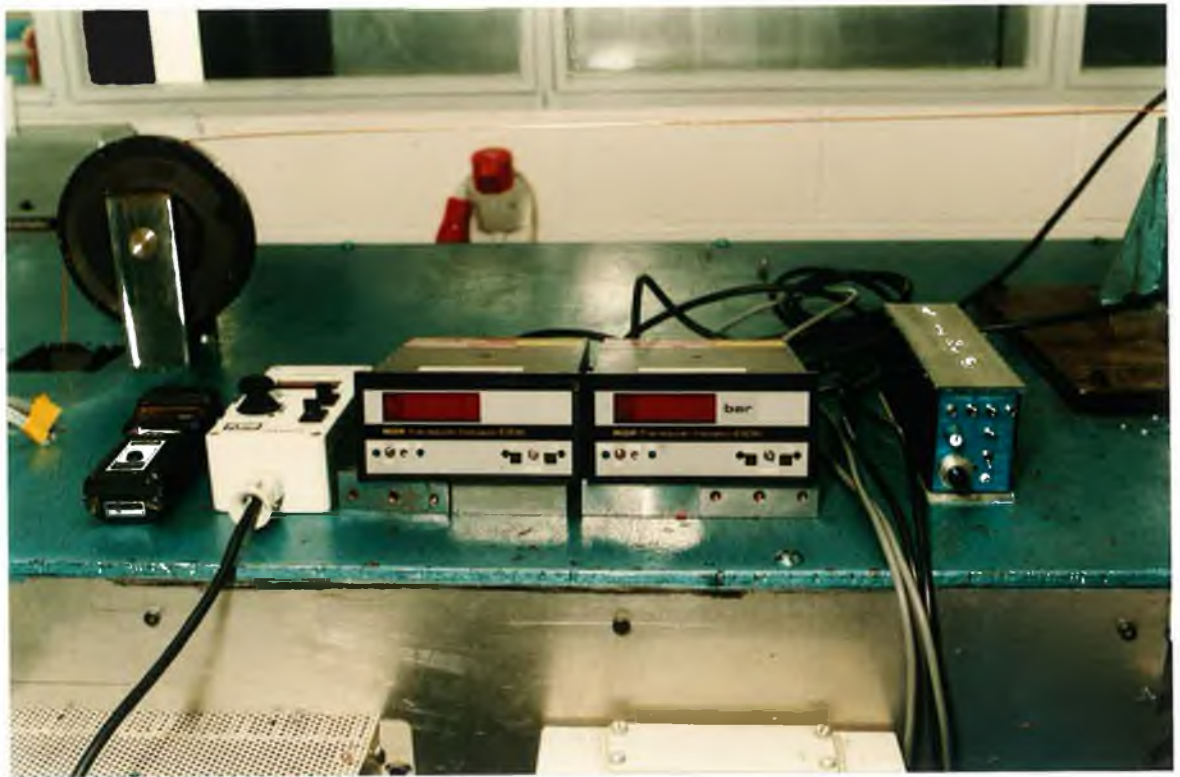


Plate No 6. *Instruments for Measurement of Speed, Pressure, Load*

CHAPTER- THREE

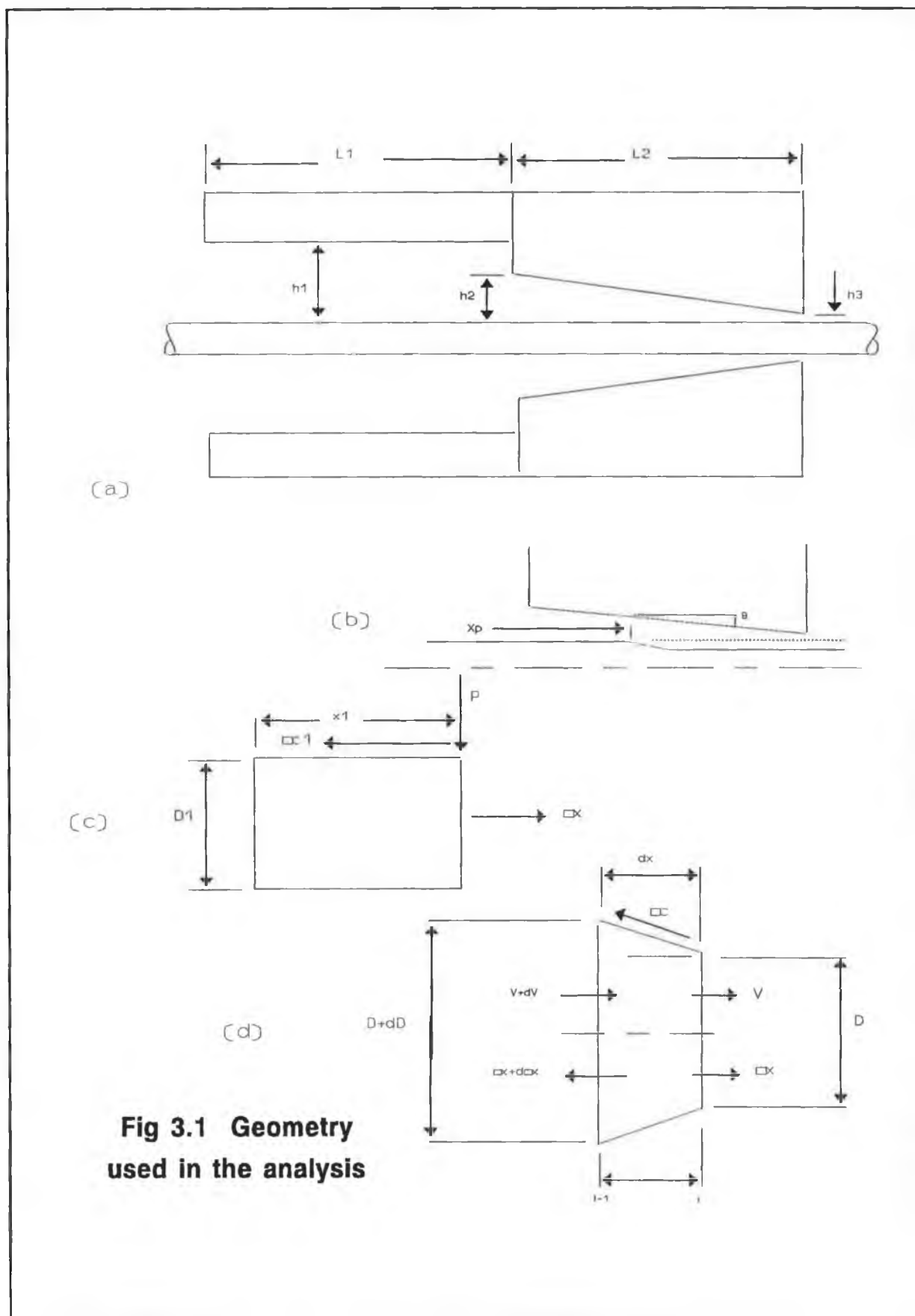
PLASTO-HYDRODYNAMIC ANALYSIS

3.1- Introduction

Several mathematical models developed, for wire drawing were reviewed in chapter 1, with the objectives of determining the friction coefficient, evaluating the drawing stress and the drawing limit. Theoretical and experimental works have also been carried out to observe the effectiveness of different lubricants and to calculate the film thickness during deformation process the presence of hydrodynamic lubrication. All these works were related to the use of conventional reduction dies. Theoretical solutions for a novel plasto-hydrodynamic die-less drawing process were presented in references 59 to 73 for circular cross-section wires and rectangular strip.

In the present study the geometrical configuration of the unit is different from the conventional one, in which no reduction die is used and like the die-less system the minimum bore size of the combined stepped and tapered bore reduction unit is greater than the diameter of the undeformed wire.

In order to study and verify the mechanics of the process of hydro-dynamic pressure development within both sections of the combined geometry unit, it is important to develop a suitable mathematical model. As a first step, such a model has been developed based on the assumption that the pressure medium demonstrates non-Newtonian characteristics.



3.2- Theoretical analysis

The following analysis is based on the geometrical configuration shown in Figure 3.1.

To formulate the analysis the following assumptions were made:

- i)- The flow of polymer melt is axial and laminar.
- ii)- The thickness of the polymer layer is small compared to the unit dimensions.
- iii)- The shear stress in the polymer melt is assumed to be constant for a constant drawing speed.
- iv)- The fluid has the characteristics of non-Newtonian fluid , namely, the viscosity is dependent on the shear rate and the pressure.
- v)- The deformation of the wire takes place isothermally.

3.2.1- Determination of the pressure within the combined unit

Analysis of the combined geometry reduction unit is presented in the following parts;

- 1- Determination of the pressure in the parallel part of the unit.
- 2- Determination of the pressure in the tapered part of the unit.

3.2.1.1- Determination of the pressure in the stepped parallel part of the unit

The relationship between the pressure and the shear stress gradient in the first part of the unit is given by,

$$\left(\frac{dP_1}{dx}\right) = \left(\frac{d\tau_1}{dy}\right) \quad (2)$$

An empirical equation has been proposed by RABINOWITSCH [58] for polymer melt relating shear stress to shear rate,

$$\tau_1 + k\tau_1^3 = \mu\left(\frac{du}{dy}\right) \quad (3)$$

This equation was later used by HUNG and MUSTER [74] to determine the non-Newtonian flow in a step bearing and also by SWAMY et al [75] to calculate the load capacity of a finite width journal bearing. Other workers have also used this equation to analyze the behaviour of non-Newtonian fluids [76,77,78].

Flow of polymer melt in the unit is divided into two sections, the first section being the entry part of the unit before the step and the second section being the tapered bore after the step. Considering the first part of the unit in Figure 3.1(a), the steady state flow of polymer is given by equation (2) in which after integration w.r.to y gives;

$$\left(\frac{dP_1}{dx}\right) y + C_1 = \tau_1$$

where C_1 is a constant.

At the surface of the wire $y=0$ and $\tau_1 = \tau_{cl}$ so that,

$$\left(\frac{dP_1}{dx}\right) y + \tau_{cl} = \tau_1 \quad (4)$$

Noting that $\tau = \tau_1$ in equation (3) and combining equation (3) and (4) gives,

$$\mu \left(\frac{du_1}{dy}\right) = \left(\frac{dP_1}{dx}\right) y + \tau_{cl} + k \left[\left(\frac{dP_1}{dx}\right) y + \tau_{cl} \right]^3$$

Integration of the above equation w.r.to y gives,

$$\begin{aligned} \mu u_1 = & \left(\frac{dP_1}{dx}\right) \frac{y^2}{2} + \tau_{cl} y + k \left[\left(\frac{dP_1}{dx}\right)^3 \frac{y^4}{4} + \left(\frac{dP_1}{dx}\right)^2 y^3 \tau_{cl} \right. \\ & \left. + \left(\frac{dP_1}{dx}\right) \frac{3 y^2 \tau_{cl}^2}{2} + \tau_{cl}^3 y \right] + C_2 \end{aligned}$$

where C_2 is a constant.

The boundary conditions at speeds at which slip does not occur are,

$$(a_1) \text{ at the wire surface} \quad y=0, \quad u_1=V$$

$$(b_1) \text{ at the unit surface} \quad y=h_1, \quad u_1=0$$

where V is the velocity of the undeformed wire. Substituting condition (a₁) into the above equation $V=C_2/\mu$, so that

$$u_1 = \left(\frac{dP_1}{dx}\right) \frac{y^2}{2\mu} + \frac{\tau_{cl}y}{\mu} + \frac{k}{\mu} \left[\left(\frac{dP_1}{dx}\right)^3 \frac{y^4}{4} + \left(\frac{dP_1}{dx}\right)^2 y^3 \tau_{cl} \right. \\ \left. + \left(\frac{dP_1}{dx}\right) \frac{3y^2 \tau_{cl}^2}{2} + \tau_{cl}^3 y \right] + V \quad (5)$$

Applying the boundary condition (b₁) to find τ_{cl} at the surface of the pressure unit,

$$0 = \left(\frac{dP_1}{dx}\right) \frac{h_1^2}{2\mu} + \frac{\tau_{cl}h_1}{\mu} + \frac{k}{\mu} \left[\left(\frac{dP_1}{dx}\right)^3 \frac{h_1^4}{4} + \left(\frac{dP_1}{dx}\right)^2 h_1^3 \tau_{cl} \right. \\ \left. + \left(\frac{dP_1}{dx}\right) \frac{3h_1^2 \tau_{cl}^2}{2} + \tau_{cl}^3 h_1 \right] + V$$

Rearranging the above equation in terms of the power of τ_{cl}

$$\tau_{cl}^3 + \left(\frac{dP_1}{dx}\right) \frac{3h_1 \tau_{cl}^2}{2} + \tau_{cl} \left[\frac{1}{k} + \left(\frac{dP_1}{dx}\right)^2 h_1^2 \right] \\ + \left[\left(\frac{dP_1}{dx}\right) \frac{h_1}{2k} + \left(\frac{dP_1}{dx}\right)^3 \frac{h_1^3}{4} + \frac{\mu V}{kh_1} \right] = 0$$

let,

$$J_1 = \frac{1}{k} + \left(\frac{dP_1}{dx}\right) \frac{3h_1}{2}$$

and

$$M_1 = \frac{1}{k} + \left(\frac{dP_1}{dx}\right)^2 h_1^2$$

and

$$N_1 = \left(\frac{dP_1}{dx}\right) \frac{h_1}{2k} + \left(\frac{dP_1}{dx}\right)^3 \frac{h_1^3}{4} + \frac{\mu V}{kh_1}$$

hence,

$$\tau_{cl}^3 + J_1 \tau_{cl}^2 + M_1 \tau_{cl} + N_1 = 0 \quad (6)$$

For further simplification let,

$$\tau_{cl} = \left(\Phi - \frac{j_1}{3}\right) \quad (7)$$

Substitute equation (7) into equation (6) we have,

$$\left(\Phi - \frac{j_1}{3}\right)^3 + j_1 \left(\Phi - \frac{j_1}{3}\right)^2 + M_1 \left(\Phi - \frac{j_1}{3}\right) + N_1 = 0 \quad (8)$$

Which after substituting for J_1 , M_1 and N_1 simplification becomes,

$$\Phi^3 + \Phi \left[\frac{1}{k} + \left(\frac{dP_1}{dx}\right)^2 \frac{h_1^2}{4} \right] + \frac{\mu V}{kh_1} = 0$$

Which may be written as,

$$\Phi^3 + A_1 \Phi + B_1 = 0 \quad (8.1)$$

where,

$$A_1 = \frac{1}{k} + \left(\frac{dP_1}{dx}\right)^2 \frac{h_1^2}{4}$$

and,

$$B_1 = \frac{\mu V}{kh_1}$$

Equation (8.1) is a cubic equation which could be solved as following; let

$$\phi^3 + 3P\phi + 2q = 0$$

where $3P = A_1$ or $P = A_1/3$ & $2q = B_1$ or $q = B_1/2$

The discriminant of the above equation is,

$$J_1 = -P^3 - q^2$$

Which may be written as,

$$J_1 = -\frac{A_1^3}{27} - \frac{B_1^2}{4}$$

The real root of the equation is,

$$\Phi = U + V$$

where,

$$U = [-q + (q^2 + P^3)^{\frac{1}{2}}]^{\frac{1}{3}}$$

$$V = [-q - (q^2 + P^3)^{\frac{1}{2}}]^{\frac{1}{3}}$$

That gives,

$$\Phi = [-q + (q^2 + P^3)^{\frac{1}{2}}]^{\frac{1}{3}} + [-q - (q^2 + P^3)^{\frac{1}{2}}]^{\frac{1}{3}}$$

Substituting for ϕ , A_1 , B_1 and J_1 into the above equation we obtain,

$$\begin{aligned}\tau_{cl} = & \left(-\frac{\mu V}{2kh_1} + \left[\frac{\mu^2 V^2}{4k^2 h_1^2} + \frac{1}{27} \left(\frac{1}{k} + \left(\frac{dP_1}{dx} \right)^2 \frac{h_1^2}{4} \right)^3 \right]^{\frac{1}{2}} \right)^{\frac{1}{3}} \\ & + \left(-\frac{\mu V}{2kh_1} - \left[\frac{\mu^2 V^2}{4k^2 h_1^2} + \frac{1}{27} \left(\frac{1}{k} + \left(\frac{dP_1}{dx} \right)^2 \frac{h_1^2}{4} \right)^3 \right]^{\frac{1}{2}} \right)^{\frac{1}{3}} \\ & + \frac{h_1}{2} \left(\frac{dP_1}{dx} \right)\end{aligned}\quad (9)$$

The above equation (9)² gives the shear stress on the wire before deformation for known values of (dp/dx) . The flow of liquid polymer in the axial direction within the gap before the step may be given by,

$$Q_1 = \int_0^{h_1} u_1 dy$$

Substituting for u_1 into the above equation and integrating,

$$\begin{aligned}Q_1 = & \left(\frac{dP_1}{dx} \right) \frac{h_1^3}{6\mu} + \frac{\tau_{cl} h_1^2}{2\mu} + \frac{k}{\mu} \left[\left(\frac{dP_1}{dx} \right)^3 \frac{h_1^5}{20} \right. \\ & \left. + \left(\frac{dP_1}{dx} \right)^2 \frac{h_1^4 \tau_{cl}}{4} + \left(\frac{dP_1}{dx} \right) \frac{h_1^3 \tau_{cl}^2}{2} + \frac{\tau_{cl}^3 h_1^2}{2} \right] + Vh_1\end{aligned}\quad (10)$$

The flow of liquid polymer obey the continuity equation so that,

$$\frac{dQ_x}{dx} + \frac{dQ_y}{dy} + \frac{dQ_z}{dz} = 0$$

Under axial and laminar flow condition,

² This equation does not allow to obtain Newtonian solution by putting $k=0$

$$\frac{dQ_y}{dy} = \frac{dQ_z}{dz} = 0$$

and hence,

$$\frac{dQ_x}{dx} = 0$$

Substitute for τ_{c1} from equation (9) into equation (10) and noting that h_1 , μ and V are constants and that $dQ_x/dx=0$, it is shown that,

$$\left(\frac{dP_1}{dx}\right) = \frac{P_{step}}{L_1} = \text{Constant}$$

Where P_{step} is the pressure at the step and L_1 is the length of the first part of the unit. Thus the pressure profile in the first part of the unit is linear. However, P_{step} cannot be determined at this stage since equation (10) contains the unknown variable Q_1 and it must be defined.

3.2.1.2- Determination of the pressure in the tapered part of the unit

It is necessary to establish the flow equation for the second part of the unit before P_{step} can be predicted. The pressure gradient within the second part of the unit under steady state flow condition may be expressed as,

$$\left(\frac{dP_2}{dx}\right) = \left(\frac{d\tau_2}{dy}\right) \quad (11)$$

The shear stress and the shear rate related by

$$\tau_2 + k\tau_2^3 = \mu\left(\frac{du_2}{dy}\right) \quad (12)$$

Differentiating equation (12) w.r.to y gives,

$$\left(\frac{d\tau_2}{dy}\right) + 3k\tau_2^2 \left(\frac{d\tau_2}{dy}\right) = \mu \left(\frac{d^2u_2}{dy^2}\right)$$

Substituting for $d\tau_2/dy$ from equation (11) into the above equation and integrating w.r.to y gives,

$$\left(\frac{dP_2}{dx}\right) y + 3k\tau_2^2 \left(\frac{dP_2}{dy}\right) + C_3 = \mu \left(\frac{du_2}{dy}\right)$$

where C_3 is a constant. The above equation upon integration again w.r.to y becomes,

$$\left(\frac{dP_2}{dx}\right) \frac{y^2}{2} + 3k\tau_2^2 \left(\frac{dP_2}{dx}\right) \frac{y^2}{2} + C_3 y + C_4 = \mu u_2 \quad (13)$$

where C_3 and C_4 are constants.

The boundary conditions need to be applied to determine the constants C_3 and C_4 . Thus,

the boundary condition at the wire surface, $(a_2) \quad y=0 \quad , \quad u_2=V$

and at the surface of the unit, $(b_2) \quad y=h \quad , \quad u_2=0$

where V is the velocity of the undeformed wire. Substituting condition (a_2) into the above equation gives,

$$C_4 = \mu V$$

Applying condition (b_2) gives,

$$C_3 = - \left(\frac{dP_2}{dx}\right) \frac{h}{2} - \left[\left(\frac{dP_2}{dx}\right) \frac{3hk\tau_2^2}{2} \right] - \frac{\mu V}{h}$$

Substituting for C_3 and C_4 into equation (13) gives,

$$u_2 = \left[\left(\frac{dP_2}{dx} \right) \frac{y^2}{2\mu} \right] + \left[\left(\frac{dP_2}{dx} \right) \frac{3k\tau_2 y^2}{2\mu} \right] - \left[\left(\frac{dP_2}{dx} \right) \frac{hy}{2\mu} \right] - \left[\left(\frac{dP_2}{dx} \right) \frac{3hk\tau_2^2 y}{2\mu} \right] - \frac{Vy}{h} + V \quad (14)$$

The flow equation in the second part of the unit is given by,

$$Q_2 = \int_0^h u_2 dy$$

Which after integration becomes,

$$Q_2 = - \left(\frac{dP_2}{dx} \right) \frac{h^3}{6\mu} - \left(\frac{dP_2}{dx} \right) \frac{kh^3\tau_2^2}{4\mu} + \frac{Vh}{2} \quad (15)$$

Differentiating the above equation w.r.to x and integrating again and noting that $dQ_2/dx=0$ we have,

$$\left[\left(\frac{dP_2}{dx} \right) \frac{h^3}{6\mu} \right] + \left[\left(\frac{dP_2}{dx} \right) \frac{kh^3\tau_2^2}{2\mu} \right] = Vh + C_5 \quad (16)$$

where C_5 is a constant.

The maximum pressure occurs at the point where $(dP/dx)=0$, so let $h=\bar{h}$ be the gap thickness at that point which gives,

$$C_5 = -V\bar{h}$$

Which after substituting back into equation (16) gives,

$$\left[\left(\frac{dP_2}{dx} \right) \frac{h^3}{6\mu} \right] + \left[\left(\frac{dP_2}{dx} \right) \frac{kh^3\tau_2^2}{2\mu} \right] + V[\bar{h}-h] = 0$$

Rearranging after dividing by $(h^3/6\mu)$ gives,

$$\left(\frac{dP_2}{dx}\right) = \frac{6\mu V}{[1 + 3k\tau_2^2]} \left[\frac{1}{h^2} - \frac{\bar{h}}{h^3} \right] \quad (17)$$

From the geometry of the unit in Figure 3.1(b),

$$B = \frac{h_2 - h_3}{L_2}$$

Integrating equation (17) w.r.to x and noting that the shear stress at the wire surface remains constant for a given speed,

$$P_2 = \frac{6\mu V}{B[1 + 3k\tau_2^2]} \left[\frac{1}{h_2 - Bx_2} - \frac{\bar{h}}{2(h_2 - Bx_2)^2} \right] + C_6 \quad (17.a)$$

where P_2 is the pressure at any point within the second part of the unit and C_6 is a constant.

The boundary condition that may be applied to determine the constant C_6 is,

$P_2 = 0$, at $x_2 = L_2$ and $h = h_3$ so that,

$$C_6 = \frac{-6\mu V}{B[1 + 3k\tau_2^2]} \left[\frac{1}{h_3} - \frac{\bar{h}}{2h_3^2} \right]$$

Substituting back for C_6 into the equation (17.a) we get,

$$P_2 = \frac{6\mu V}{B[1 + 3k\tau_2^2]} \left[\frac{1}{h} - \frac{1}{h_3} + \frac{\bar{h}}{2h_3^2} - \frac{\bar{h}}{2h^2} \right] \quad (18)$$

When $P_2 = P_{\text{step}}$, at $h = h_2$ this gives,

$$P_{step} = \frac{6\mu V}{B[1 + 3k\tau_2^2]} \left[\frac{1}{h_2} - \frac{1}{h_3} + \frac{\bar{h}}{2h_3^2} - \frac{\bar{h}}{2h_2^2} \right] \quad (19)$$

The continuity of flow gives,

$$Q_1 = Q_2$$

Equating equation (10) and equation (15) gives,

$$Q_2 = - \left[\left(\frac{dP_2}{dx} \right) \frac{h^3}{12\mu} \right] - \left[\left(\frac{dP_2}{dx} \right) \frac{kh^3\tau_2^2}{4\mu} \right] + \frac{Vh}{2} = Q_1 \quad (19.a)$$

For maximum pressure $(dP_2/dx) = 0$ at $h = \bar{h}$ so that,

$$Q_2 = \frac{V\bar{h}}{2} = Q_1$$

and,

$$\bar{h} = \frac{2Q_1}{V} \quad (20)$$

Then the maximum pressure equation is obtained by substituting $\bar{h}$ for h in equation (18).

Thus,

$$P_{max} = \frac{6\mu V}{B[1 + 3K\tau_2^2]} \left[-\frac{1}{h_3} + \frac{\bar{h}}{2h_3^2} + \frac{1}{2\bar{h}} \right] \quad (21)$$

The drawing force in the second part of the unit is given by,

$$F_d = - \int_0^{x_2} \pi D \tau_2 dx$$

which after integration becomes,

$$F_d = \pi D x_2 \tau_2 \quad (21.a)$$

The drawing stress within the second part of the unit is given by,

$$\sigma_2 = \frac{4F_d}{D^2} = \frac{4x_2\tau_2}{D} \quad (21.b)$$

where D is the wire diameter.

3.2.2- Solution procedure

It is shown that the pressure profile in the second part of the unit is not linear. It is known that the viscosity of polymer melt is dependent on the pressure and this effect should be taken into account in the analysis for satisfactory solution. With reference to Figure (3.1.a) a generalized equation relating viscosity and pressure may be shown to take the form,

$$\mu = \mu_0 + \frac{(a + b P_{av}^2)}{\dot{\gamma}} \quad (22)$$

where a and b are constants and μ_0 is the initial viscosity of polymer melt at ambient pressure. $\dot{\gamma}$ is the apparent shear rate and is given by,

$$\dot{\gamma} = \frac{V}{h_a}$$

where V is the velocity and $h_a = (h_2 + h_3)/2$, is the average tapered gap thickness. Equation (22) gives the pressure and the shear rate dependent viscosity of the pressure fluid. The solution for the pressure distribution is then obtained using a systematic solution programme combining equations (21),(9),(10),(15),(18),(19),(19.a) and (20).

The first step is to assume an arbitrary low value for the P_{av} in equation (22) for a selected drawing speed, V and determine viscosity, μ . The next step is to assume an arbitrary low value for the pressure P_{step} and calculate τ_{c1} , Q_1 and $\bar{h}$ using equation (9), (10) and (20)

respectively. Then, in order to verify, calculate, P_{step} , using equation (19) and compare with the assumed value of P_{step} . If they are not equal within a set level of error limit then the assumed magnitude is increased by certain step size and the process is repeated iteratively until agreement is reached.

Then the area under the pressure distribution curve is determined making use of equation (18) and the average pressure is calculated. Should this calculated P_{av} be equal (within certain error margin of ± 0.5 percent) with the previously assumed value of P_{av} and $Q_1 = Q_2$ (from equation (20)), then the values of μ , τ_{c1} , Q_1 , P_{step} and P_{max} have been established. If not, then increase the assumed magnitude of P_{av} and repeat the calculations as above until the agreement is reached.

3.2.3- Plastic yielding

The combined effect of the axial stress and the hydrodynamic pressure will cause plastic yielding of the wire at any point " x_p " within the pressure unit as soon as the plastic yield criteria is satisfied. If the material of the wire is assumed to be rigid non-linearly strain hardening such that the flow stress could be expressed as,

$$Y = Y_0 + S\epsilon^n$$

Then according to the Tresca yield criterion plastic yielding will commence at a point x_p , provided that,

$$P + \sigma_x = Y_0 \quad (23)$$

3.2.3.1- Before the step

Hence, for a known value of Y_0 , equation (23) could be solved for x_p after substituting for P and x_p from equations (18) and (21.b) respectively. Once plastic yielding

is predicted to commence for a given value of V and the geometrical parameters of the unit, further permanent deformation of the wire should continue to take place as long as,

$$P + \sigma_x \geq Y = Y_0 + S\varepsilon^n \quad (24)$$

is satisfied. At distance x_p from the entry of the unit where yielding just occur the principal stresses acting on the wire are,

$$\sigma_1 = \sigma_{xp} \quad \text{and} \quad \sigma_2 = \sigma_3 = -P_{xp}$$

where σ_{xp} is the axial stress on the wire and P_{xp} is the radial pressure at point x_p . From equation (23) we get,

$$\sigma_{xa} + P_{xa} = Y$$

Equilibrium of forces on the wire in x direction gives,

$$\sigma_{xa} \left(\frac{\pi D_1^2}{4} \right) = (\pi D_1 x_a) \tau_{cl}$$

hence,

$$\sigma_{xa} = \frac{4x_a \tau_{cl}}{D_1} \quad (24.a)$$

Also the pressure at any point may be expressed as,

$$P_{xa} = \frac{P_{step} x_a}{L_1} \quad (24.b)$$

So the yield characteristics of the wire will take the form of equation (24) and yield will occur as soon as,

$$Y = Y_0$$

Substituting equations (23), (24.a), into equation (24.b) and rearranging, the yielding position

is obtained as,

$$x_a = \frac{Y_0}{\frac{4\tau_{cl}}{D_1} + \frac{P_{step}}{L_1}} \quad (24.c)$$

Plastic deformation will continue as long as equation (24) is satisfied.

Consider a section of the first part within the unit in which the wire is plastically deformed as shown in Figure (3.1.d) Since the variation of the wire diameter is to be determined theoretically, and is not pre-defined as function of x_p , the equations containing this variable, cannot be solved analytically. Hence a finite-difference technique is adopted to solve the differential equations governing the deformation zone assuming that between any two points of distance dx apart on the deforming wire, the deformation takes place linearly,

$$\frac{dD}{2dx} = \text{constant} = B$$

Expressing this equation in finite-difference form gives,

$$D_i = D_{i-1} - 2B_i\Delta x \quad (24.d)$$

And similarly, for the variation of the gap,

$$dh = \frac{dD}{2}$$

hence,

$$h_i = h_{i-1} + B_i\Delta x \quad (24.e)$$

where B_i is the slope of the deformation profile within distance Δx . Considering a small section of the wire, the radial equilibrium of forces gives,

$$\sigma_r (\pi D dx) = - P (\frac{\pi D dx}{\cos \alpha}) \cos \alpha + \tau_c (\frac{\pi D dx}{\cos \alpha}) \sin \alpha$$

hence,

$$\sigma_r = - P (1 - \frac{\tau_c}{P} \tan \alpha)$$

The value of τ_c/p has been shown to be very small and since α also is very small, the term $(\tau_c/p) \tan \alpha$ is therefore, ignored. Knowing the principal stress and using equation (23) solving for the equilibrium of forces in x direction gives,

$$2dD \sigma_x + D d\sigma_x + 4P \tan \alpha + 4dx \tau_c = 0$$

But $\tan \alpha = (dD/2 dx)$ and substituting for $(p + \sigma_x) = y$ gives,

$$d\sigma_x = - \frac{2dD y}{D} - \frac{4\tau_c dx}{D}$$

This is the governing differential equation in the deformation zone for the axial stress in the wire. So re-writing this equation in finite-difference form gives,

$$\sigma_{xi} = 2 (\frac{D_{i-1} - D_i}{D_i}) y_i + \frac{4\tau_{ci} \Delta x}{D_i} + \sigma_{xi-1} \quad (24.f)$$

Equation (24.f) is a function of shear stress on the wire and it must be determined independently. Therefore equation (9) may be written as,

$$\begin{aligned} \tau_{ci} = & (- \frac{\mu V_i}{2kh_i} + (\frac{\mu^2 V_i^2}{4k^2 h_i^2} + \frac{1}{27} (\frac{1}{k} + \frac{p_i^2 h_i^2}{4})^3)^{1/2})^{1/3} \\ & + (- \frac{\mu V_i}{2kh_i} - (\frac{\mu^2 V_i^2}{4k^2 h_i^2} + \frac{1}{27} (\frac{1}{k} + \frac{p_i^2 h_i^2}{4})^3)^{1/2})^{1/3} - \frac{p_i h_i}{2} \end{aligned} \quad (24.g)$$

Equation (24.g) contains the pressure gradient and variation of the wire velocity in the deformation zone and they must be determined separately. Hence, flow of the polymer melt in this region may be expressed as,

$$Q_i = \frac{p_i h_i^3}{6\mu} + \frac{\tau_{ci} h_i^2}{2\mu} + \frac{k}{\mu} \left(\frac{p_i^3 h_i^5}{20} + \frac{h_i^2 \tau_{ci}^3}{2} + \frac{p_i^2 h_i^4 \tau_{ci}}{4} + \frac{p_i h_i^3 \tau_{ci}^2}{2} \right) + V_i h_i = Q_1 \quad (24.h)$$

Equations (24.g) and (24.h) may be solved simultaneously in order to determine P_i and τ_{ci} by iterating P_i at point i in the deformation zone. Therefore,

$$p_i = p_i \Delta x + p_{i-1} \quad (24.i)$$

Variation of speed of the wire in the deformation zone may also be included in the analysis.

The continuity of flow of metal through the element in Figure 3.1(d) gives,

$$(V + dV) \frac{\pi}{4} (D + dD)^2 = \frac{\pi}{4} V D^2$$

Ignoring the powers of dD and re-writing the equation in finite-difference form gives;

$$V_i = \frac{V_{i-1}}{1 - \frac{2(D_{i-1} - D_i)}{2D_{i-1} - D_i}} \quad (24.l)$$

The drawing stress may be expressed as,

$$\sigma_{xi} = 2 \left(\frac{D_{i-1} - D_i}{D_i} \right) \left(Y_0 + S \left(2 \ln \left(\frac{D_i}{D_i} \right) \right)^n \right) + \frac{4\tau_{ci} \Delta x}{D_i} + \sigma_{xi-1} \quad (24.m)$$

3.2.3.2- After the step

Equation (17) when expressed in finite-difference form, gives pressure values at different points, distance Δx apart. It may be reasonable to assume that plastic deformation takes place in a straight-line profile over very small length, Δx thus,

$$P_i = P_{i-1} + \frac{6\mu V_i}{[1 + 3k\tau^2]} \left[\frac{1}{h_i^2} - \frac{\bar{h}}{h_i^3} \right] \Delta x \quad (25)$$

where,

$$h_i = h_{i-1} - (B - k_j) \Delta x \quad (26)$$

and,

$$V_i = V_{i-1} \left(\frac{D_{i-1}}{D_i} \right)^2 \quad (26.a)$$

and,

$$D_i = D_{i-1} - 2k_j \Delta x \quad (26.b)$$

Referring to Figure (3.1.d), the increment in axial stress may be expressed as,

$$d\sigma_x = -2 \frac{dD}{D} (Y + \tau_x \cot \alpha)$$

where α is the semi-angle of the conical deformation profile. But the diameter $D = D_1 - (2k_j \Delta x)$ such that $dD = -2k_j \Delta x$ and $\cot \alpha = -1/k_j$

Now the assumption given before that, the shear stress is constant for a given drawing speed gives,

$$d\sigma_x = \frac{-4k_j \Delta x}{D} \left[Y + \frac{\tau}{k_j} \right]$$

Which in finite difference form becomes,

$$\sigma_{x_i} = \sigma_{x_{i-1}} + \frac{4k_j \Delta x}{D} \left[Y_i + \frac{\tau}{k_j} \right] \quad (27)$$

Equation (24) in finite difference form "for very small angle" can be written as,

$$Y_i = Y_0 + S \left[\ln \left(\frac{D_1}{D_i} \right)^2 \right]^n \quad (28)$$

From reference [80] the strain rate sensitivity of the wire material may also be included in the analysis. The mean strain rate of the wire material over a small distance " Δx " may be expressed as,

$$\dot{\epsilon} = \left(-2 \frac{dD}{D} \right) \frac{1}{dt}$$

Or it may be written as,

$$\dot{\epsilon}_{mi} = \frac{1}{X_i - X_{i-1}} \int_{D_{i-1}}^{D_i} \dot{\epsilon} dx$$

where $x = x_{i-1}$ at $D = D_{i-1}$ and $x = x_i$ at $D = D_i$

Substituting for $\dot{\epsilon}$ gives,

$$\dot{\epsilon}_{mi} = \frac{1}{\Delta x} \int_{D_{i-1}}^{D_i} -2 \left(\frac{dD}{D} \right) \left(\frac{dx}{dt} \right)$$

Because of $(dx/dt) = V_i$ therefore,

$$\dot{\epsilon}_{mi} = - \frac{2V_i}{\Delta x} \int_{D_{i-1}}^{D_i} \left(\frac{dD}{D} \right)$$

In which by integration gives,

$$\dot{\bar{\epsilon}}_{mi} = \frac{2V_i}{\Delta x} \ln\left(\frac{D_{i-1}}{D_i}\right) \quad (29)$$

A flow rule of the form,

$$\frac{Y_d}{Y_s} = K_0 = 1 + \left(\frac{\dot{\bar{\epsilon}}_{mi}}{N}\right)^{\frac{1}{r}} \quad (30)$$

has been proposed by HASHMI [80], where Y_d is the dynamic yield stress and Y_s is the static yield stress of the material. In a finite difference form the above equation (30) will be,

$$K_0 = 1 + \left(\frac{\dot{\bar{\epsilon}}_{mi}}{N}\right)^{\frac{1}{r}} \quad (31)$$

Combining equation (31) with equation (28) gives,

$$Y_i = K_{0i} (Y_0 + S (2\ln(\frac{D_1}{D_i}))^n) \quad (32)$$

Equation (32) represents the yield stress of the wire, incorporating strain hardening and strain rate sensitivity of the wire material. Substituting for Y_i into equation (27) gives,

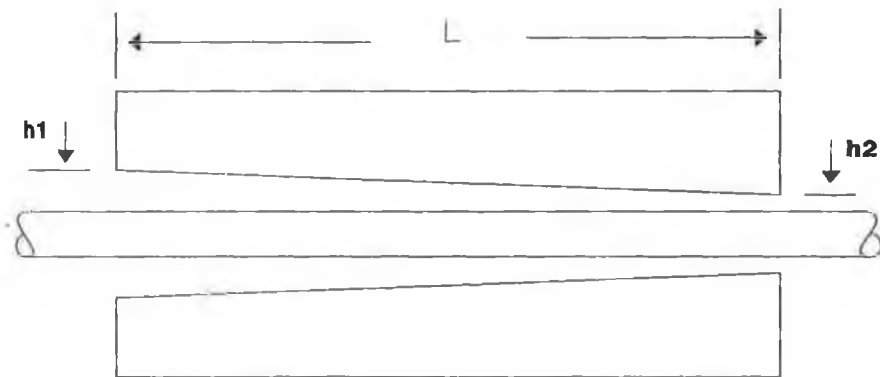
$$\sigma_{xi} = \sigma_{x_{i-1}} + \frac{4K_f \Delta x}{D_i} \left[K_{0i} \left(Y_0 + S \left(2\ln \left(\frac{D_1}{D_i} \right) \right)^n \right) + \frac{\tau}{K_j} \right] \quad (33)$$

Also re-writing equation (23) in finite difference form becomes;

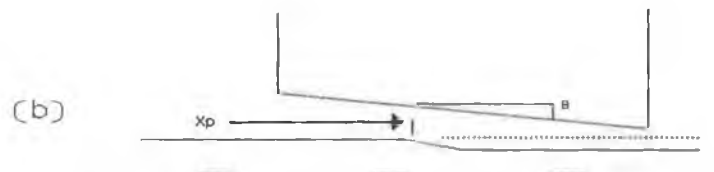
$$P_i + \sigma_{xi} = Y_i$$

3.2.3.3- Plastic yielding Solution Procedure

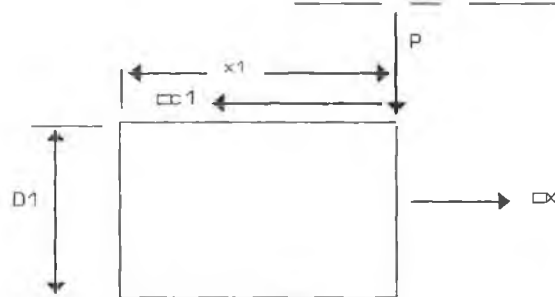
The procedure for predicting the theoretical results, involved determination of x_p , the distance from the entry to the tapered part of the pressure unit where plastic deformation commences, by iterative computation of equation (23) in conjunction with equations (18), (20), and (21.b). From this point onward, the extent of plastic deformation is calculated by equation (24) when combined with equations (25) and (27) for small increment Δx , from x_p . the current slope of the deformation profile, k_j , is determined by iterative computation of equation (24), the current diameter being then given by equation (26).



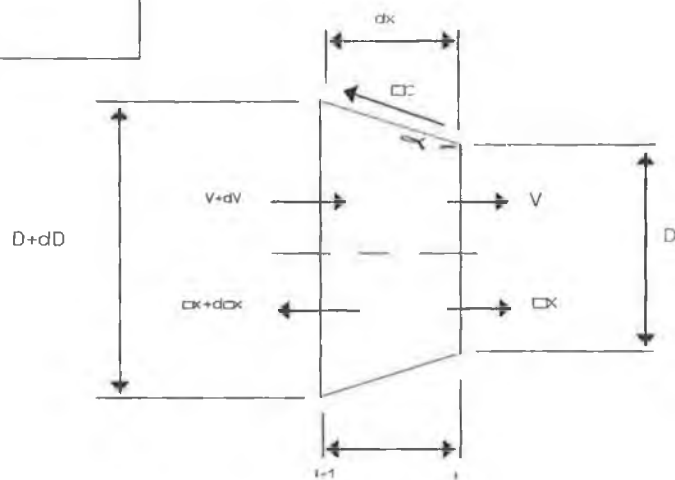
(a)



(b)



(c)



(d)

Fig 3.2 Geometry used in simple taper analysis

3.2.4- Determination of the pressure within the simple tapered unit

In formulating the relevant equations the following assumptions were made;

- i)- The pressure medium has the characteristics of non-Newtonian fluid, namely, the viscosity is dependent of the shear rate and the pressure.
- ii)- The flow of the fluid is axial and laminar.
- iii)- The thickness of the fluid layer is small compared to the bore size of the tubular orifice.
- iv)- The pressure in the fluid is uniform in the thickness and the direction at any point along the length of the orifice.
- v)- The shear stress is constant for a given drawing speed.

The relationship between the pressure and the shear-stress gradient within the gap for non-Newtonian fluid medium may be expressed as,

$$\left(\frac{dP}{dx}\right) = \left(\frac{d\tau}{dy}\right) \quad (1)$$

The equation relating the polymer shear-stress and the shear-rate has been proposed by RABINOWITSCH [58] as;

$$\tau + k\tau^3 = \mu\left(\frac{du}{dy}\right) = \mu\dot{\gamma} \quad (2)$$

where μ is the viscosity and u is the velocity of the fluid at a distance y from the surface of the wire within the gap, hence, differentiating equation (2) and substituting into equation (1) we obtain,

$$\left(\frac{dP}{dx}\right) + 3k\tau^2 \left(\frac{dP}{dx}\right) = \mu\left(\frac{d^2u}{dy^2}\right)$$

Integrate the above equation w.r.to y gives,

$$\left(\frac{dP}{dx}\right) y + 3k\tau^2 y \left(\frac{dp}{dx}\right) + C_1 = \mu \left(\frac{du}{dy}\right)$$

where C_1 is a constant.

Integrate again w.r.to y gives,

$$\left(\frac{dP}{dy}\right) \frac{y^2}{2} + \frac{3}{2}k\tau^2 y^2 \left(\frac{dP}{dx}\right) + C_1 y + C_2 = \mu u \quad (3)$$

where C_1 and C_2 are constants.

The boundary conditions to find C_1 and C_2 ,

at the wire surface $y=0$, $u=V$

at the surface of the unit $y=h$, $u=0$

$$C_1 = - \left(\frac{dP}{dx}\right) \frac{h}{2} - \left(\frac{dP}{dx}\right) k\tau^2 \frac{3h}{2} - \frac{\mu V}{h}$$

and the constant $C_2 = \mu V$

Substituting for C_1 and C_2 into equation (3) gives,

$$u = \left(\frac{dP}{dx}\right) \frac{y^2}{2\mu} + \left(\frac{dP}{dx}\right) k\tau^2 \frac{3y^2}{2\mu} - \left(\frac{dP}{dx}\right) \frac{hy}{2\mu} - \left(\frac{dP}{dx}\right) k\tau^2 \frac{3hy}{2\mu} - \frac{Vy}{h} + V \quad (4)$$

The flow of the polymer is given by the equation,

$$Q = \int_0^h u \, dy \quad (5)$$

in which after substituting for u gives,

$$Q = - \left(\frac{dP}{dx} \right) \frac{h^3}{6\mu} + \left(\frac{dP}{dx} \right) k\tau^2 \frac{h^3}{4\mu} + \frac{Vh}{2} \quad (6)$$

Differentiate w.r.to x and integrate noting that $\{dQ/dx\}=0$

$$\left(\frac{dP}{dx} \right) \frac{h^3}{6\mu} + \left(\frac{dP}{dx} \right) k\tau^2 \frac{h^3}{2\mu} = Vh + C_3$$

The optimum pressure condition is at $\{dp/dx\}=0$ where $h=\bar{h}$

$$C_3 = - V\bar{h}$$

Substitute into the above equation and rearrange gives,

$$\left(\frac{dP}{dx} \right) = \frac{6\mu V}{[1 + 3k\tau^2]} \left[\frac{1}{h^2} - \frac{\bar{h}}{h^3} \right] \quad (7)$$

Using the unit geometrical configuration, the integration of the above equation w.r.to x knowing that the shear stress remains constant for a given speed,

$$P = \frac{6\mu V}{B [1 + 3k\tau^2]} \left[\frac{1}{h_1 - Bx} - \frac{\bar{h}}{2(h_1 - Bx)^2} - \frac{1}{h_1} + \frac{\bar{h}}{2h_1^2} \right] \quad (8)$$

To find ($\bar{h}$) using the boundary condition that $P=0$ at $x=L$ and $h_1-Bx=h_2$

$$\bar{h} = \frac{2h_1h_2}{(h_1 + h_2)} \quad (9)$$

The drag force may be given by,

$$F_d = \int_{x=0}^{x=L} \pi D_1 \tau_x dx \quad (10)$$

The drawing stress is given by,

$$\sigma_x = \frac{4 x \tau_x}{D} \quad (11)$$

Where D is the wire diameter.

3.2.4.1- Solution procedures

It is shown that the pressure profile within the simple tapered bore unit is not linear, the viscosity of the pressure fluid is dependent on the pressure and the shear rate.

With reference to Figure (3.2.a) a generalized equation relating viscosity, pressure and shear rate may be shown to take the form,

$$\mu = \mu_0 + \frac{(a + b P_{av})}{\dot{\gamma}} \quad (12)$$

where a and b are constants and μ_0 is the initial viscosity of the pressure fluid at ambient pressure. $\dot{\gamma}$ is the apparent shear rate and it is given by;

$$\dot{\gamma} = \frac{2V}{(h_1 + h_2)} \quad (13)$$

where V is the wire drawing speed.

Equation (12) gives the pressure and the shear rate dependent viscosity of the pressure fluid. The solution for the pressure distribution is then obtained using a systematic solution programme combining equations (12), (22), (8), (9), (10), (11).

The first step is to assume an arbitrary low value for P_{av} in equation (12) for a selected drawing speed, V and determine viscosity μ .

The next step is to calculate the shear stress using equation (24) and the pressure using equation (9) and (8) respectively.

The area under the pressure distribution curve is determined making use of equation (8), the average pressure is calculated. Should this calculated P_{av} be equal (within certain error margin of ± 0.5 percent) with the previously assumed value of P_{av} from equation (12), then the values of μ , τ , P have been established.

If not, then increase the assumed magnitude of P_{av} and repeat the calculation as above until the agreement is reached.

3.2.5- Plastic yielding

The combined effect of the axial stress and the hydro-dynamic pressure will cause plastic yielding of the wire at any point, x , within the orifice as soon as the plastic yield criteria becomes satisfied. If the material of the wire is assumed to be rigid non-linearly strain hardening such that flow stress could be expressed as;

$$Y = Y_0 + S\epsilon^n \quad (14)$$

Then according to the Tresca yield criterion plastic yielding will commence at a point x_p , provided that,

$$P + \sigma_x = Y_0 \quad (15)$$

Thus for a known value of Y_0 equation (13) can be solved for x_p after substituting for P and σ_x from equation (8) and (11) respectively.

Once plastic yielding is predicted to commence for given value of μ , V and the geometrical parameters of the orifice further permanent deformation of the wire should continue to take

place as long as,

$$P + \sigma_x \geq Y = Y_0 + S\varepsilon^n \quad (16)$$

is satisfied at any distance x_p .

3.2.5.1- Pressure in the deformation zone

Equation (7), when expressed in finite-difference form, gives pressure values at different points, distance Δx apart.

It may be in straight line profile over a very small length Δx thus;

$$P_i = P_{i-1} + \left[\left(\frac{6\mu V_i}{(1 + 3k\tau^3)} \right) \left(\frac{1}{h_i^2} - \frac{\bar{h}}{h_i^3} \right) \right] \Delta x \quad (17)$$

where

$$h_i = h_{i-1} - (k-b_i) \Delta x \quad (18)$$

and

$$V_i = V_{i-1} \left(\frac{D_{i-1}}{D_i} \right)^2 \quad (19)$$

and

$$D_i = D_{i-1} - 2b_i \Delta x \quad (20)$$

3.2.5.2- Axial stress in the deformation zone

Referring to Figure 3.2 which shows an element of the wire within a straight conical profile, The increase in axial stress may be expressed as

$$d\sigma_x = - \frac{2dD}{D} (Y + \tau_x \cot \alpha) \quad (21)$$

where α is the semi-angle of the conical deformation profile. But the diameter $D = D_1 - 2bx$ such that $dD = -2b dx$ and $\cot \alpha = -1/b$.

Now, from equation (2) the shear stress τ_x is given by

$$\tau + \frac{1}{k} \tau^3 = \left(\frac{\mu \dot{\gamma}}{k} \right)$$

let,

$$M_1 = \frac{1}{k}$$

and

$$N_1 = \frac{\mu \dot{\gamma}}{k}$$

hence,

$$\phi^3 + M_1 \phi - N_1 = 0 \quad (22)$$

which is a cubic equation and could be solved as following;let

$$\Phi^3 + 3P\Phi - 2q = 0 \quad (23)$$

where $3P=M_1$ or $P=M_1/3$ & $2q=N_1$ or $q=N_1/2$

The real root of the equation is,

$$\Phi = U - V$$

where,

$$U = [q + (q^2 + P^3)^{\frac{1}{2}}]^{\frac{1}{3}}$$

$$V = [-q + (q^2 + P^3)^{\frac{1}{2}}]^{\frac{1}{3}}$$

That gives,

$$\Phi = [q + (q^2 + P^3)^{\frac{1}{2}}]^{\frac{1}{3}} - [-q + (q^2 + P^3)^{\frac{1}{2}}]^{\frac{1}{3}}$$

Substituting for ϕ , q and P into the above equation we obtain³,

$$\tau = \left(\frac{\mu \dot{\gamma}}{2k} + \left[\left(\frac{1}{3k} \right)^3 + \left(\frac{\mu \dot{\gamma}}{2k} \right)^2 \right]^{\frac{1}{2}} \right)^{\frac{1}{3}} - \left(\frac{-\mu \dot{\gamma}}{2k} + \left[\left(\frac{1}{3k} \right)^3 + \left(\frac{\mu \dot{\gamma}}{2k} \right)^2 \right]^{\frac{1}{2}} \right)^{\frac{1}{3}} \quad (24)$$

Substituting for τ_x , $\cot \alpha$ and dD in equation (21) becomes,

$$d\sigma_x = \frac{-4b dx}{D} \left[Y + \frac{\tau}{b} \right]$$

Which in finite difference form,

³ Equation (24) does not allow to obtain Newtonian solution by putting $k=0$

$$\sigma_i = \sigma_{x-1} - \frac{4b_i}{D_i} \Delta x \left[Y_i - \frac{\tau}{b_i} \right] \quad (25)$$

where,

$$Y_i = Y_0 + S \left[\ln \left(\frac{D_1}{D_i} \right)^2 \right]^n \quad (26)$$

3.2.5.3- Plastic yielding solution procedures

The procedure for predicting the theoretical results, thus, involved determination of x_p , the distance from the entry to reduction unit where plastic deformation commences, by iterative computation of equation (15) in conjunction with equations (8), (9), (24) and (10). From this point onward, the extent of plastic deformation is calculated on the basis of equation (16) when combined with equations (17) and (25) for small increment, Δx , from x_p . The current slope of the deformation profile, b_i , is determined by iterative computation of equation (16), the current diameter being then given by equation (20).

CHAPTER- FOUR

RESULTS FROM THE COMBINED UNIT

4.1- Theoretical Results

4.1.1- Introduction

Theoretical results were obtained using the equations derived in the previous chapter, also a complete programme was written utilizing iteration technique and finite difference method to solve the equations simultaneously. Developments and listing of the program is provided in appendix [BB,CC]. The speed was varied from 0.005 m/sec to 4 m/sec.

The results presented in this section were calculated using the following standard values of the parameters shown.

Reference viscosity, $\mu_0 = 50 \text{ N.sec/m}^2$

Length of the unit up to the step, $L_1 = 145 \text{ mm}$

Length of the tapered part of the unit, $L_2 = 35 \text{ mm}$

Gap at the entry end of the unit, $h_1 = 1.5 \text{ mm}$

Gap at the step, $h_2 = 0.5 \text{ mm}$

Gap at the exit end of the unit, $h_3 = 0.05 \text{ mm}$

Diameter of the wire $D = 2 \text{ mm}$

4.1.2- Pressure distribution

In order to study the manner in which the pressure distribution and the maximum pressure are affected, the magnitudes of some of the above parameters were varied systematically.

The gap ratios h_1/h_2 and h_2/h_3 were varied to obtain different combination and the resulting

pressure distribution are shown in Figure 4.1(a) to (b).

In Figure 4.1(a) it is evident that for lower h_2/h_3 ratio 3, the difference in the magnitudes of the maximum pressure and that at the step is considerable. $P_{\max}$ being larger of the two by as much as 3 times.

In contrast Figure 4.1(b) shows that for lower h_1/h_2 and higher h_2/h_3 ratios, the maximum pressure is only marginally higher than the pressure at the step. The pressure distribution curve is almost linear up to the maximum pressure level before falling sharply to zero at the exit point.

Keeping the ratio h_2/h_3 constant at 5 and increasing the ratio h_1/h_2 from 2 to 4 changes the profile of the pressure distribution curve from that in Figure 4.1(b) to that in Figure 4.1(c) which are similar to those in Figure 4.1(a). Also increasing the h_2/h_3 to 7 keeping h_1/h_2 ratio low at 2.85, see Figure 4.1(d), changes the profile of the pressure distribution curve from that of in Figure 4.1(a) and 4.1(c).

It is evident from Figure 4.1 that maximum pressure is obtained for a certain combination of h_1/h_2 and h_2/h_3 ratios.

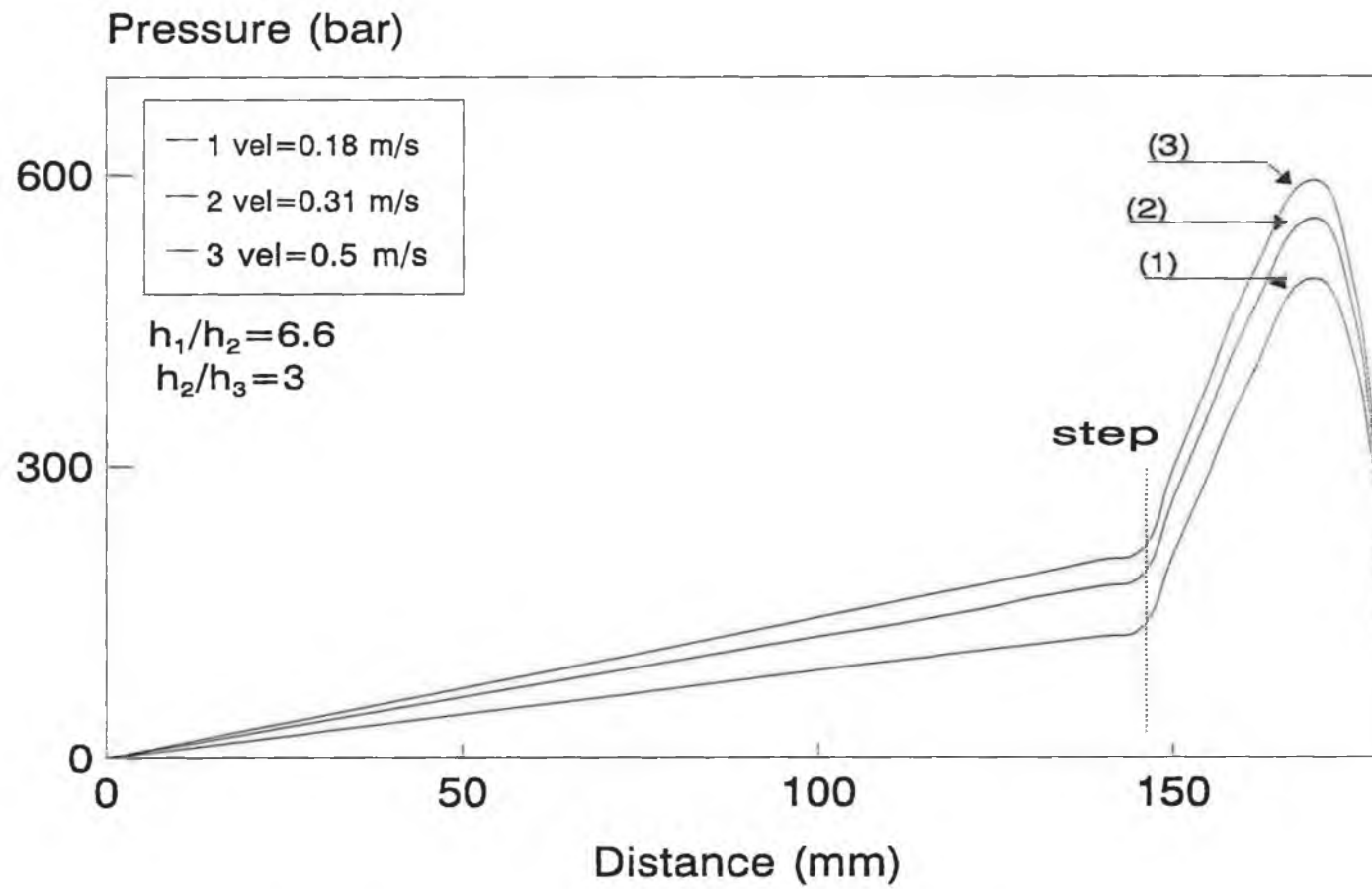


Fig. 4.1(a) Theoretical effect of drawing speed on pressure distribution for combined unit

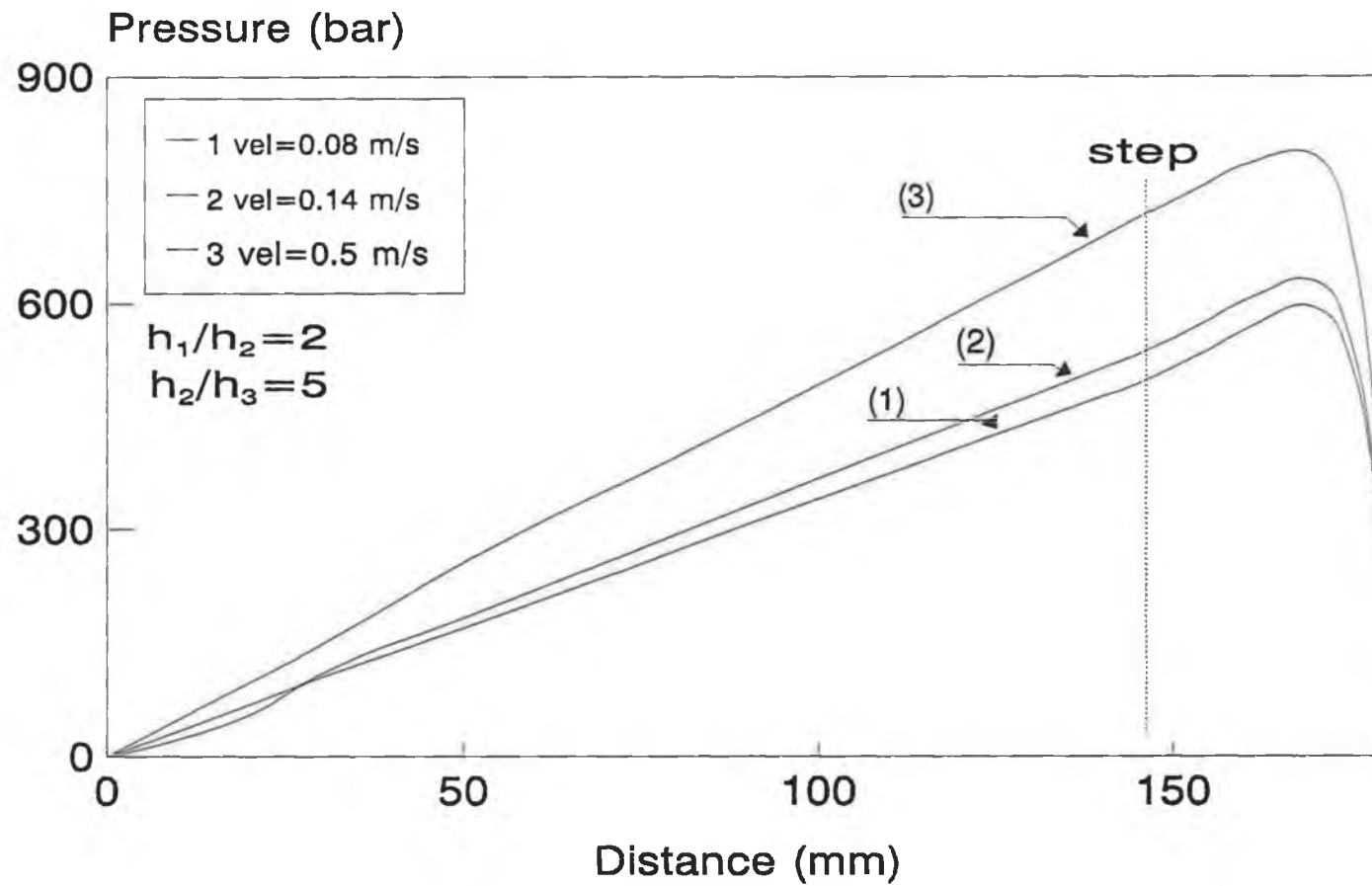


Fig. 4.1(b) Theoretical effect of drawing speed on pressure distribution for combined unit

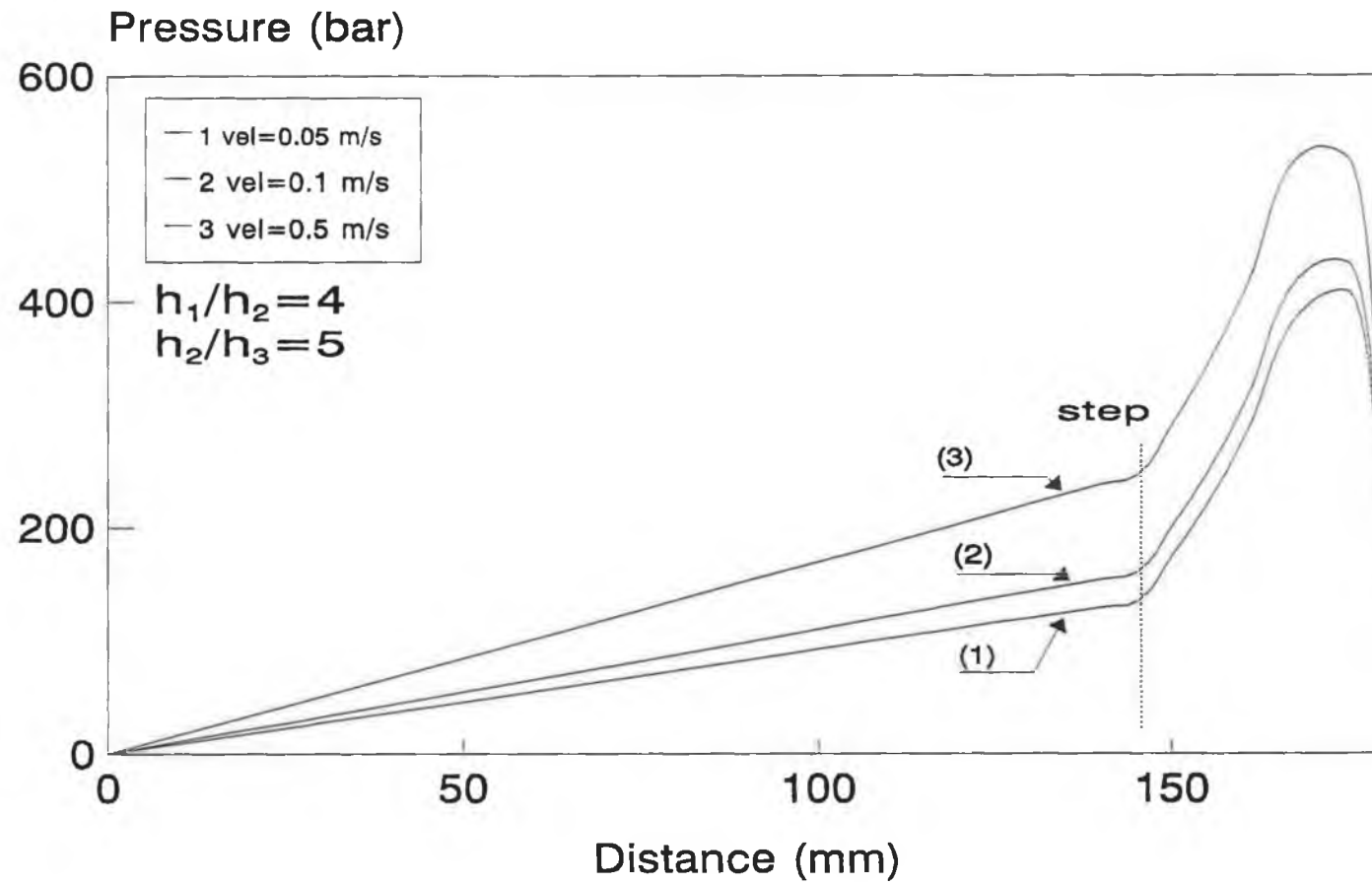


Fig. 4.1(c) Theoretical effect of drawing speed on pressure distribution for combined unit

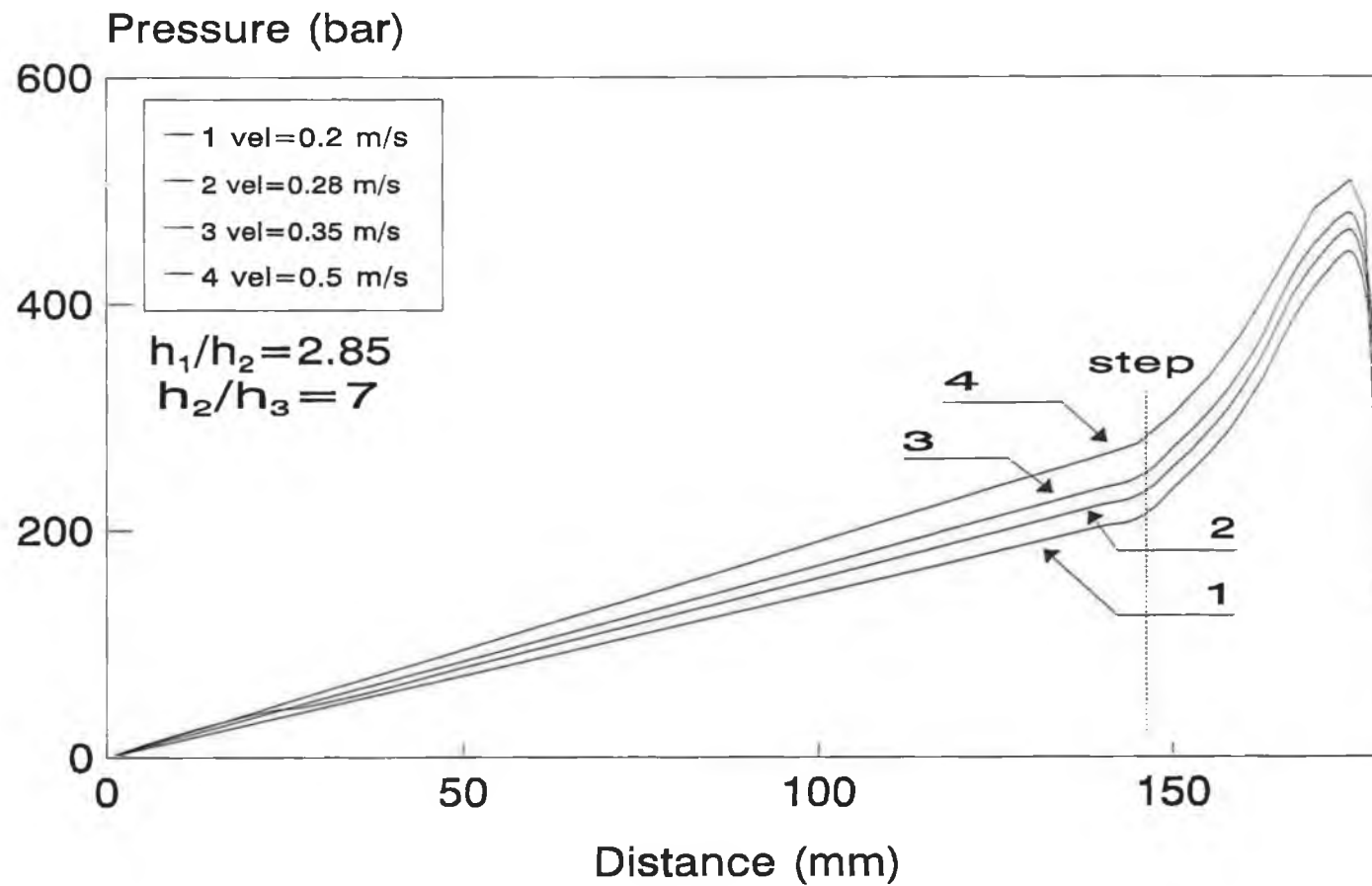


Fig. 4.1(d) Theoretical effect of drawing speed on pressure distribution for combined unit

4.1.3- Maximum pressure

In order to determine the optimum conditions for which the magnitude of the maximum pressure is predicted to be the largest, theoretical results were calculated for different h_1/h_2 ratios while keeping h_2/h_3 ratio the same. Different h_1/h_2 ratios were obtained by changing the values of h_1 only. It is evident from Figure 4.2(a) that for $h_2/h_3=2$, the optimum ratio for h_1/h_2 is also about 2 for different drawing speeds.

For drawing speed of 2.5 m/sec the maximum pressure is predicted to be about 2300 bar under this optimum ratio of h_1/h_2 and h_2/h_3 . Results were calculated keeping h_2/h_3 ratios fixed at 3 and 5 and varying h_1/h_2 ratio by changing h_1 only, as shown in Figures 4.2(b) and (c) respectively. It is evident from these figures that as the h_2/h_3 ratio is increased the h_1/h_2 ratio for maximum pressure move closer to 1 for different drawing speeds. Further more, for a given drawing speed the magnitude of the maximum pressure corresponding to theses optimum h_1/h_2 ratios decreases considerably.

Theoretical results were also calculated in terms of the maximum pressure for h_2/h_3 ratio of 2 and different h_1/h_2 ratios, but assuming Newtonian characteristics of the pressure fluid at $\mu_0 = 50 \text{ N}\cdot\text{sec}/\text{m}^2$. The results plotted in Figure 4.3 for two different drawing speeds suggests that the optimum combination for maximum pressure h_1/h_2 and h_2/h_3 do not changes with the speed.

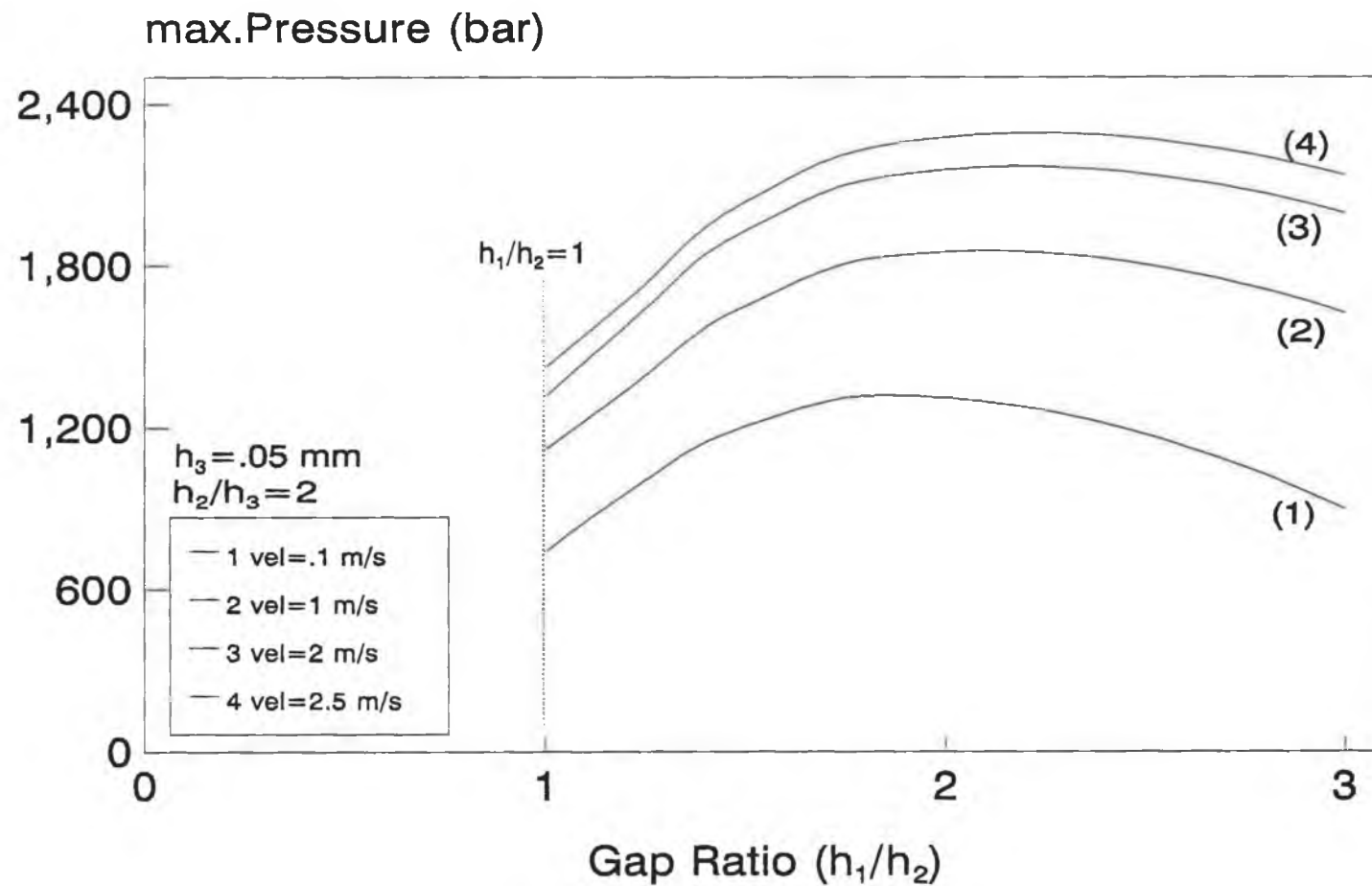


Fig. 4.2(a) Theoretical effect of the gap ratio h_1/h_2 on the maximum pressure keeping $h_2/h_3 = \text{constant}$

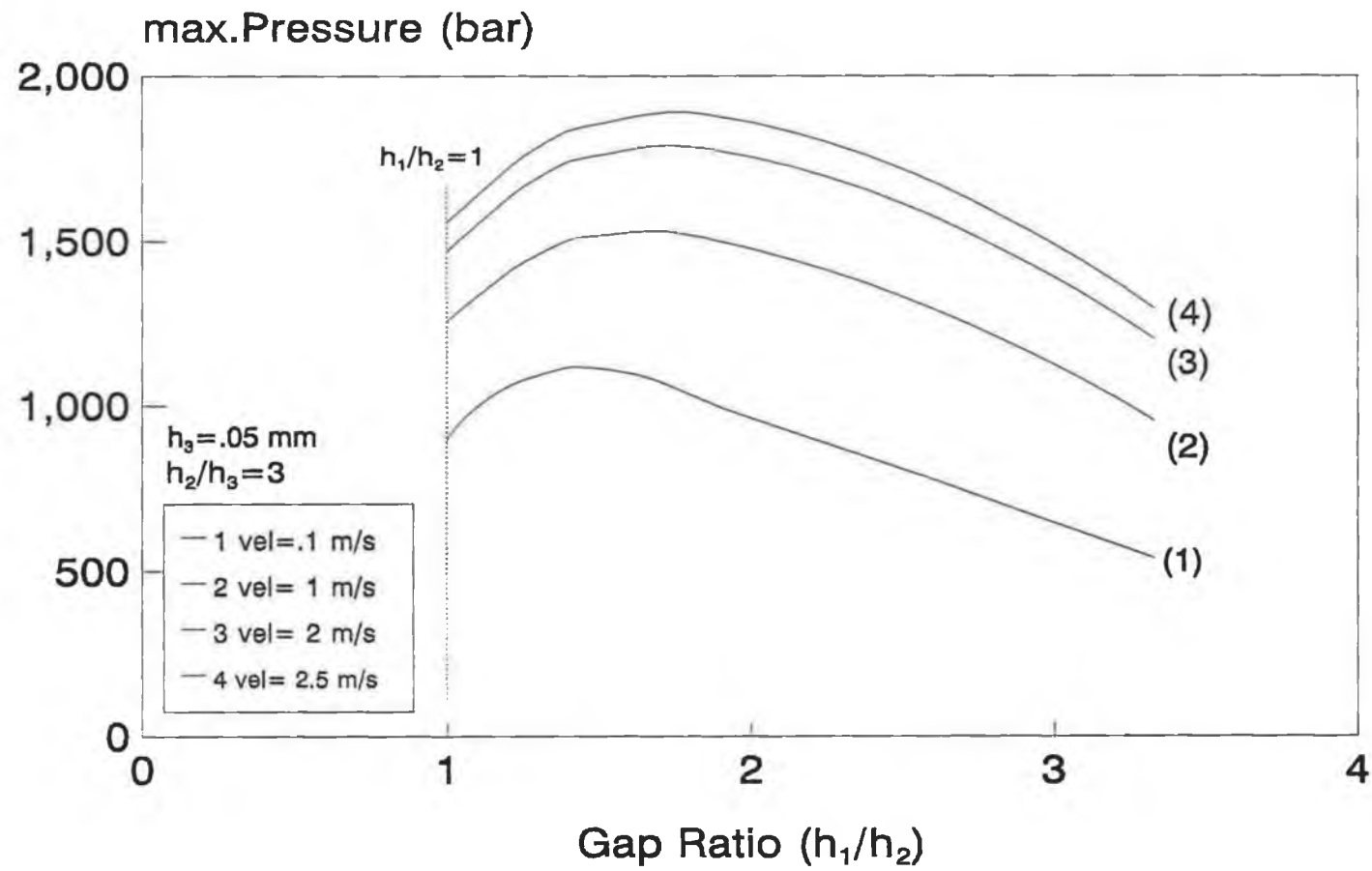


Fig. 4.2(b) Theoretical effect of the gap ratio h_1/h_2 on the maximum pressure keeping $h_2/h_3 = \text{constants}$

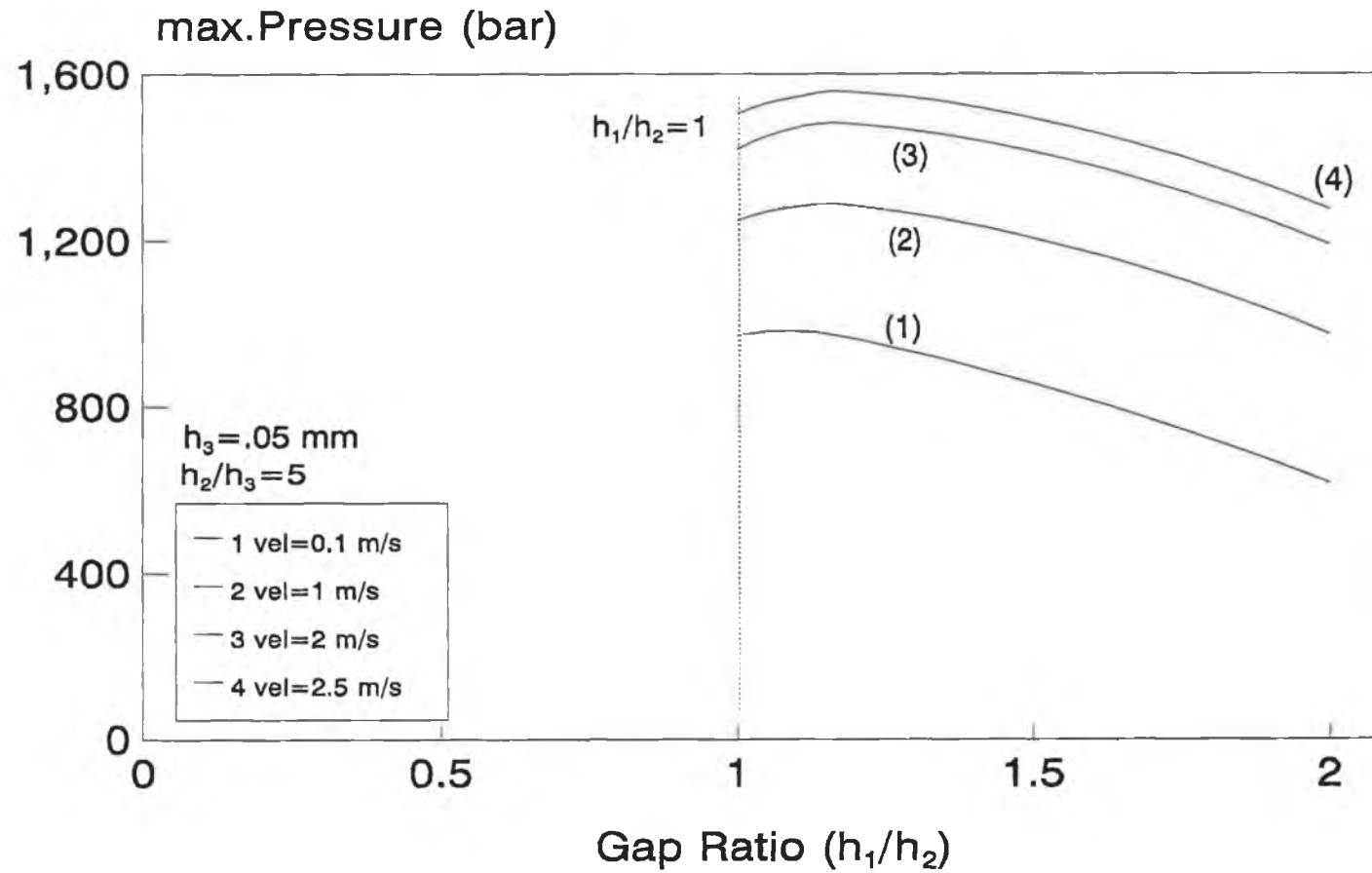


Fig. 4.2(c) Theoretical effect of gap ratio h_1/h_2 on the maximum pressure keeping h_2/h_3 =constant

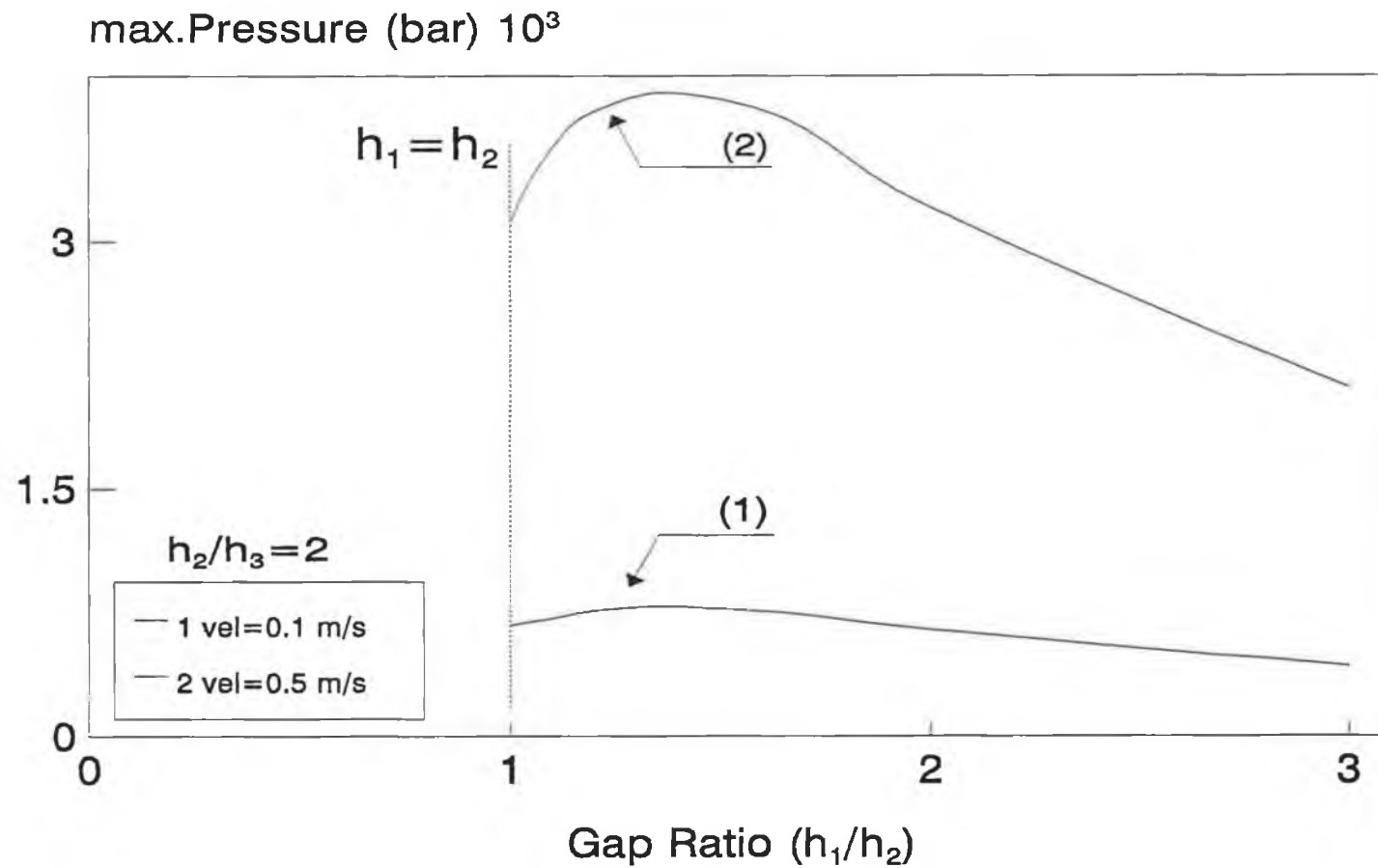


Fig 4.3 Theoretical effect of the gap ratio h_1/h_2 on maximum pressure for "Newtonian solution"

4.1.4- *The length effect on pressure*

In order to study the effect of the length ratio, L_1/L_2 , on the pressure, results were calculated by changing L_1 as well as L_2 . As can be seen from Figures 4.4(a) and (b) that both the pressure distribution and the magnitude of the maximum pressure are affected by changes in L_1/L_2 ratio. Maximum pressure being greatest for longer L_1 for a constant L_2 and for longer L_2 for a constant L_1 (drawing speed of 0.5 m/sec).

The effect of the relative lengths of the parallel bore and the tapered bore sections of the pressure unit on the maximum pressure for a given combination of h_1/h_2 and h_2/h_3 ratios can be seen in Figure 4.5 for the drawing speed of 0.5 m/sec. Results were calculated for two cases, the first corresponding to L_1 constant at 25 mm but L_2 changes, the second corresponding for L_2 constant at 25 mm but L_1 changes. The result indicates that greater lengths of the tapered section gives higher magnitude of the maximum pressure for the unit length of more than 50 mm.

The effect of similar relative lengths of different sections of the unit on the viscosity for two different drawing speeds are shown in Figure 4.6 which suggest that variation in the length of either sections influence the viscosity only marginally as long as the drawing speed remain constant.

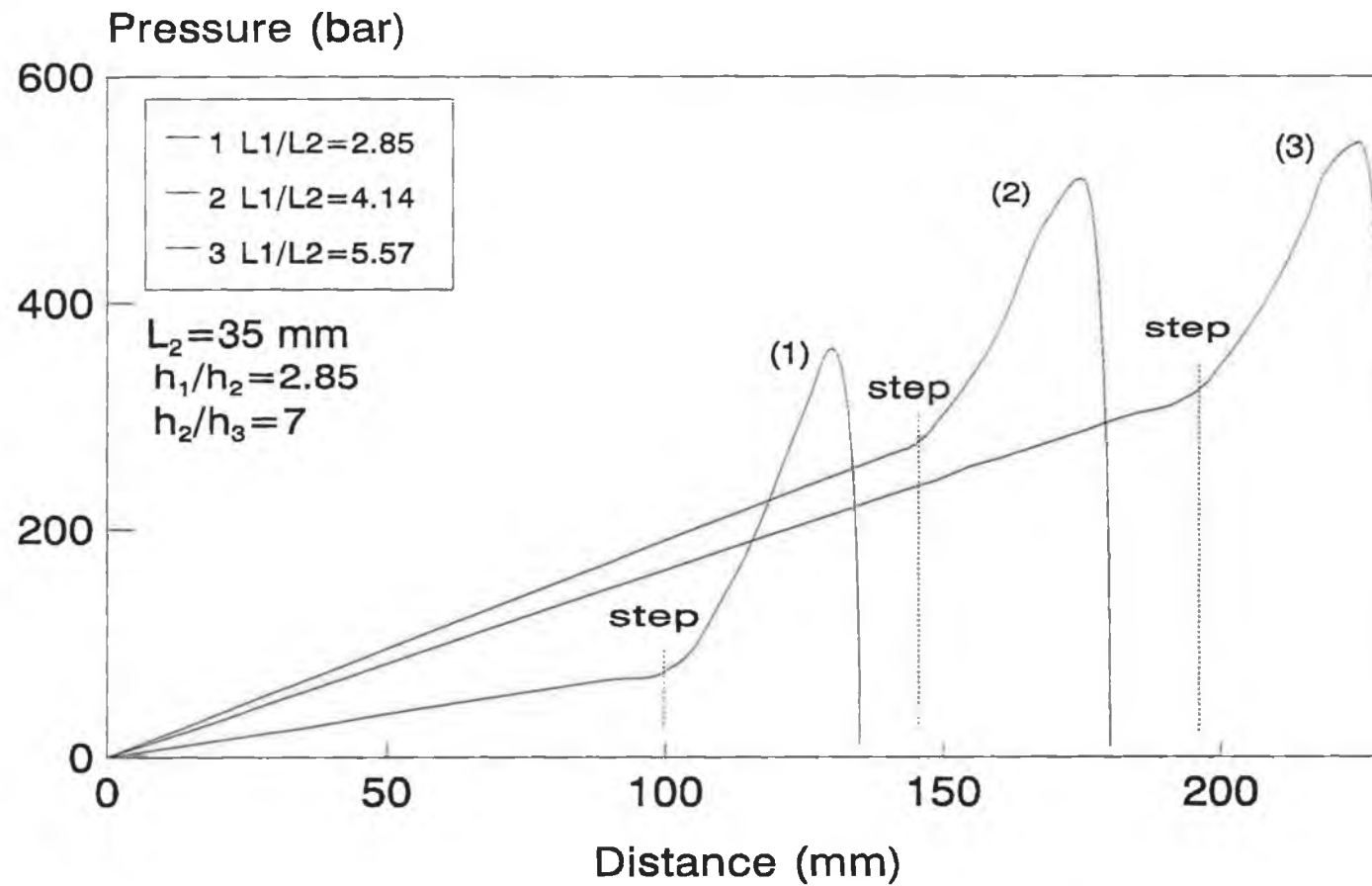


Fig. 4.4(a) Theoretical effect of changing L_1 on pressure distribution for combined unit

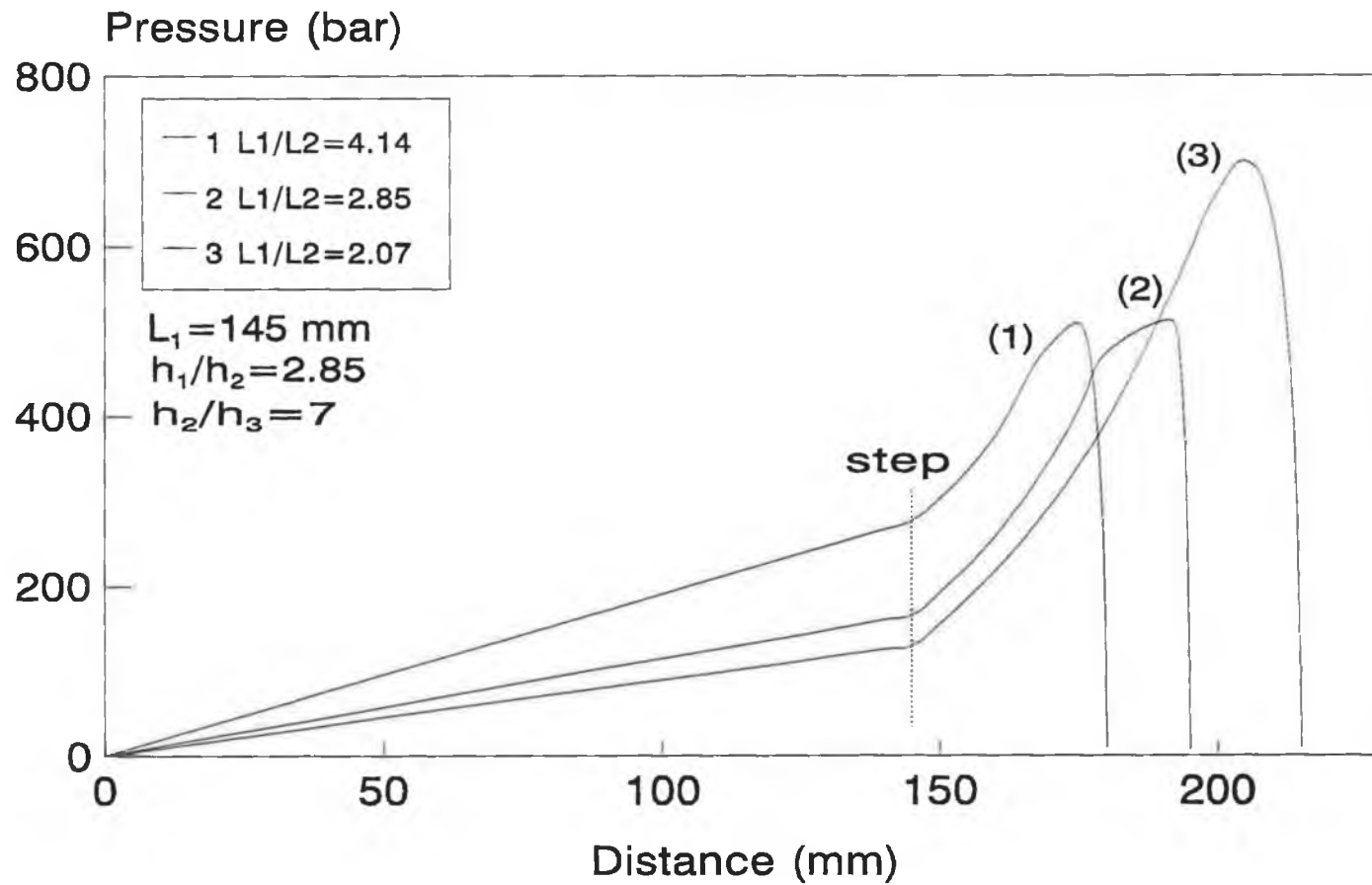


Fig. 4.4(b) Theoretical effect of changing L_2 on pressure distribution for combined unit

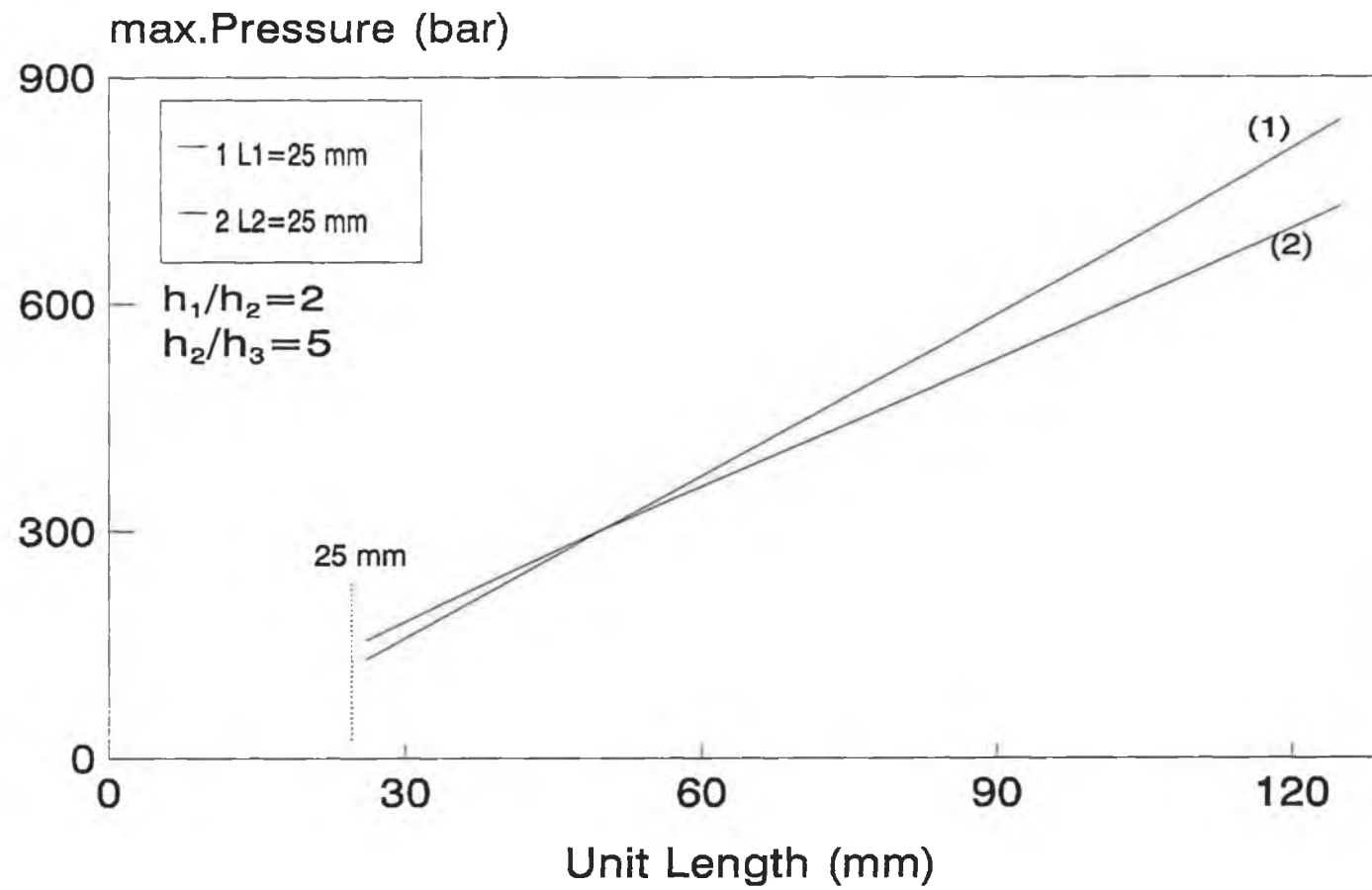


Fig. 4.5 Theoretical effect of the unit length on the maximum pressure

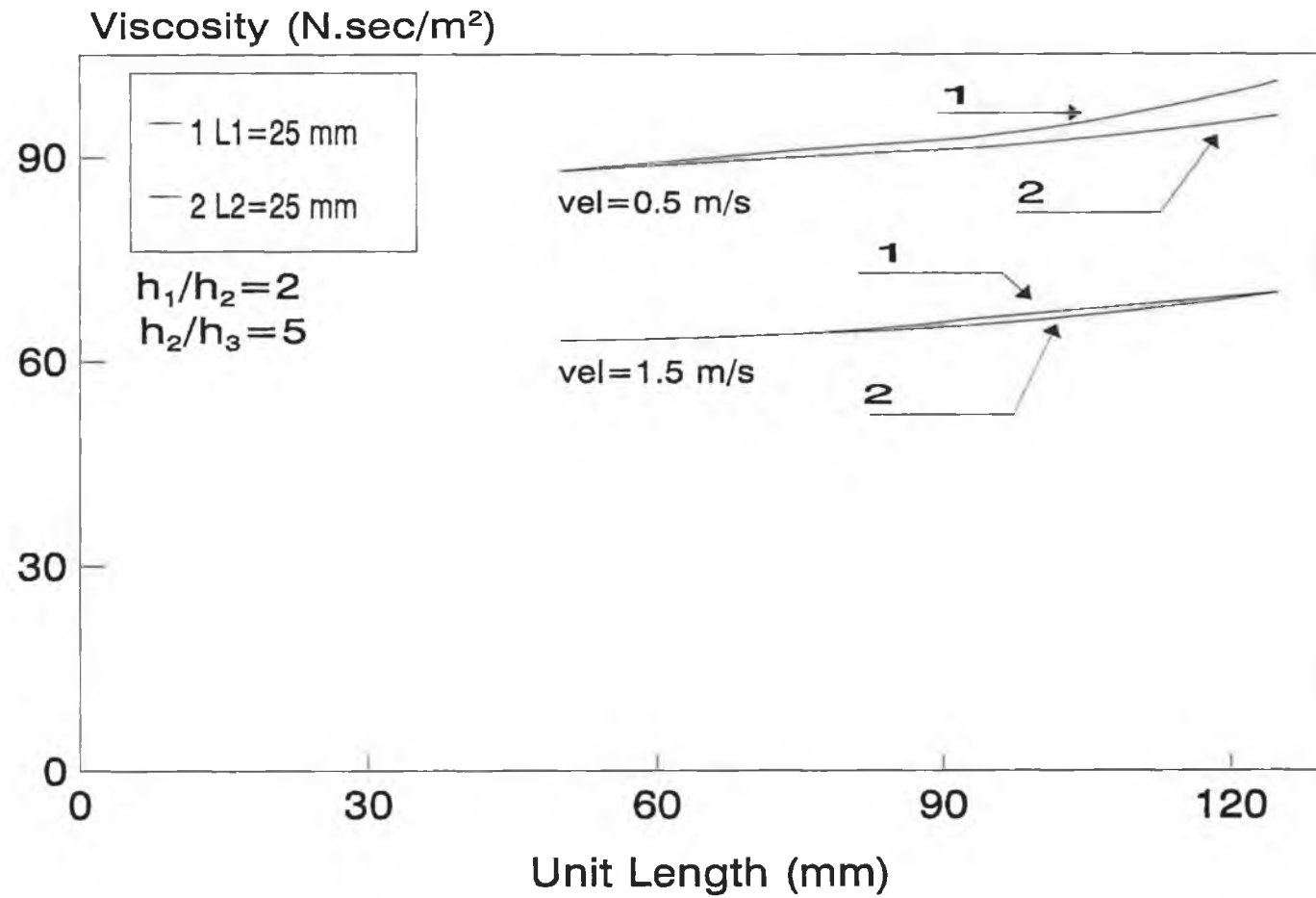


Fig 4.6 Theoretical effect of unit length on the viscosity of the pressure medium

4.1.5- *The viscosity effect on pressure*

The effect of the magnitude of the initial viscosity μ_0 on the pressure distribution for drawing speed of 0.5 m/sec and given $h_1/h_2=6.6$ and $h_2/h_3=3$ ratios can be seen in Figure 4.7(a). It is evident that variation in μ_0 causes approximately equal changes in the pressure at the step and the maximum pressure. The profiles of the pressure distribution curves are very similar in shape.

The theoretical effect of the viscosity and pressure coefficients on the pressure distribution is shown in Figure 4.7(b) and 4.7(c). Both the Figures suggests that a large change in "a" and "b" is necessary for considerable change in the pressure.

Figure 4.7(d) shows the effect of the non-Newtonian factor on the pressure distribution which also suggests that a large change in the non-Newtonian factor is needed for a large change in pressure.

The effect of the gap ratio and the drawing speed is given in Figure 4.8 by varying the inlet gap h_1 while h_2/h_3 kept constant, the Figure suggest that higher magnitudes of viscosity could be obtained with smaller inlet gap ratio and increasing the gap ratio will results in reduced magnitudes of viscosity.

The effect of the drawing speed on the viscosity is also given in Figure 4.8 which shows a high viscosity with low drawing speed, as the drawing speed increases the viscosity decreases and almost constant viscosity is obtained as the drawing speed increases.

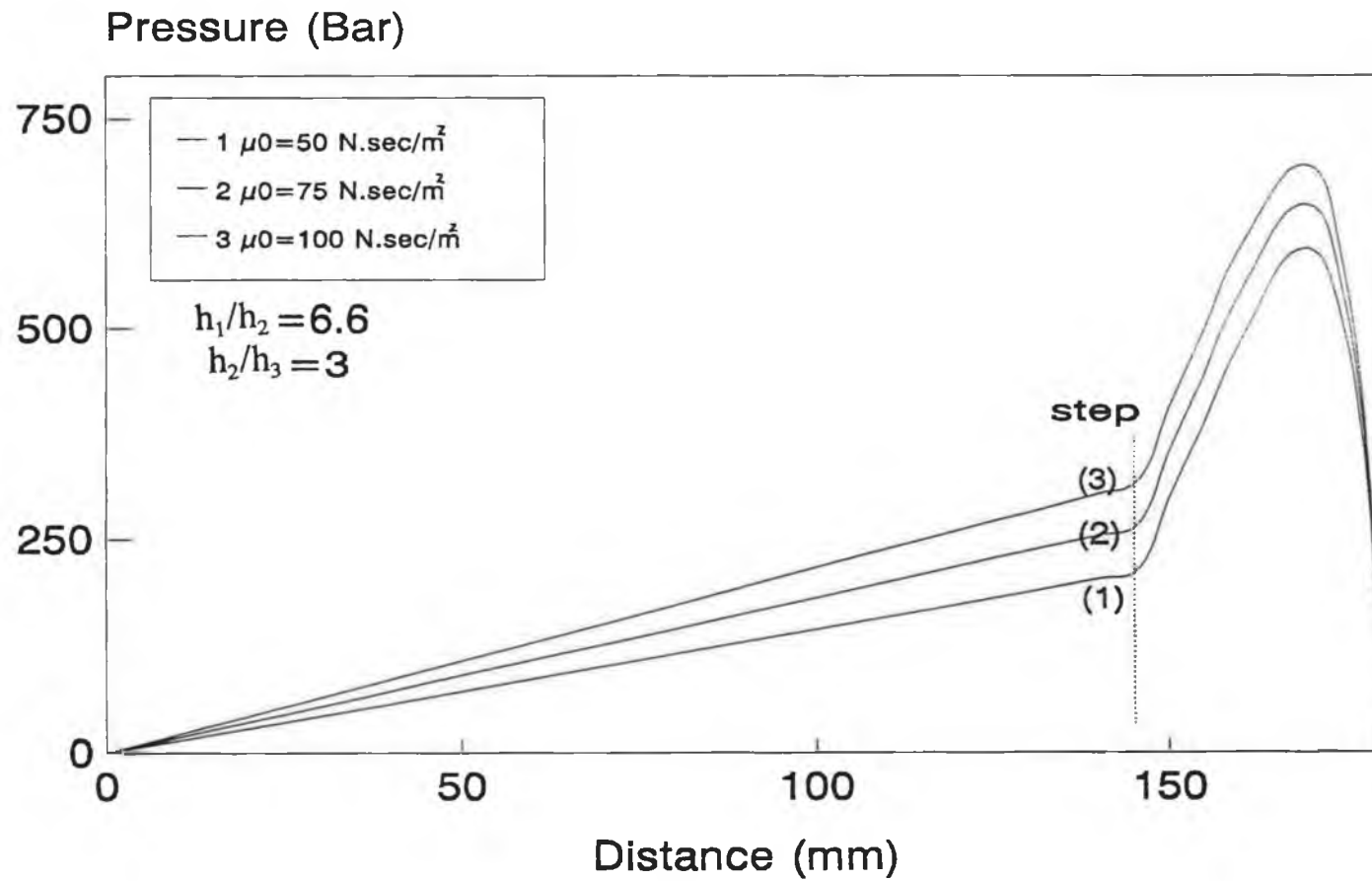


Fig. 4.7(a) Theoretical effect of reference viscosity on pressure distribution for combined unit

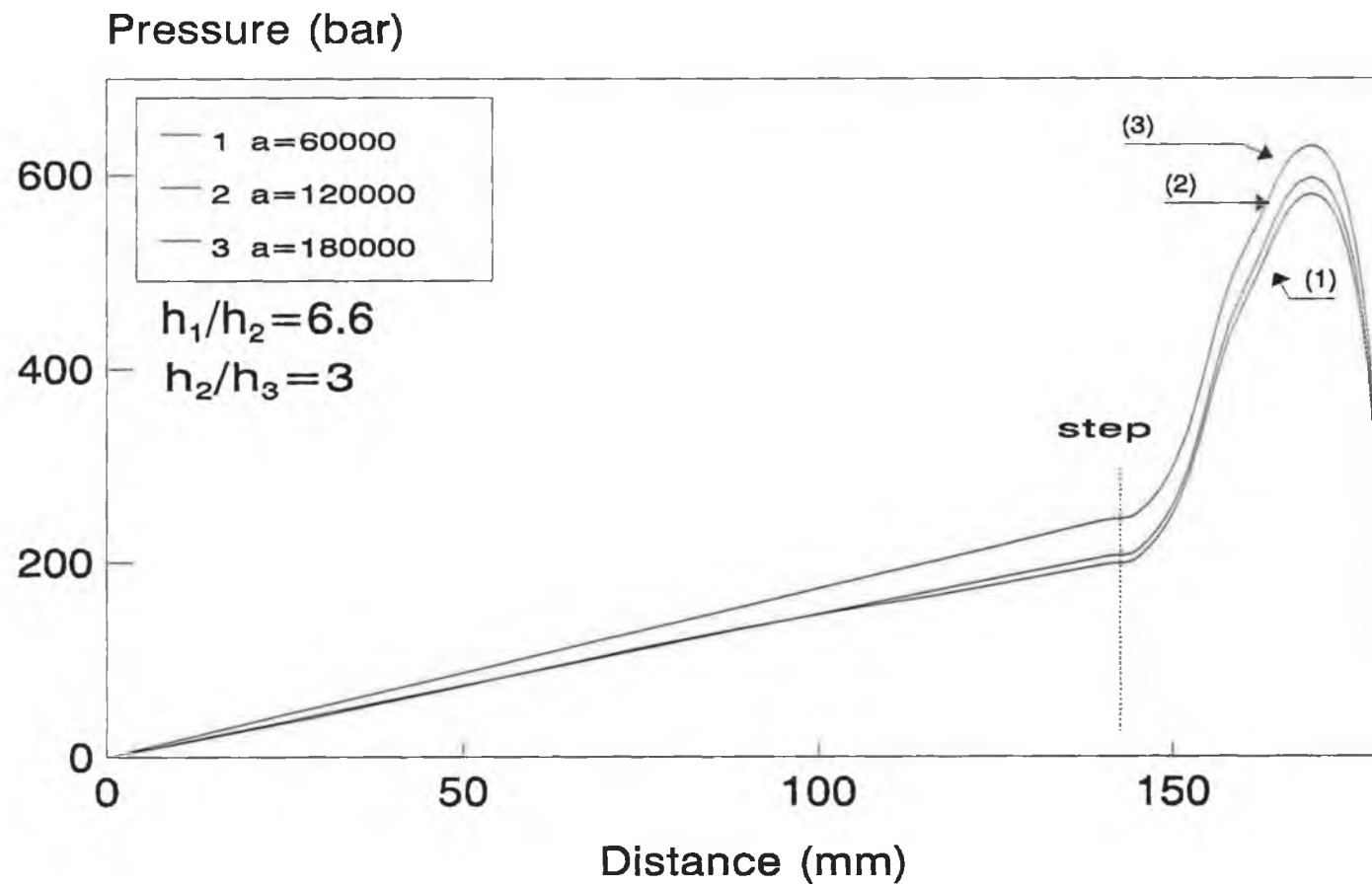


Fig. 4.7(b) Theoretical effect of viscosity coefficient on pressure distribution

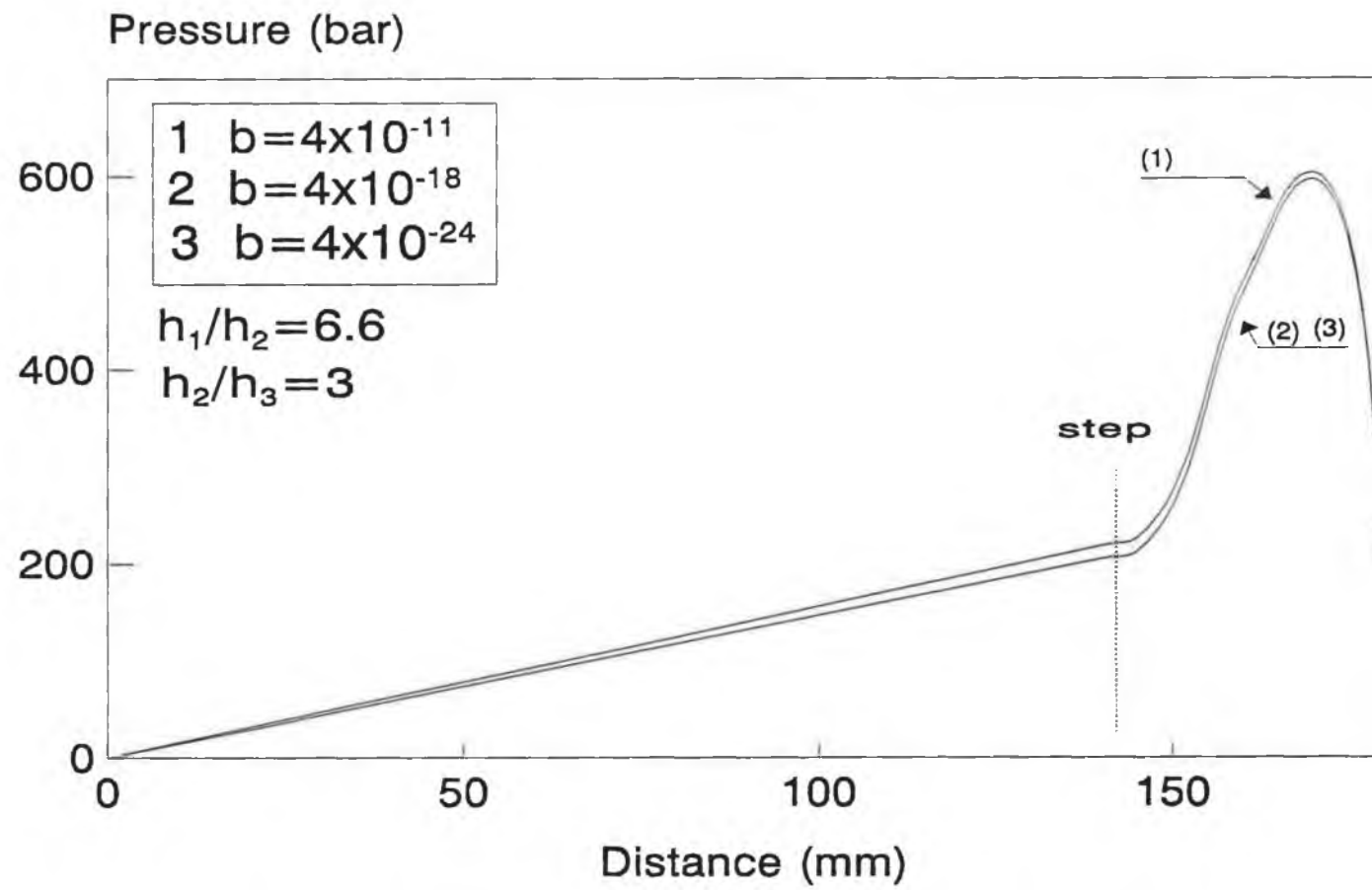


Fig. 4.7(c) Theoretical effect of pressure coefficient on pressure distribution

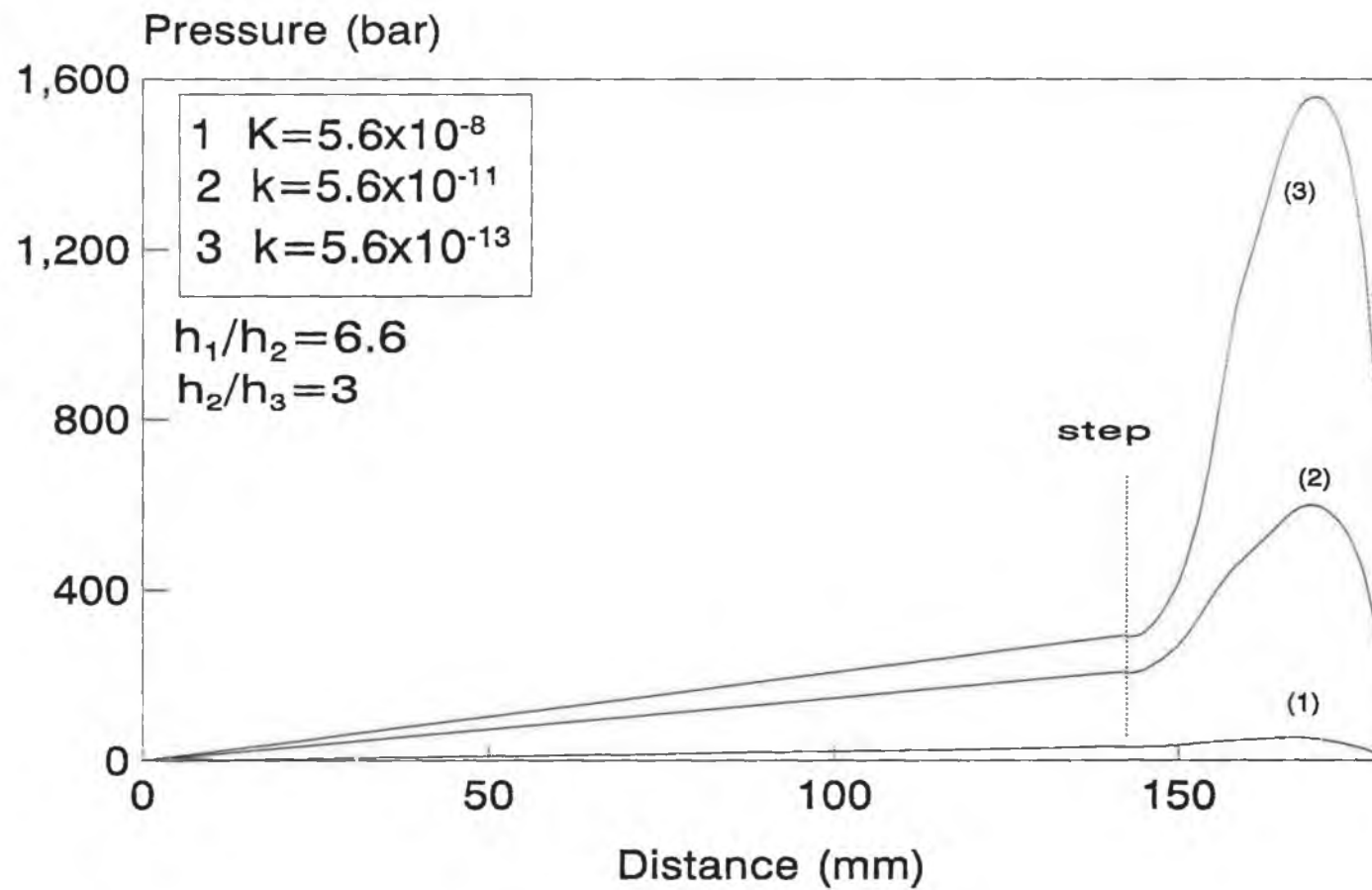


Fig. 4.7(d) Theoretical effect of non-Newtonian constant on pressure distribution

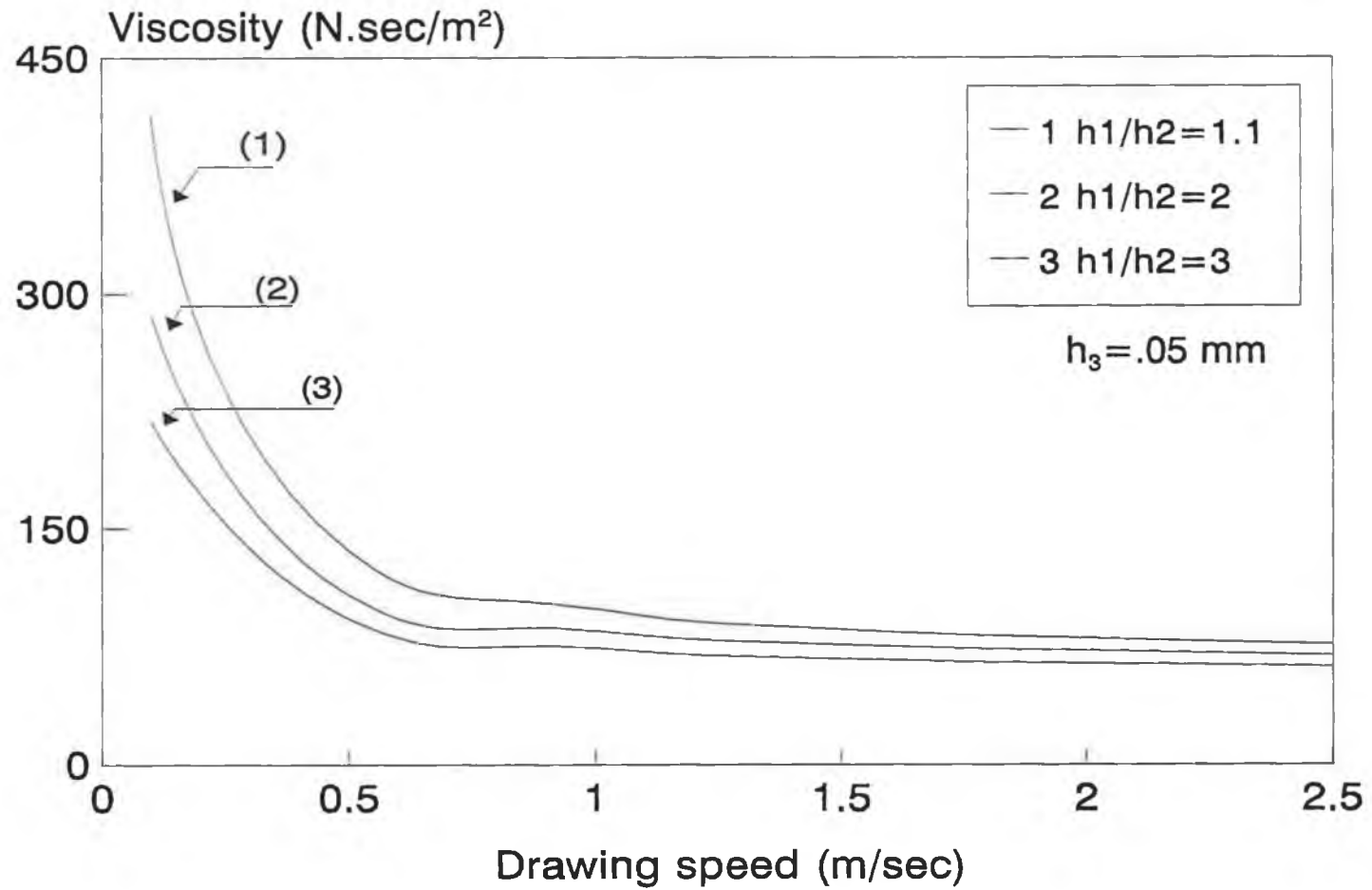


Fig 4.8 Theoretical effect of the drawing speed on the viscosity at different inlet gap h_1

4.1.6- Drawing stress

The effect of the dimensions of the unit on the drawing stress has been fully studied in addition to the effect of drawing speed and the results were given in complete graphical form in this section.

The effect of the drawing speed on the drawing stress for a given combination of h_1/h_2 and h_2/h_3 ratios can be seen in Figure 4.9, which shows a linear increase of drawing stress along the unit. Also, a higher magnitude of drawing stress is predicted for higher drawing speed. In order to study the effect of the inlet gap ratio h_1/h_2 on the drawing stress, results were calculated by changing h_1 keeping h_2 and h_3 constants. It can be seen from Figure 4.10 that smaller h_1/h_2 ratios results in higher magnitudes of drawing stress.

The effect of the outlet gap h_3 on drawing stress distribution is demonstrated in Figure 4.11 which indicates that higher drawing stress is obtained with smaller outlet gap thickness h_3 . For a given combination of the gap ratios the effect of the reference viscosity on the drawing stress distribution is shown in Figure 4.12, higher reference viscosity results in higher drawing stress. The actual viscosity of the polymer is of course influenced by the mean pressure and prevailing average shear rate (constant for a given drawing speed).

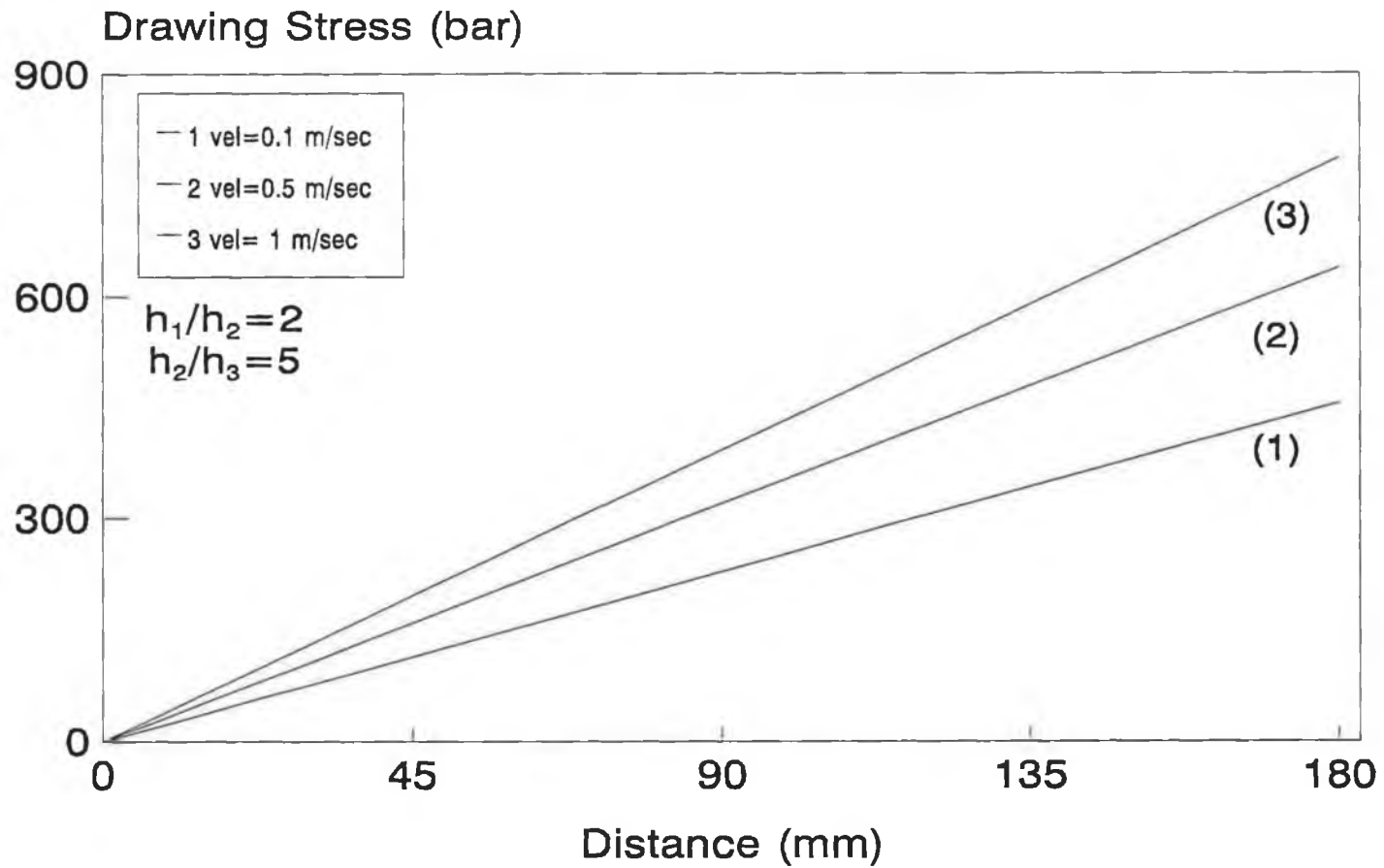


Fig. 4.9 Theoretical effect of the drawing speed on the drawing stress distribution

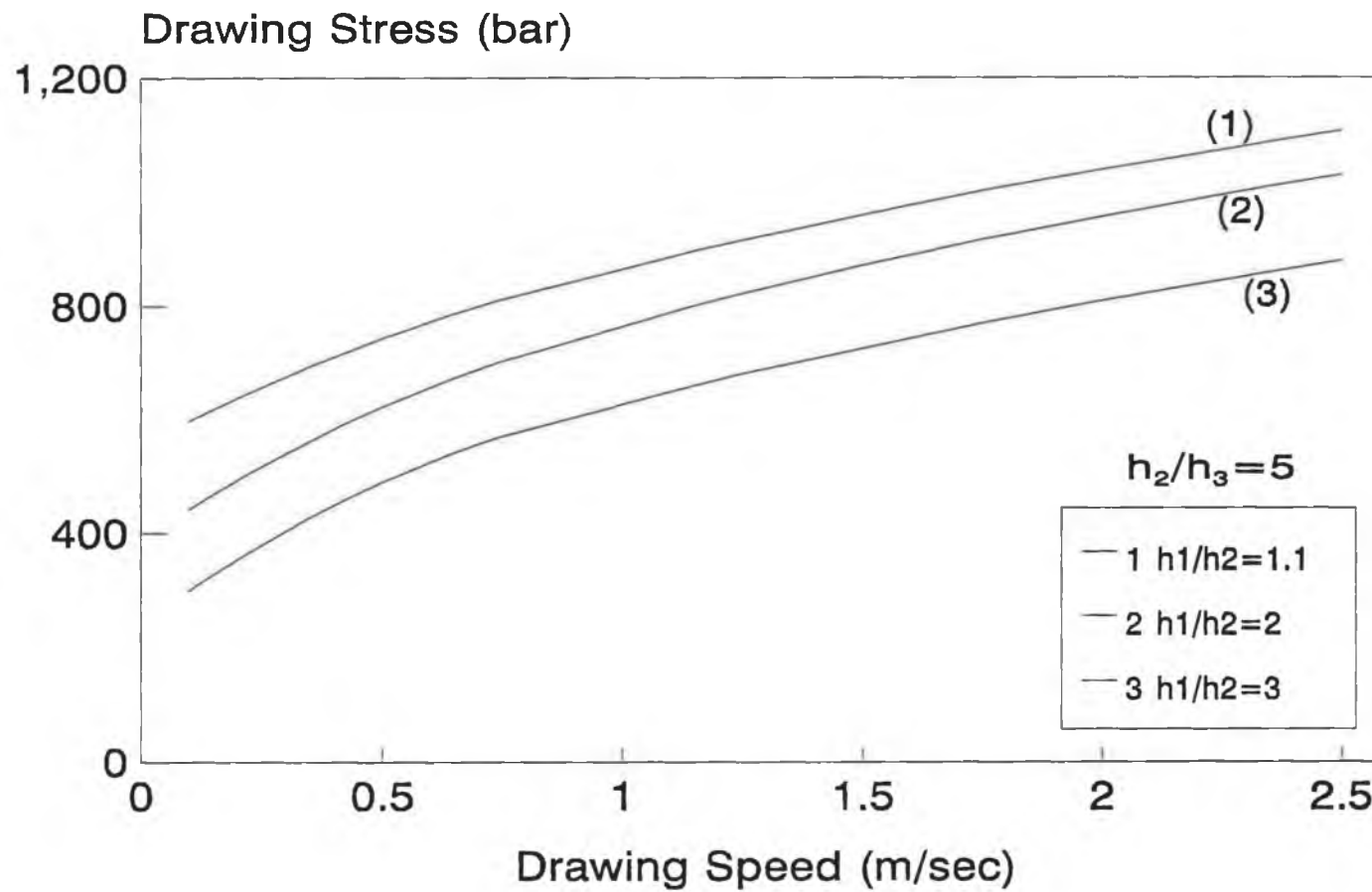


Fig. 4.10 Theoretical effect of the gap ratio h_1/h_2 on the drawing stress at different gap ratios

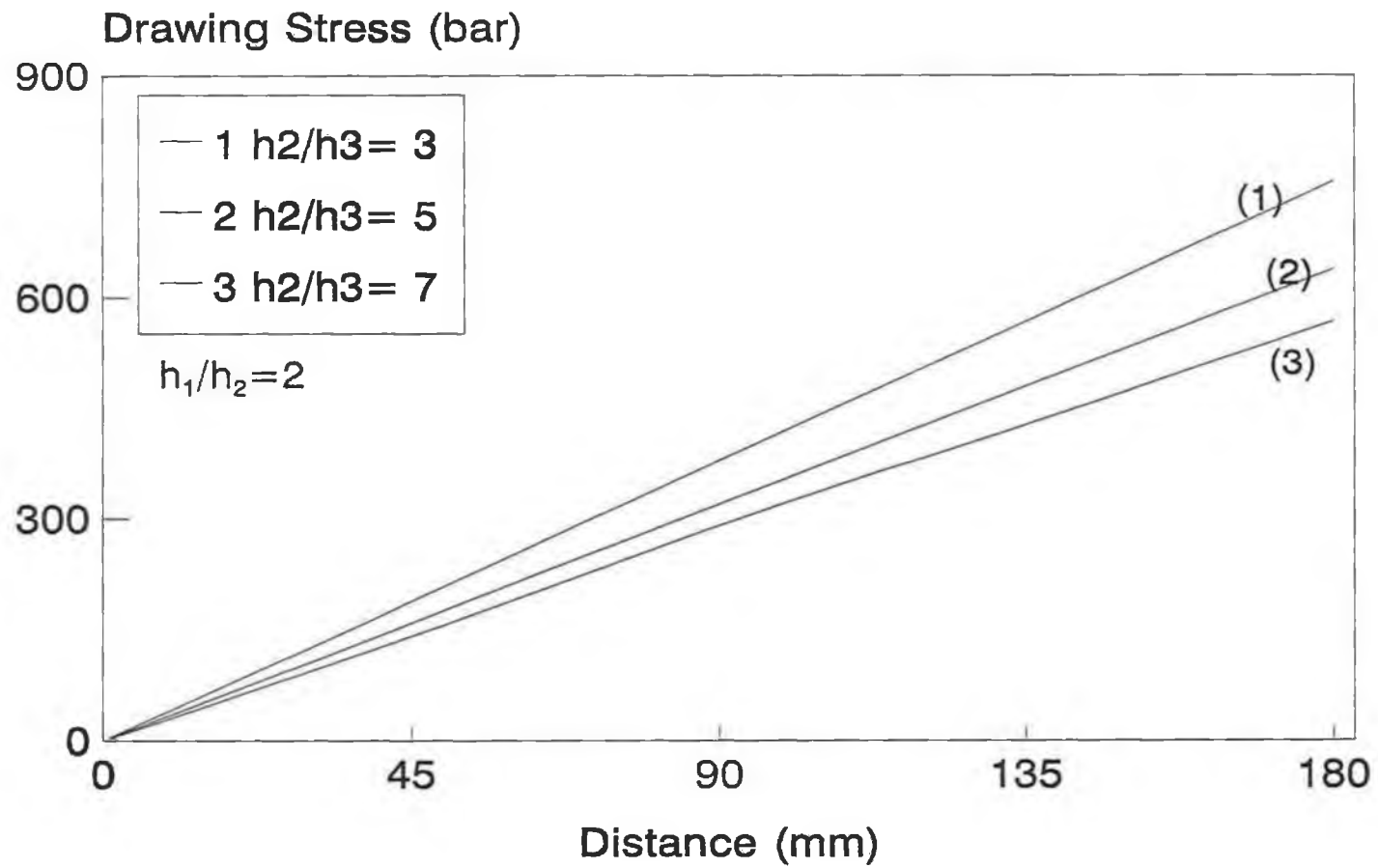


Fig. 4.11 Theoretical effect of the gap ratio h_2/h_3 on the drawing stress distribution

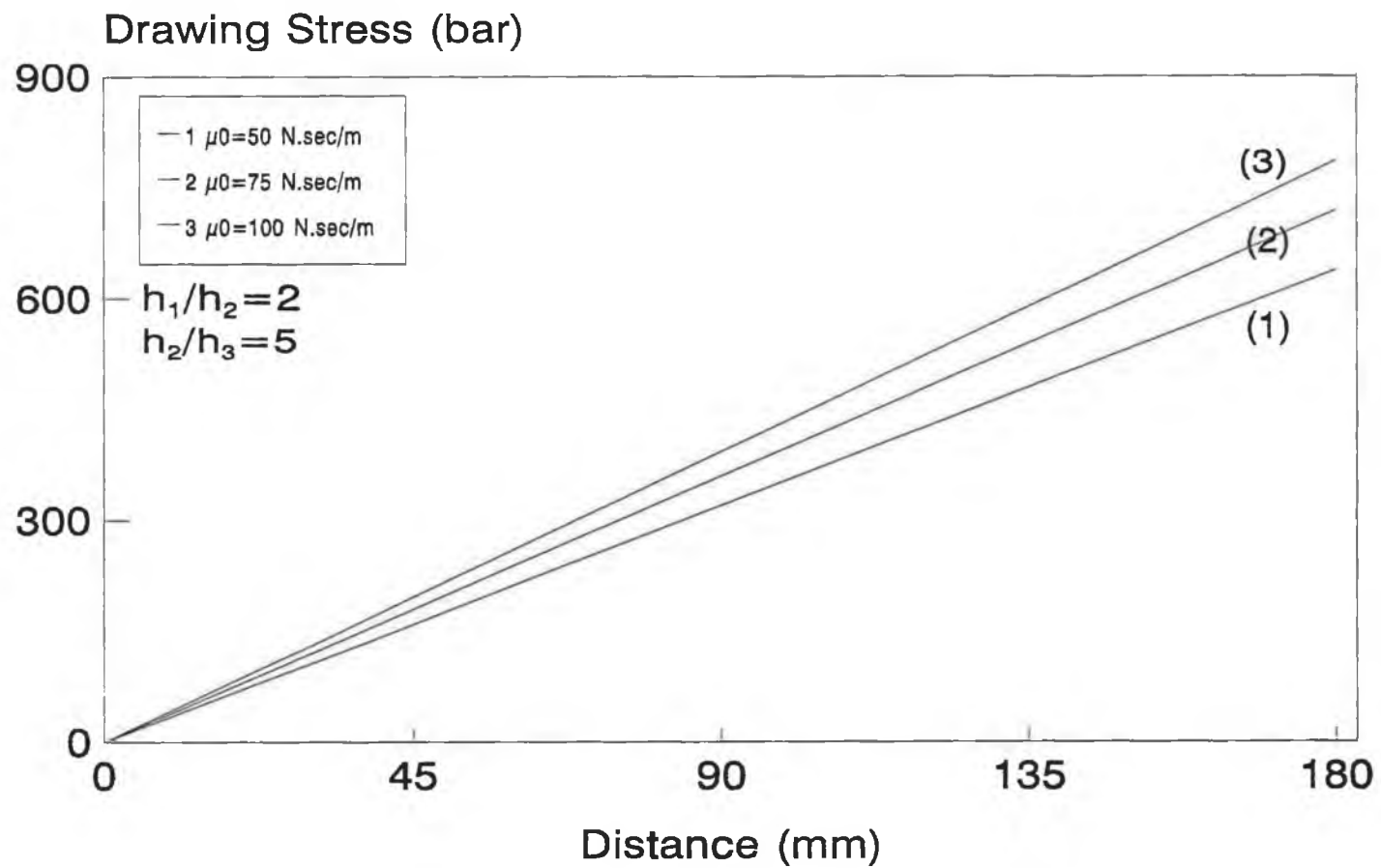


Fig. 4.12 Theoretical effect of reference viscosity on drawing stress distribution

4.1.7- Comparative performance of the combined unit with the stepped parallel and tapered bore unit

In order to compare the theoretical results of pressure distribution and maximum pressure for the combined pressure unit to those of the parallel and the tapered bore pressure units, theoretical results were obtained and presented in graphical form for different overall gap ratios.

Figure 4.13(a) compares the trends and magnitudes of the calculated pressure distribution for all the pressure units for an overall gap ratio of $G.R=10$. The Figure suggests that a higher pressure is predicted for the simple tapered unit as compared to the other units which produce almost half the magnitude of the pressure using the simple tapered pressure unit. For a higher overall gap ratio of $G.R=20$ and drawing speed of 0.5 m/sec as seen in Figure 4.13(b) still a very high pressure could be predicted for the simple tapered pressure unit (almost three times the combined unit) as compared to the other two units.

Further increase to the overall gap ratio $G.R=30$ results in lower magnitudes of press for all the pressure units but still higher pressure could be observed for the simple tapered pressure unit.

It is very important to notice that the inlet and the step gap of the combined geometry unit affects the pressure generated, which means that for the same overall gap ratio any change in those gaps may results in higher or lower pressure compared to that in Figure 4.13.

The results for maximum pressure could be seen in Figure 4.14 for an overall gap ratio of 10 which suggests that the simple tapered pressure unit produces higher pressure for all drawing speeds.

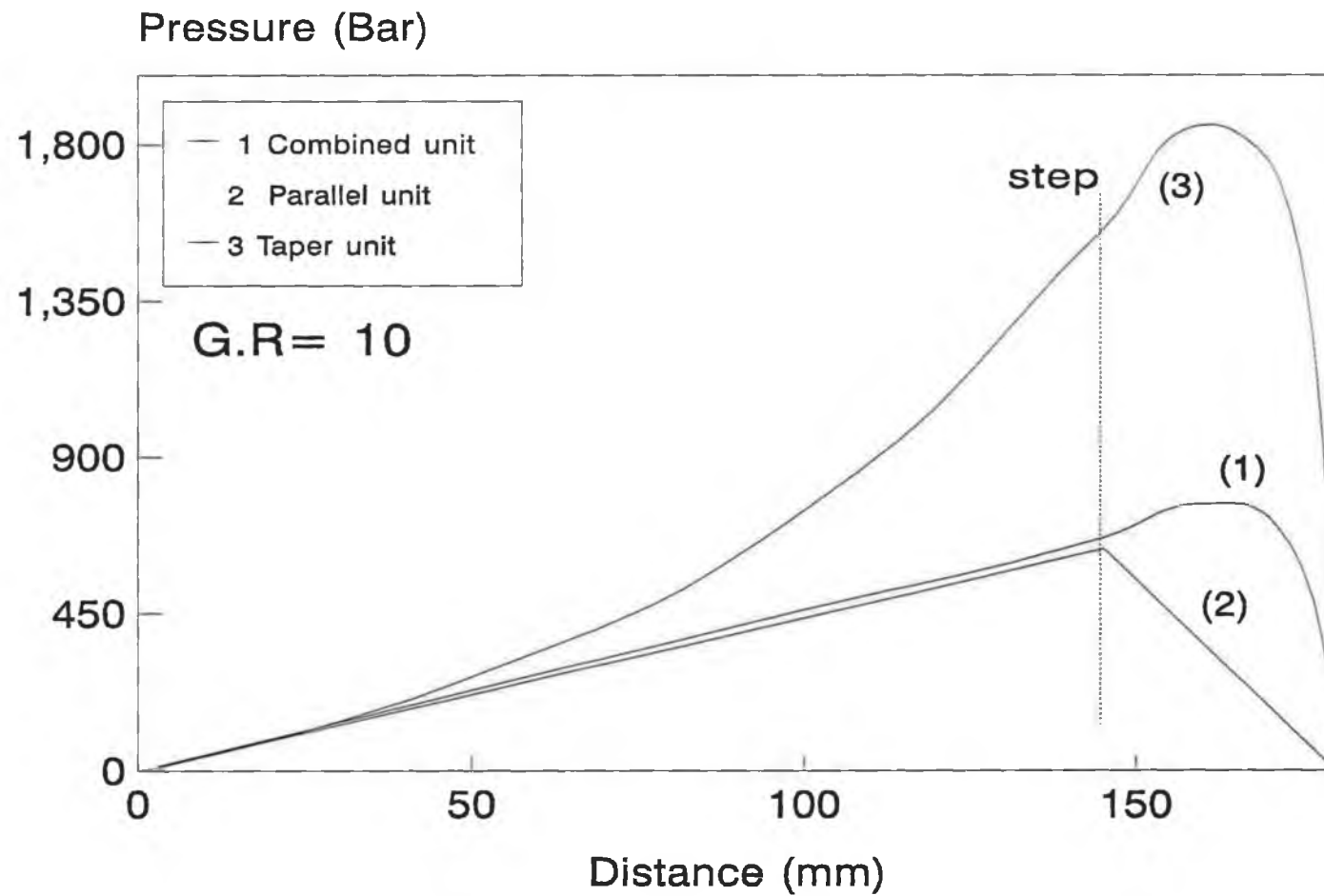


Fig. 4.13(a) Comparison between the pressure units performance

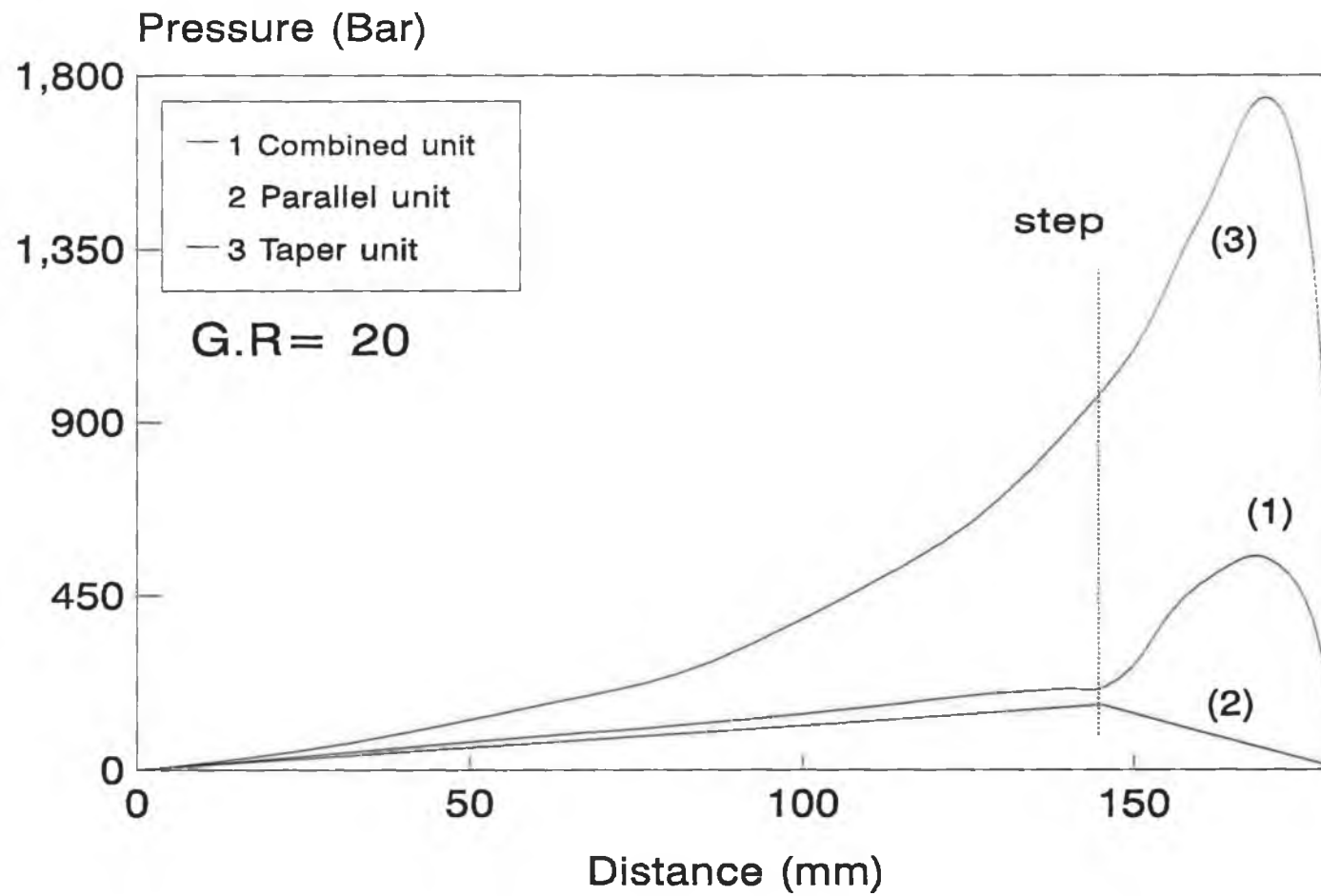


Fig. 4.13(b) Comparison between the pressure units performance

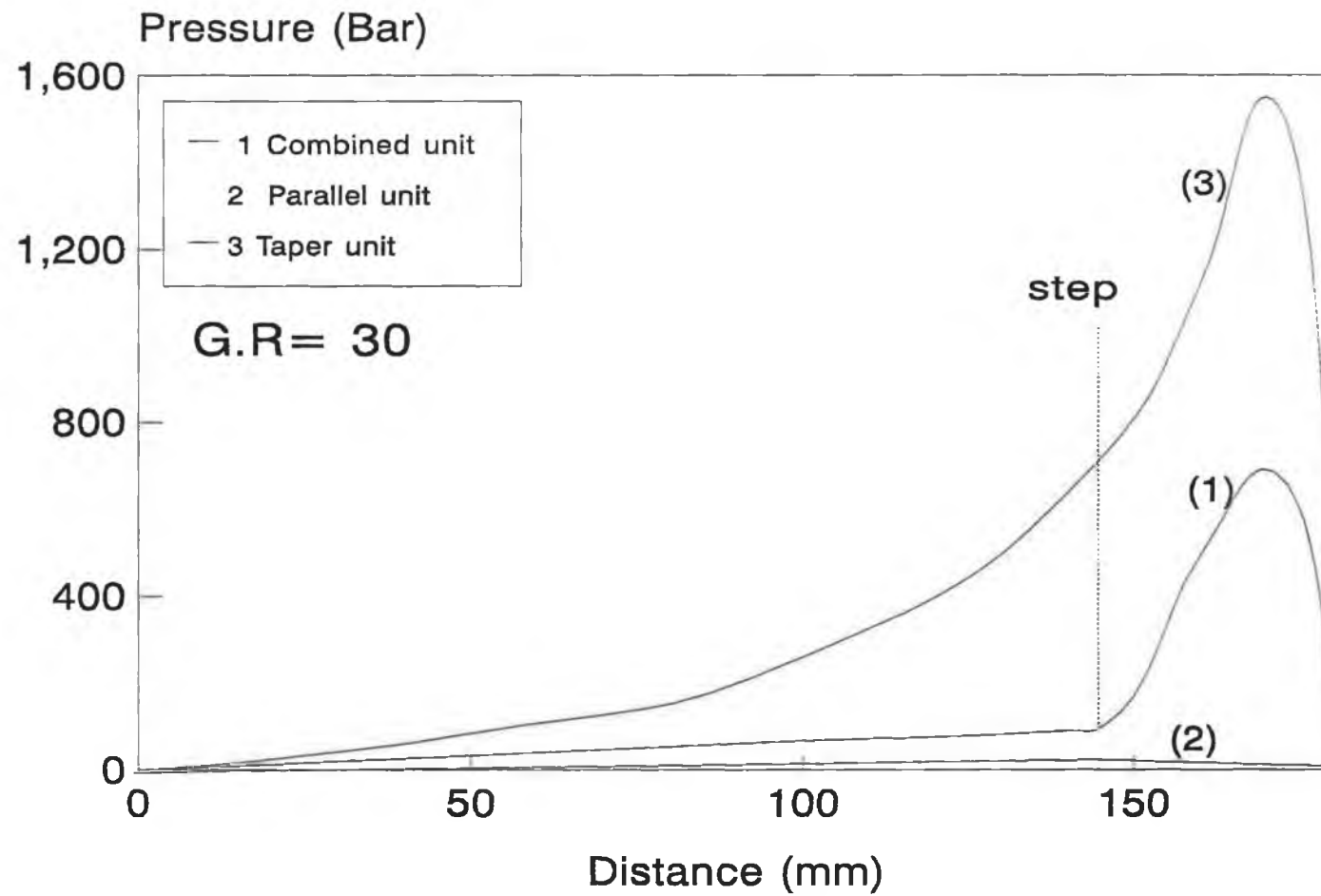


Fig. 4.13(c) Comparison between the pressure units performance

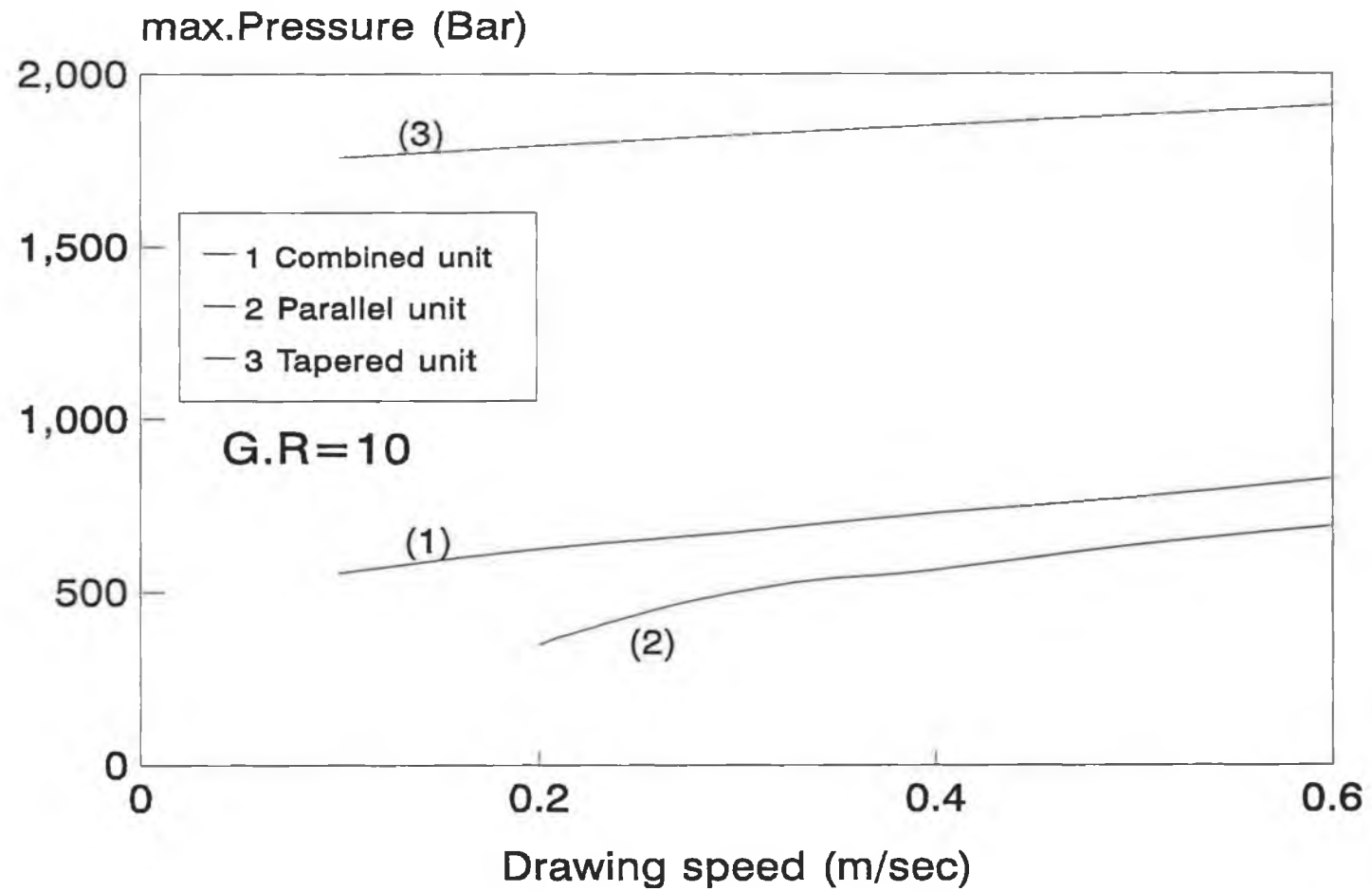


Fig. 4.14 Effect of drawing speed on maximum pressure

4.2- Experimental Results

4.2.1- Introduction

In obtaining experimental results, tests were carried out by changing the inlet gap ratio, h_1/h_2 , and the outlet gap ratio h_2/h_3 . Stainless steel and copper wires have been used for these tests in which the outlet gap h_3 , was kept constant at 0.05 mm.

To achieve change in the gap ratios, the parameters h_1 and h_2 were changed. Borosiloxane polymer melt was used as the pressure medium and the melt temperature was kept constant at 110 ± 5 °C for all the tests. For each combination of h_1/h_2 and h_2/h_3 gap ratios, tests were performed at a number of drawing speeds ranging between about 0.05 and about 0.7 m/sec for both the stainless steel and copper wires of 2 mm diameter. The stress strain properties of these two wire materials have been determined as shown in appendix [DD]. The plastic yield stresses are approximately 456 MPa and 304 MPa for the stainless steel and copper wire materials respectively.

4.2.2- Pressure distribution

The pressure distributions within the complex geometry pressure unit, based on experimentally measured pressure at four different points, two in the parallel bore part and two in the tapered bore part, have been obtained and plotted for the gap ratio combination of $h_1/h_2 = 2$, and $h_2/h_3 = 5$. These pressure distribution curves are presented for different drawing speeds in Figures 4.15(a) and 4.15(b) for stainless steel and copper wires respectively.

It is evident from Figure 4.15(a) that for the range of drawing speeds considered, the peak pressure occurs in the tapered zone and that this peak pressure increases with the drawing speed. For example, at the drawing speed of 0.04 m/sec the peak pressure is about 600 bar whereas at 0.14 m/sec drawing speed a peak pressure of 1400 bar is obtained.

It is to be noted that one of the four locations where the pressure was measured appears to be the location at which the peak pressure occurs. This is also true for the pressure distribution obtained for the copper wire as shown in Figure 4.15(b), except the magnitudes of the peak pressure are generally much lower for copper wires than for stainless steel for comparable drawing speeds.

For the same geometrical parameters of the pressure unit and same wire diameter and drawing speed, the pressure distribution curve and the magnitude of the peak pressure in the unit should be the same for drawing wires of different materials provided that their elastoplastic deformation properties are identical. In the present case, the copper wire is much softer than the stainless steel wire. As such, elastic as well as plastic deformation (if any) of the copper wire would be greater than that for the stainless steel wire. Such greater deformation will cause relatively higher magnitudes of h_3 and possibly of h_2 which in turn will reduce the pressure. It is therefore evident that elastic-plastic deformation takes place in the copper wire. Measurements of the drawn wire shows that the diameter of the copper wire is reduced as much as 0.2 percent whereas there is 0.01 percent reduction in the stainless steel wire.

For a higher inlet gap ratio h_1/h_2 of 4 and outlet gap ratio h_2/h_3 of 5, Figure 4.16(a) illustrate the effect of the drawing speed on pressure distribution for stainless steel wire, a peak pressure of 730 bar was obtained with the drawing speed of 0.1 m/sec which is low compared to that in Figure 4.15(a).

The pressure distribution curve is almost linear up the step of the unit, whereas the peak pressure occurs within the tapered part of the unit. Similar trend could be observed in Figure 4.16(b) which shows pressure distribution curves for different drawing speeds when drawing copper wire. Figure 4.17 shows the pressure distribution curve for a copper wire, for inlet

and outlet gap ratios of 6 and 5 respectively, in which a very low magnitude of maximum pressure was obtained with these gap ratios as compared to those in Figures 4.15(b) and 4.16(b). For the inlet and outlet gap ratio combination of 2.85 and 7 respectively, the pressure distribution curves for different drawing speeds are presented in Figures 4.18(a) and 4.18(b) for stainless steel and copper wires respectively. Again it is evident from Figure 4.18(a) that for the range of drawing speeds considered, a very high pressure is obtained within the tapered part of the unit (almost twice the step pressure), a maximum pressure magnitude of 2000 bar was obtained with drawing speed of 0.35 m/sec, the same observation could be noticed in Figure 4.18(b) for drawing copper wire. However, much lower magnitudes of pressure were obtained, eg. 900 bar at drawing speed of 0.56 m/sec.

Varying the inlet and the outlet gap ratio to 6.6 and 3 respectively, the pressure distribution curves for stainless steel and copper wires were plotted in Figure 4.19(a) and 4.19(b) for different drawing speeds. This Figure shows similar trends as in other Figures, ie, higher pressure when drawing stainless steel and lower pressure when drawing copper wire for the same drawing speed.

For a range of drawing speed of up to 0.5 m/sec and unit configuration of h_1/h_2 ratio of 10 and h_2/h_3 ratio of 3, the pressure curves for both the stainless steel and copper wires are illustrated in Figure 4.20(a) and 4.20(b) respectively.

Almost similar trends of pressure distribution could be noticed from these Figures even for these gap ratios, the difference is that the overall gap ratio effects the magnitude of the pressure generated as increasing or decreasing it.

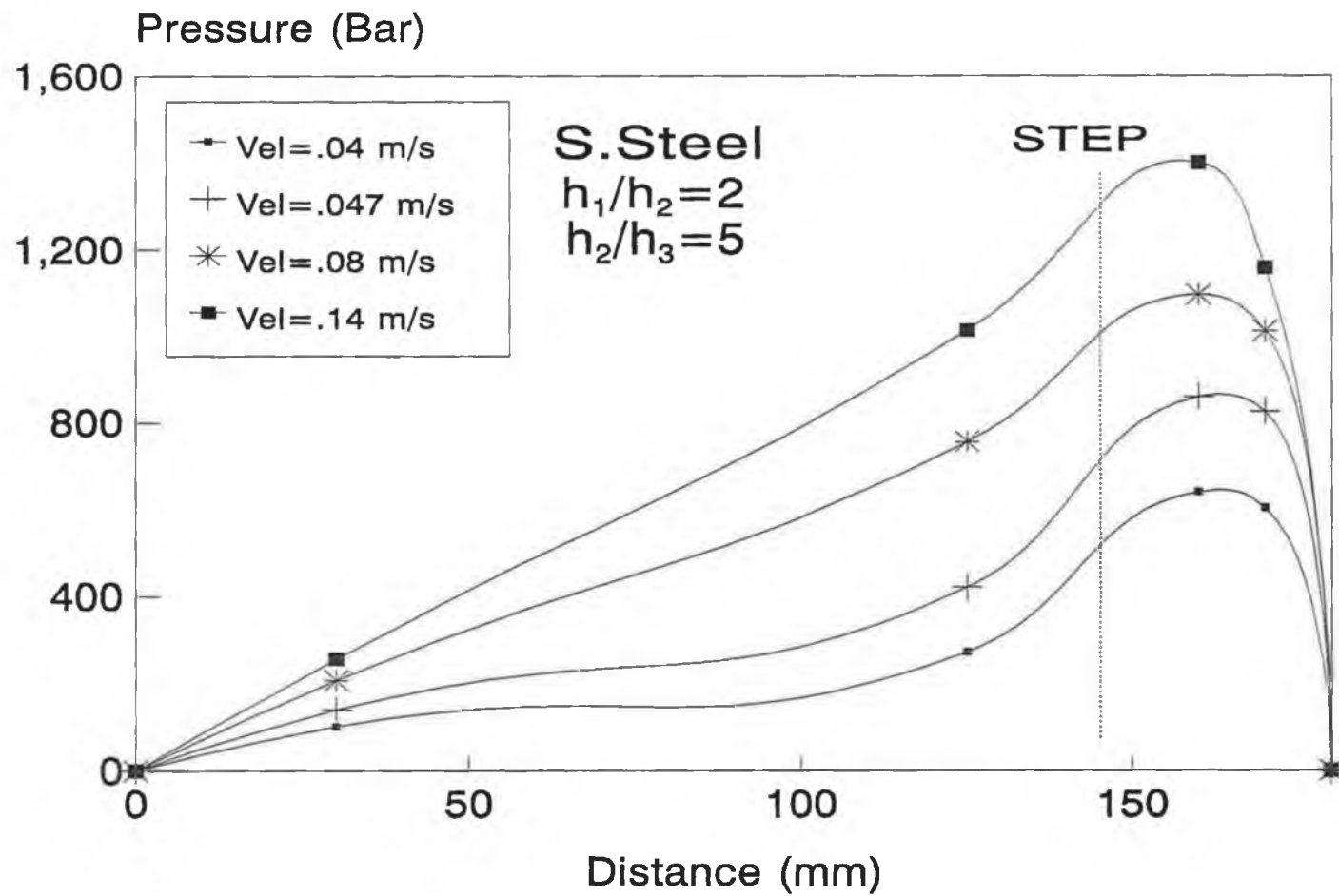


Fig. 4.15(a) Pressure distribution within the combined unit

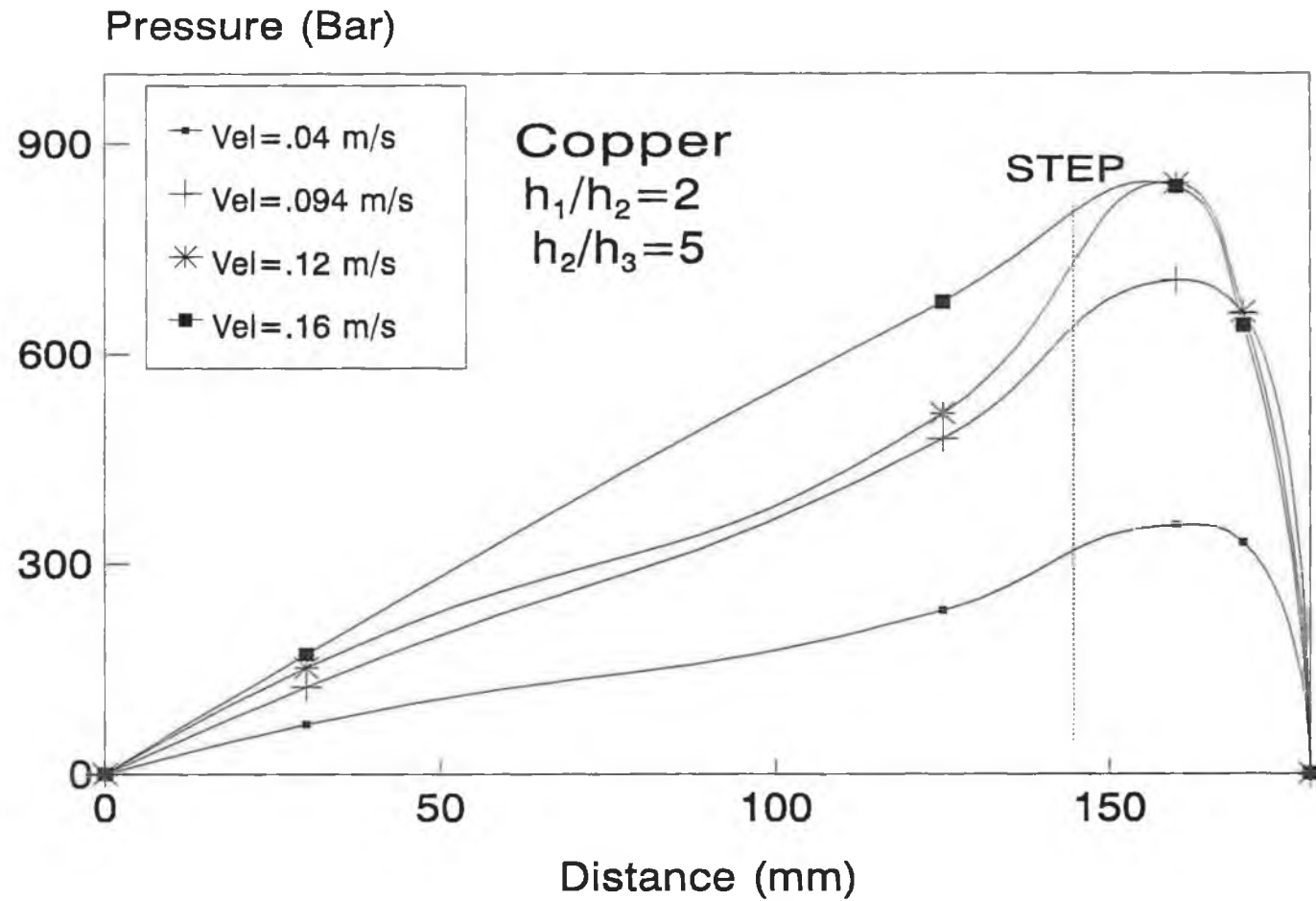


Fig. 4.15(b) Pressure distribution within the combined unit

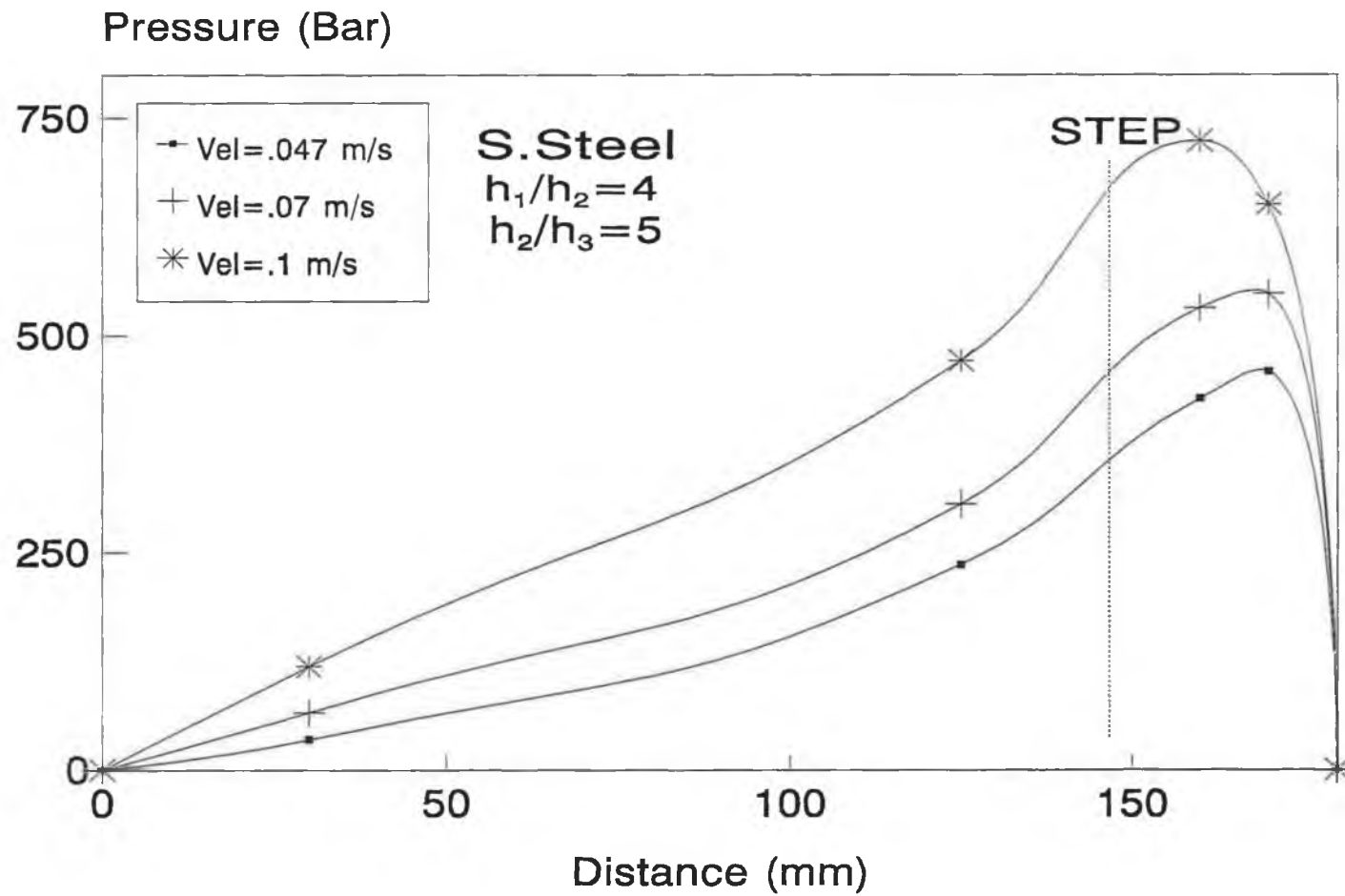


Fig. 4.16(a) Pressure distribution within the combined unit

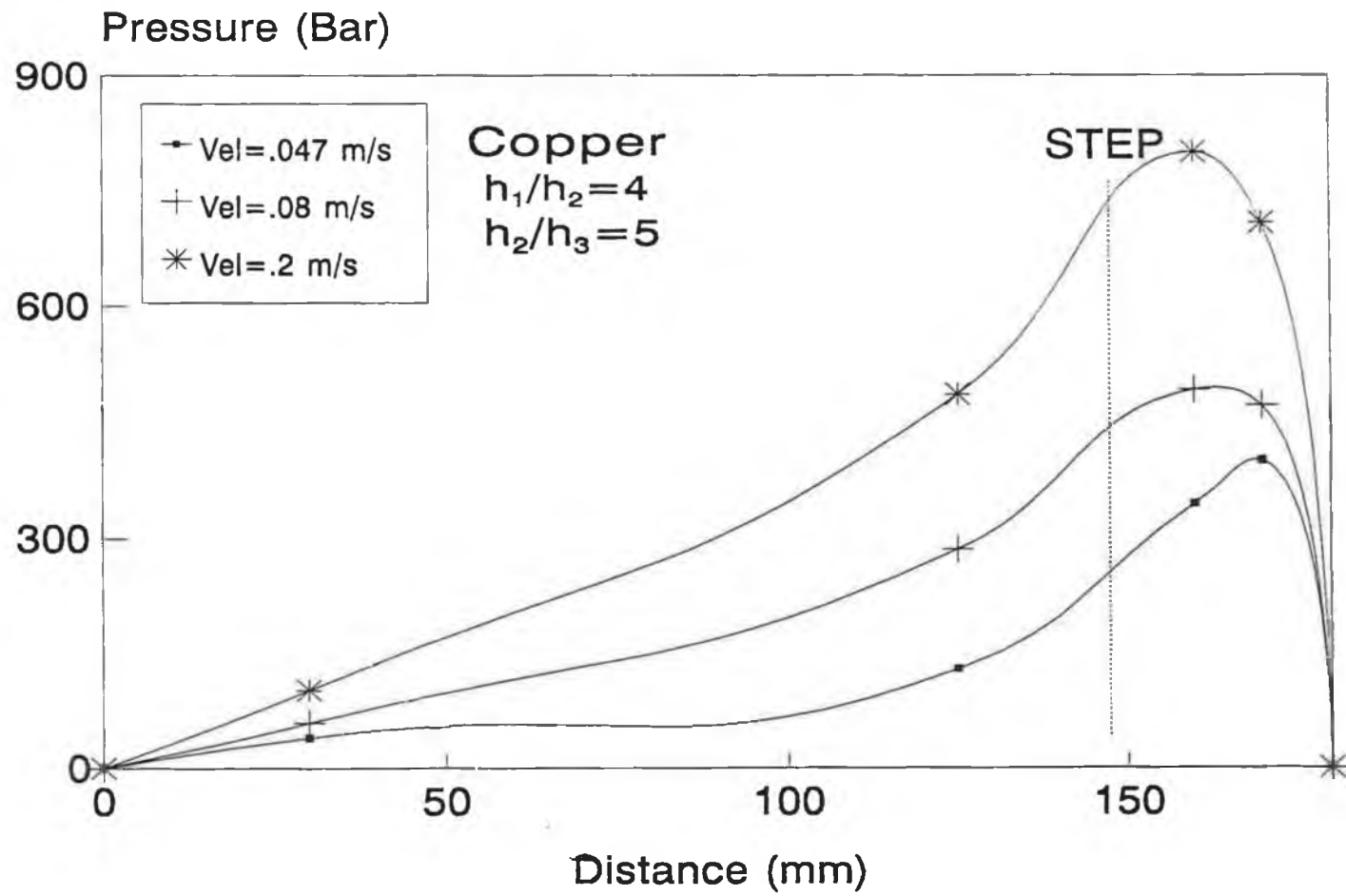


Fig. 4.16(b) Pressure distribution within the combined unit

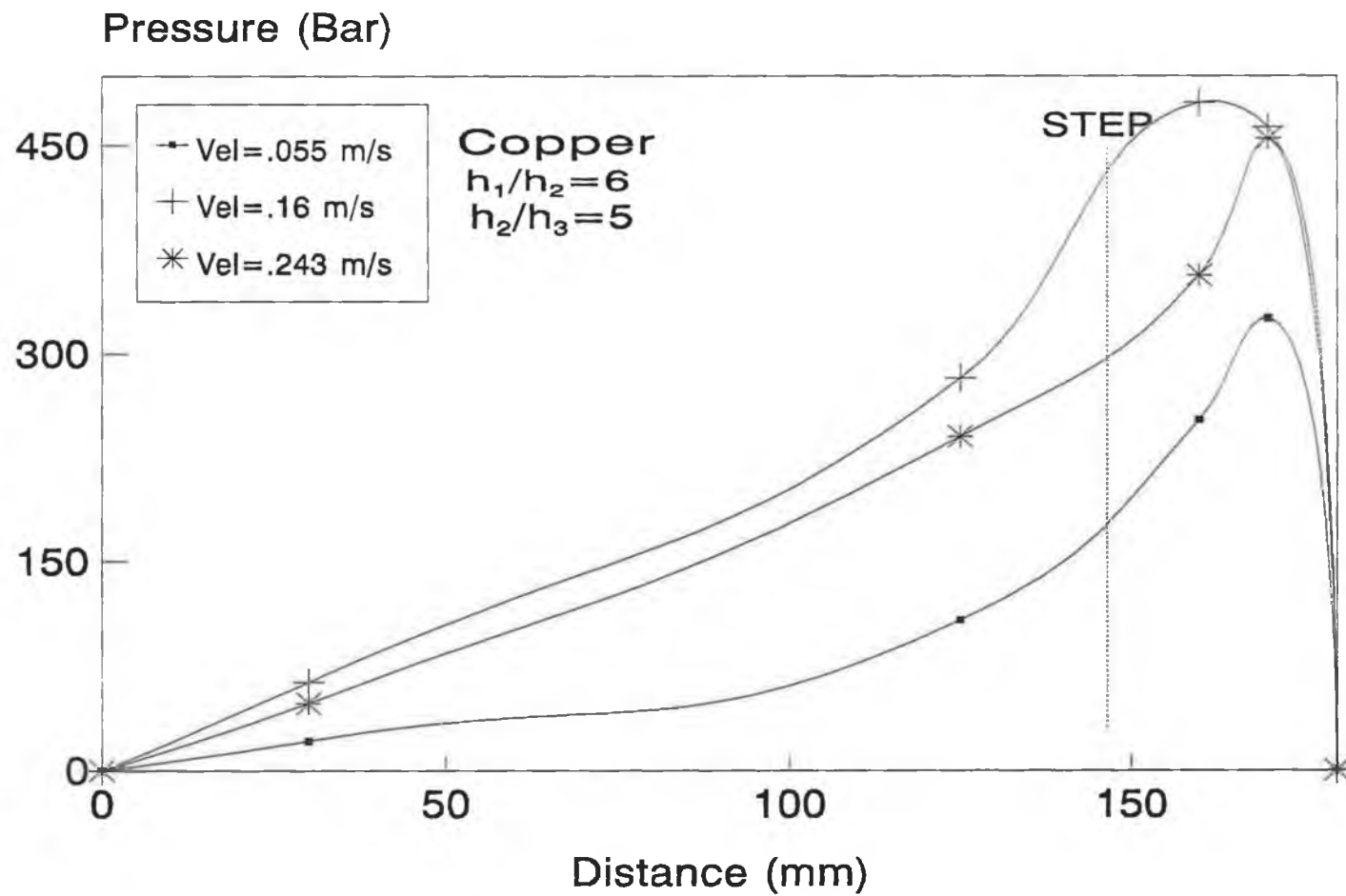


Fig. 4.17 Pressure distribution within the combined unit

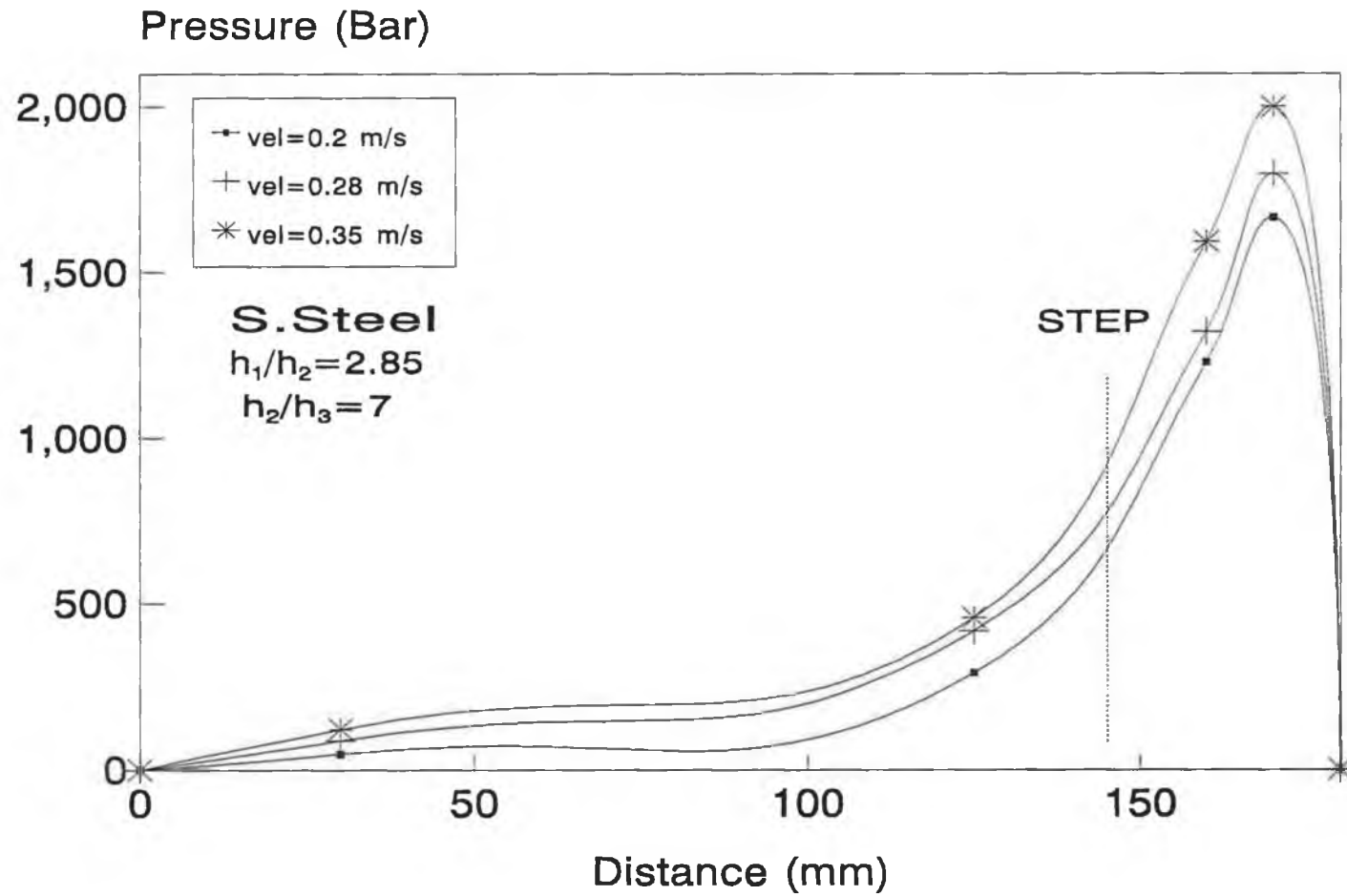


Fig. 4.18(a) Pressure distribution within the combined unit

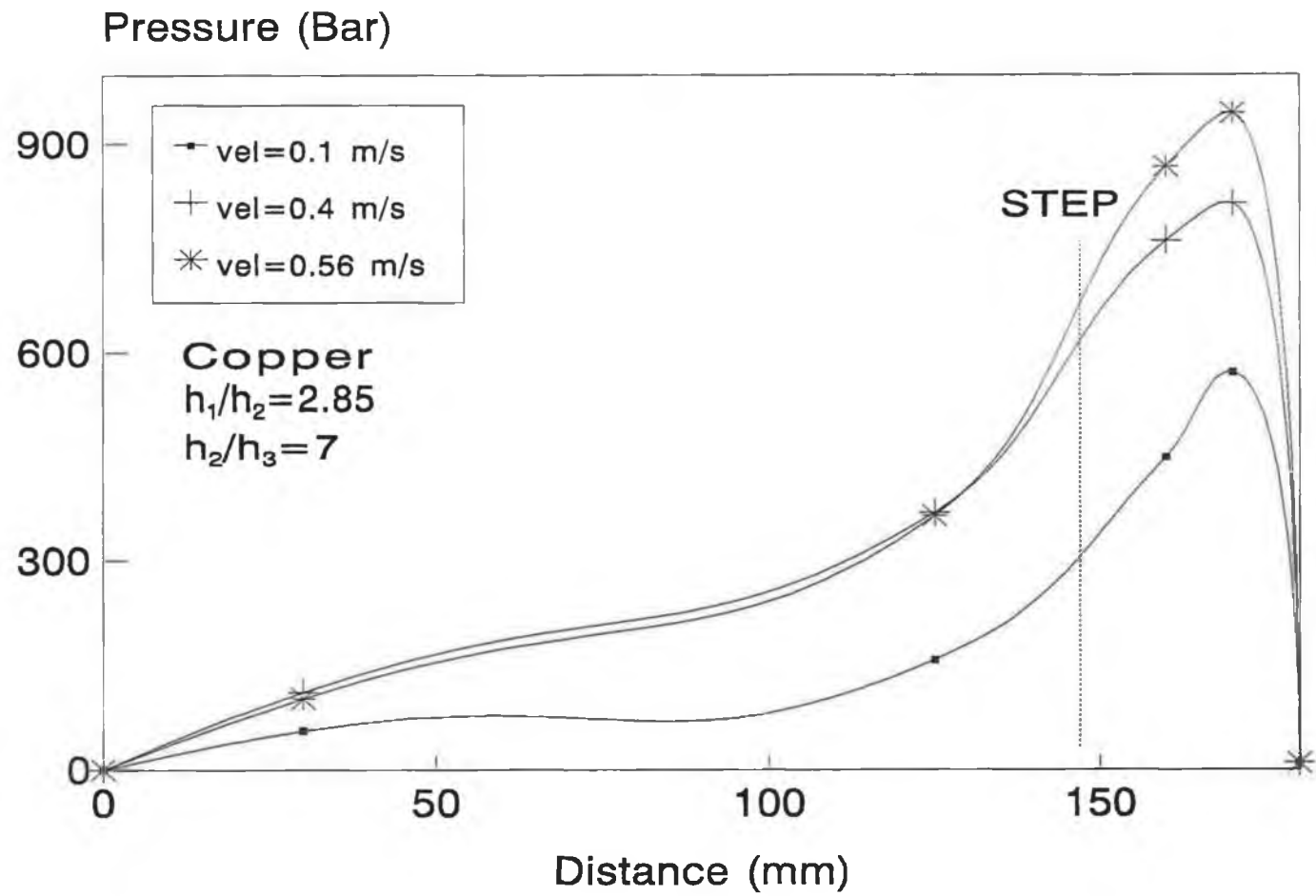


Fig. 4.18(b) Pressure distribution within the combined unit

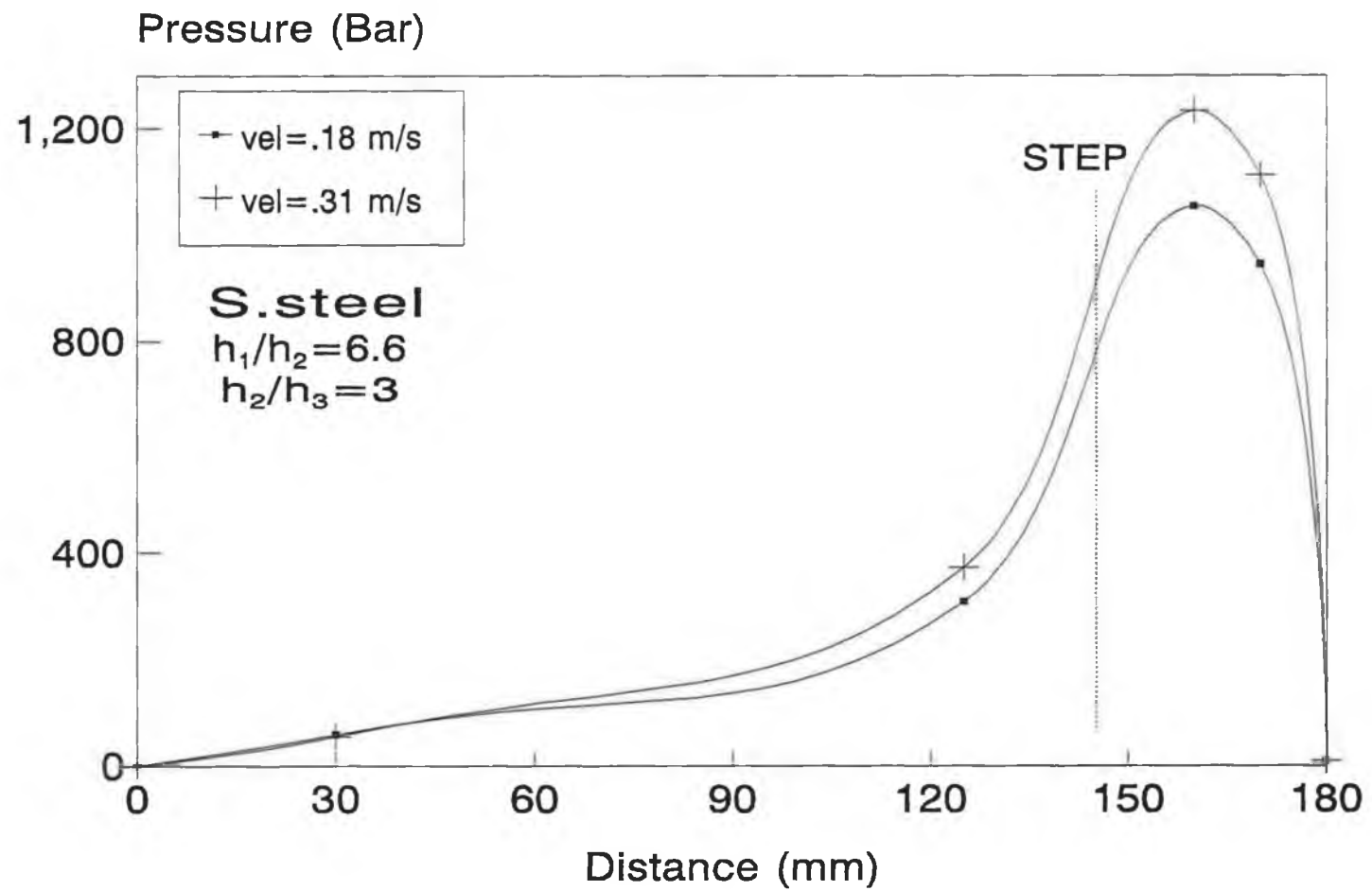


Fig. 4.19(a) Pressure distribution within the combined unit

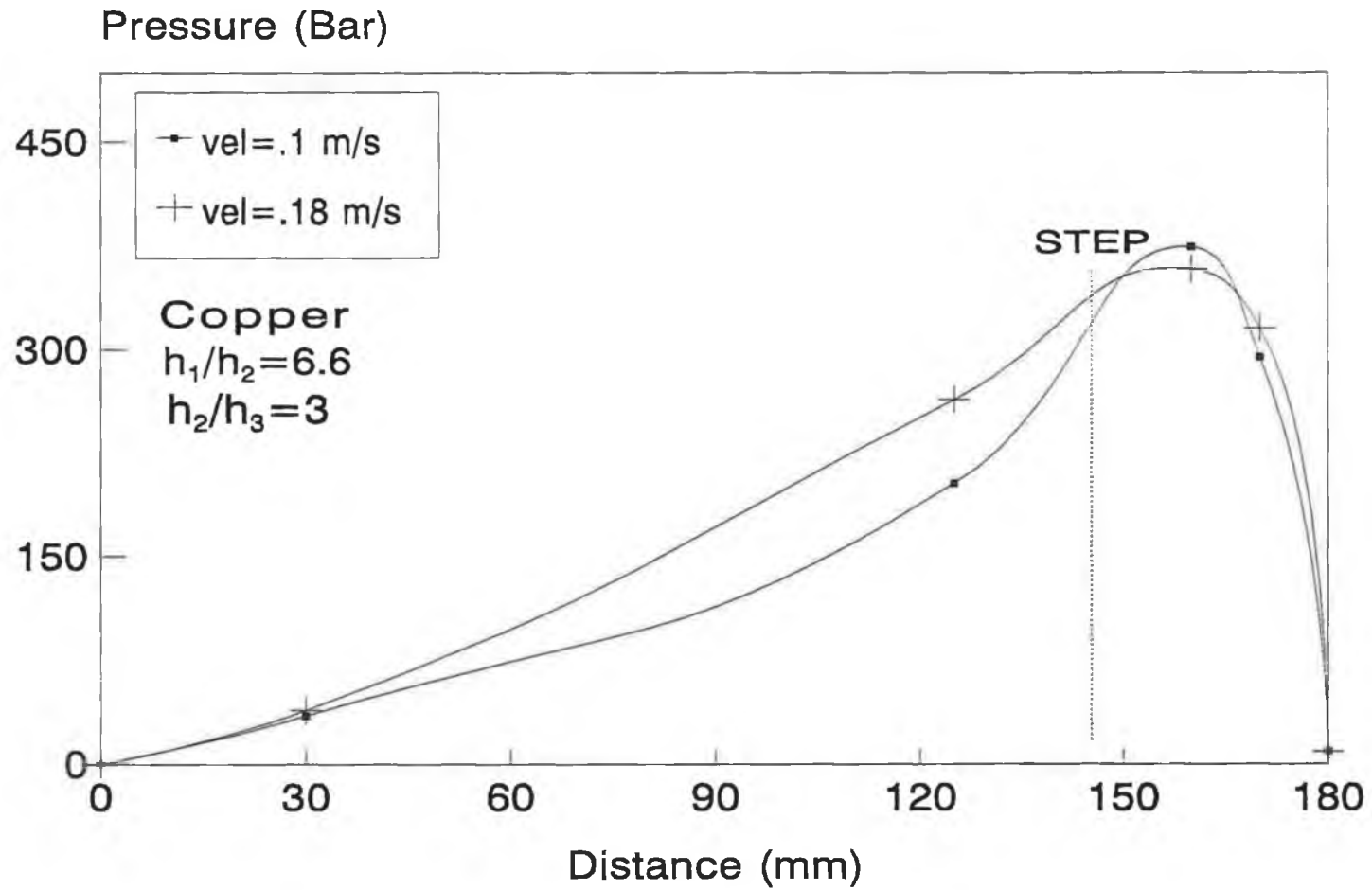


Fig. 4.19(b) Pressure distribution within the comined unit

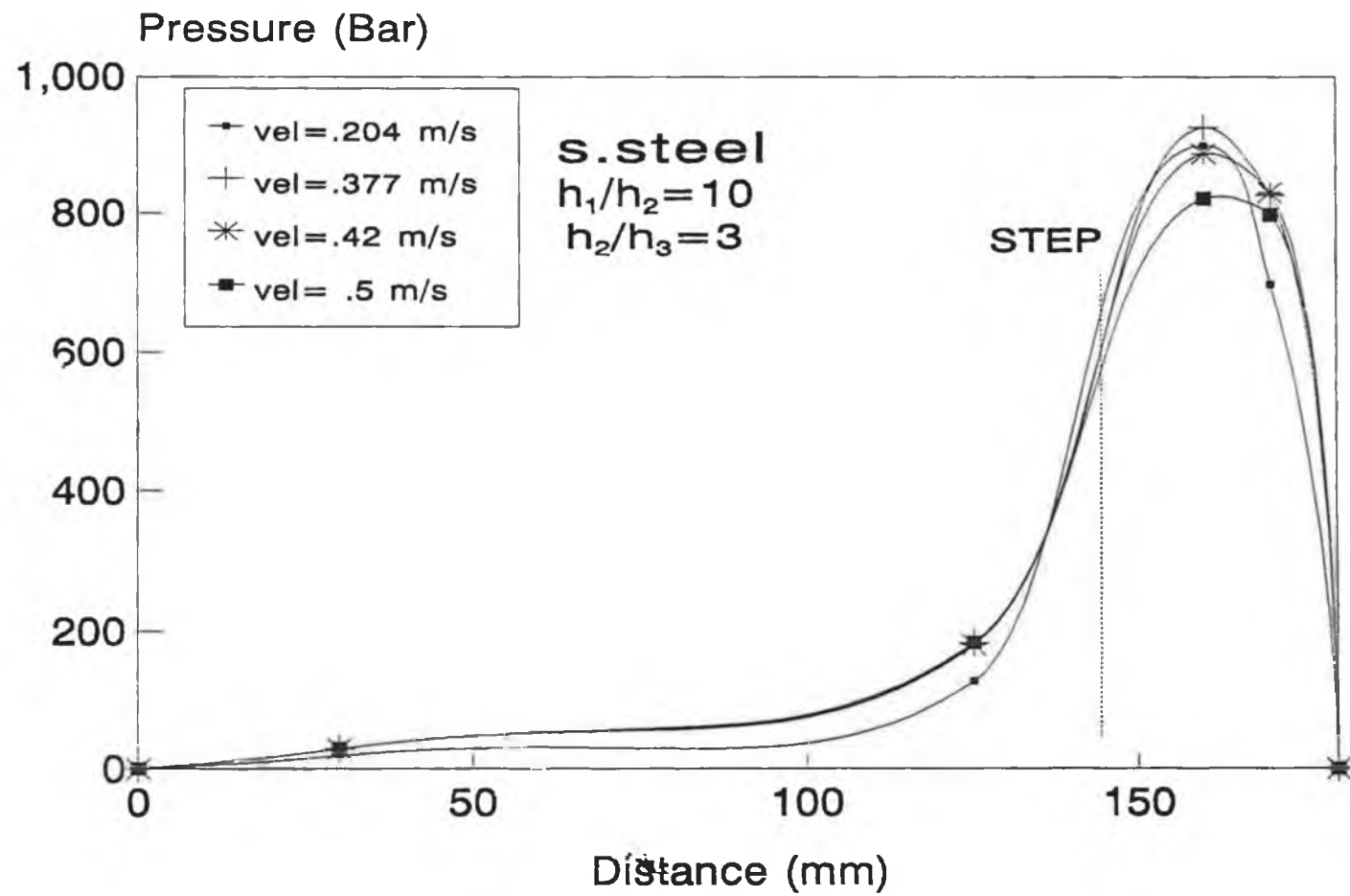


Fig. 4.20(a) Pressure distribution for a combined unit

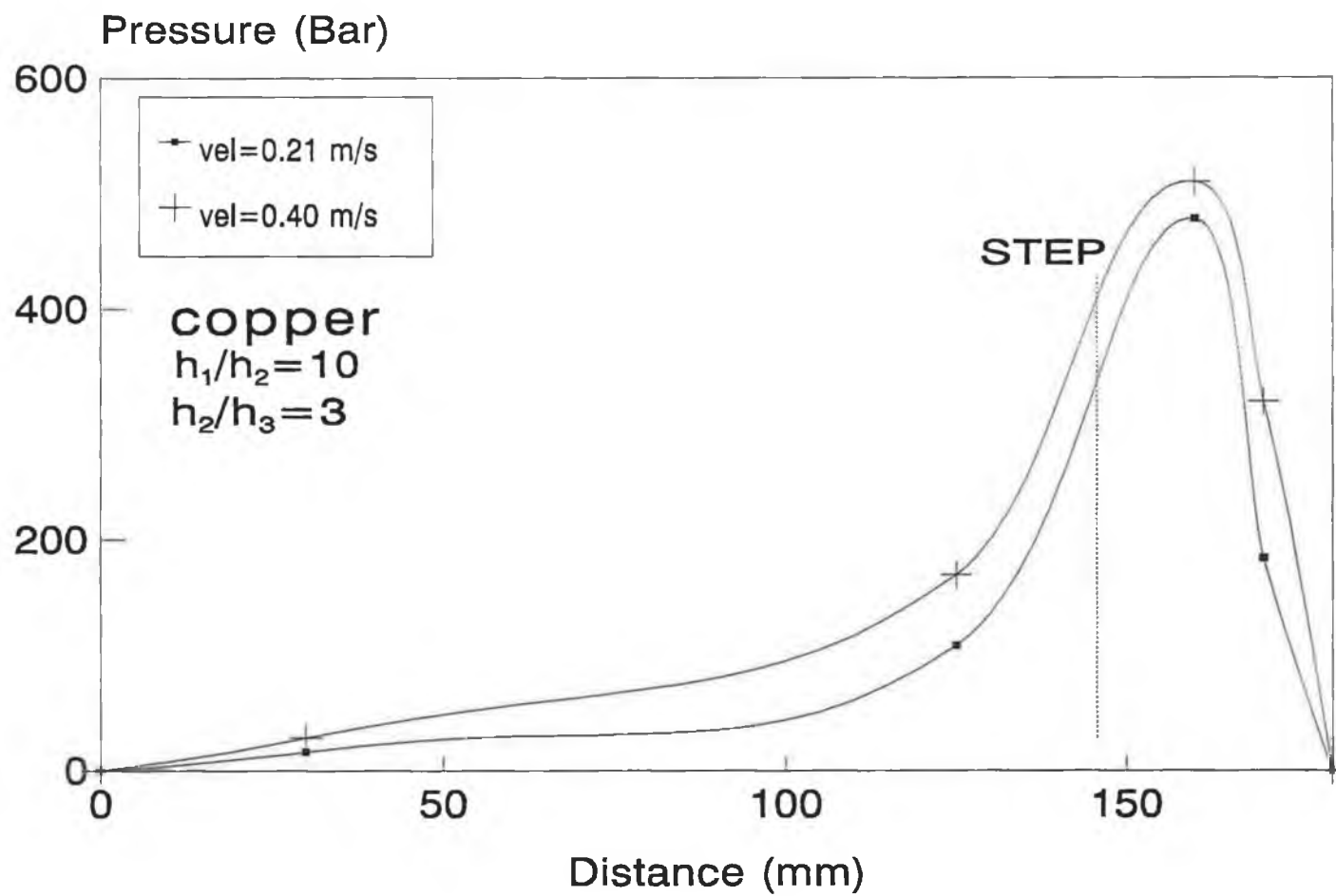


Fig. 4.20(b) Pressure distribution within the combined unit

4.2.3- Pressure distribution in stepped parallel bore unit

In order to compare the effectiveness of the combined geometry pressure unit in relation to a stepped bore unit of the same inlet and outlet gaps experiments were carried out for $h_2/h_3=1$ and $h_1/h_2=(10, 20, 30)$. For a range of drawing speed up to 0.28 m/sec, the pressure distribution results for an overall gap ratio of 10 and 20 is given in Figures 4.21 and 4.22 respectively using copper wire, a maximum pressure of almost 700 bar is obtained with drawing speed of 0.133 m/sec, whereas for almost the same drawing speed and higher gap ratio h_1/h_2 of 10 Figure 4.22 the maximum pressure obtained is 180 bar. As shown in Figures 4.23(a) and 4.23(b) the pressure distribution is linear up to the step after which it falls almost linearly to zero at the exit end of the unit, almost equal magnitudes of pressure were obtained when drawing both types of the wire materials. This suggests that the very low pressure was not sufficient to cause any plastic deformation in either of the wires.

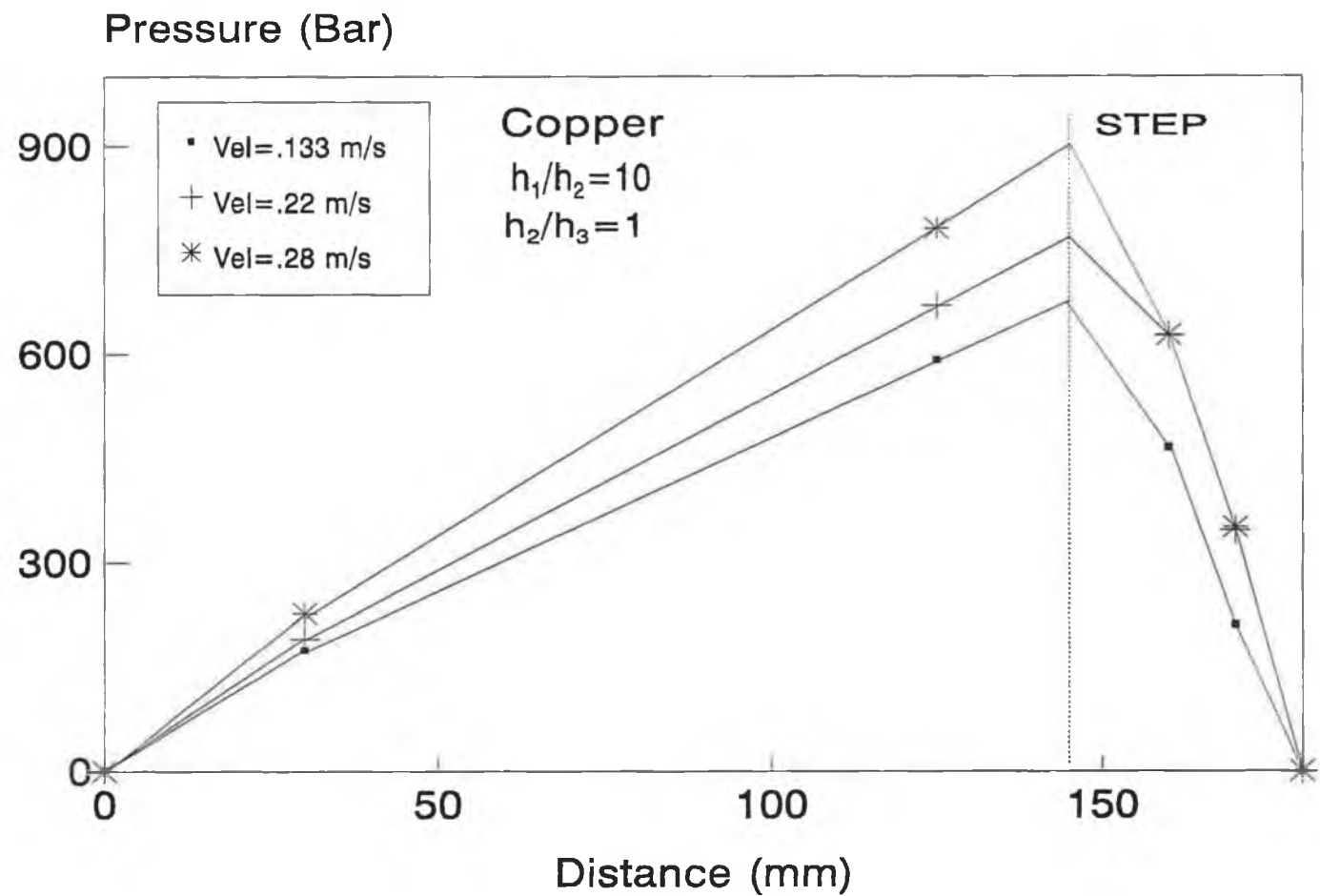


Fig 4.21 Pressure distribution within the parallel bore unit

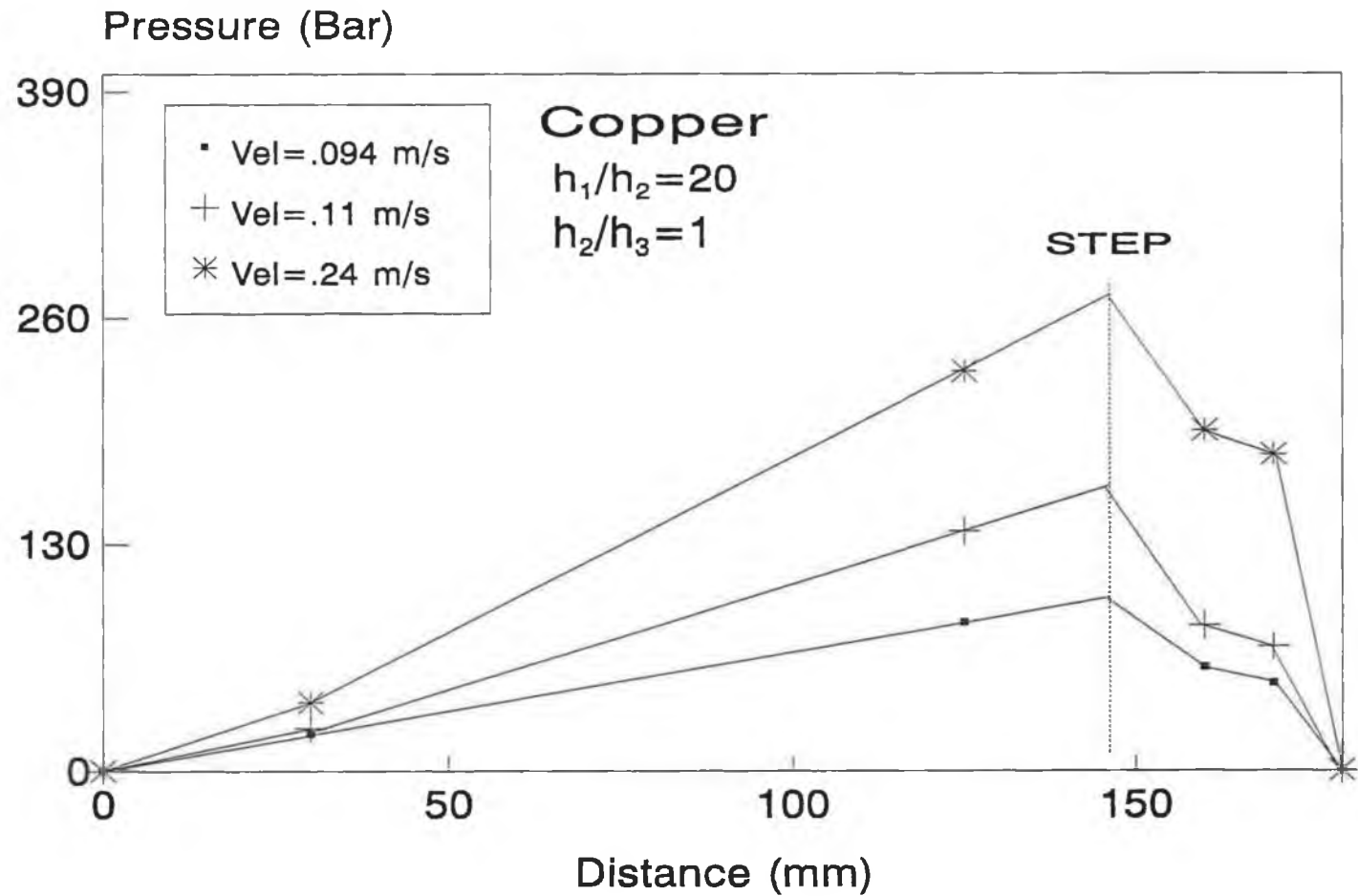


Fig 4.22 Pressure distribution within the parallel bore unit

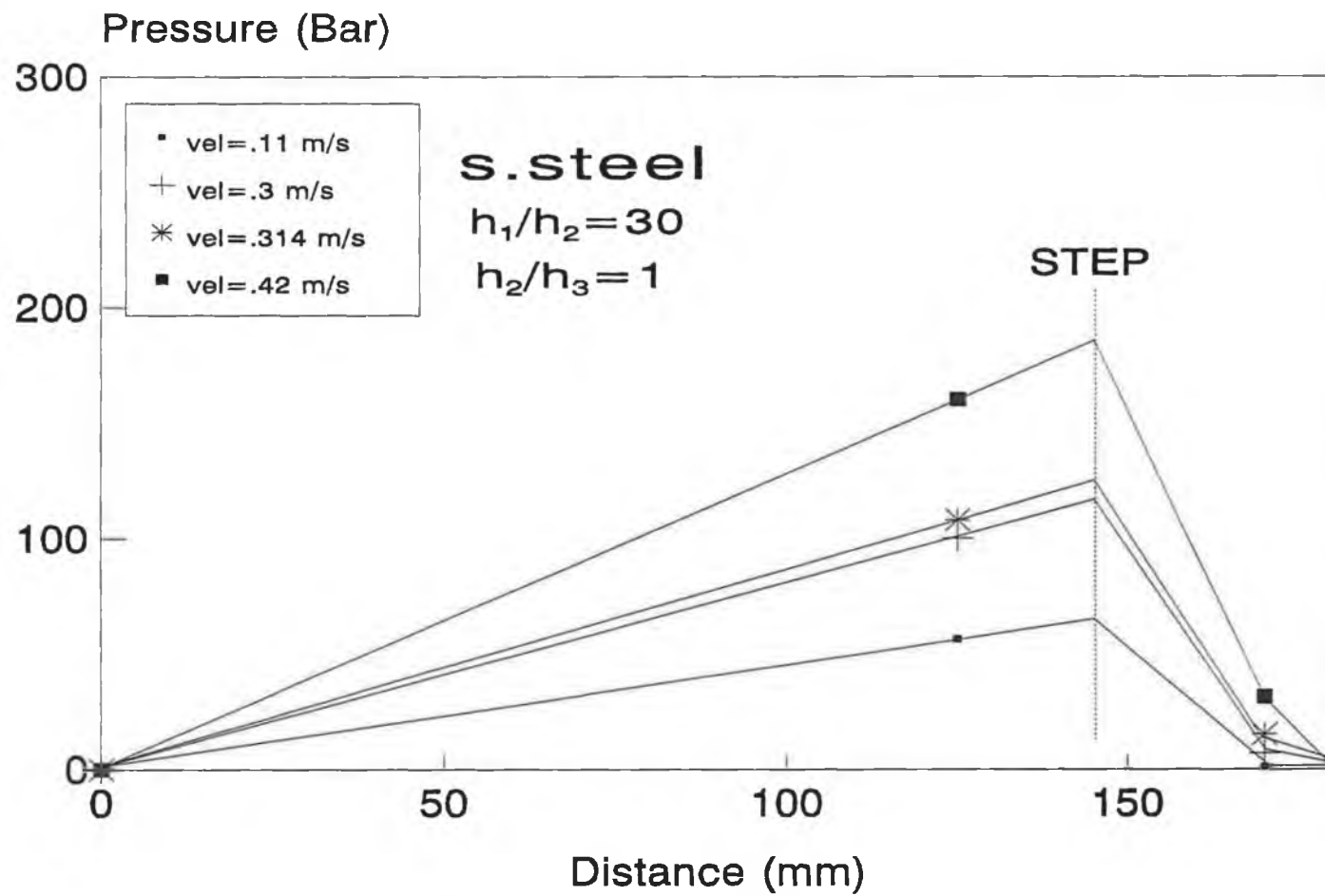


Fig. 4.23(a) Pressure distribution for parallel bore unit

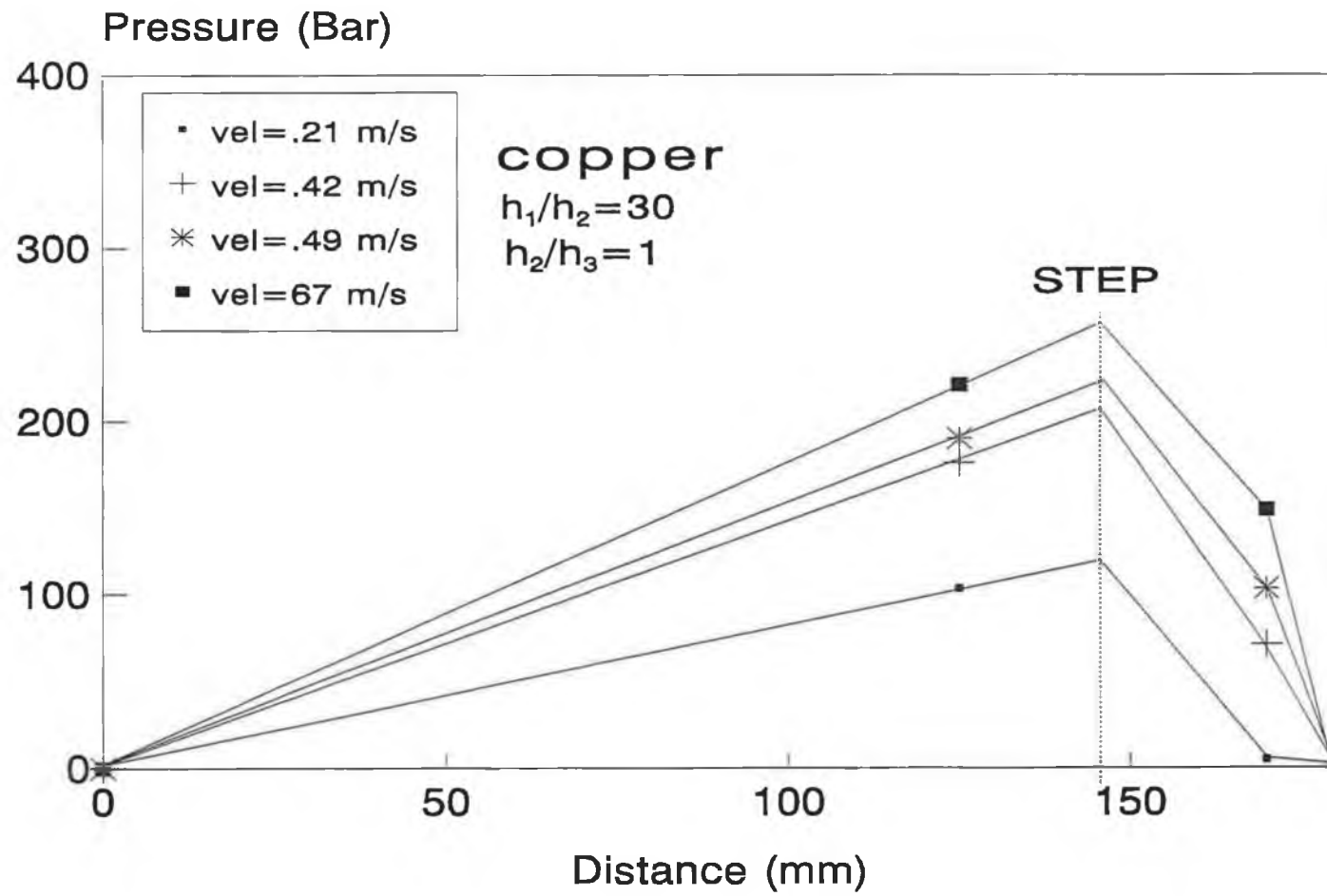


Fig. 4.23(b) Pressure Distribution within parallel bore unit

4.2.4- Comparative performance of the combined unit to the stepped parallel bore unit

In the previous sections the results of pressure distribution using both the combined and the parallel bore units was given. This section is aimed to compare the pressure distribution results for both the pressure units. Figures 4.24(a) and 4.24(b) compares the pressure distribution for both the combined unit and the parallel unit having the same overall gap ratios for stainless steel and copper wires respectively. Figure 4.24(a) demonstrates the pressure distribution curves for both the units at drawing speed of 0.1 m/sec, the combined unit gap ratios are $h_1/h_2=2$ and $h_2/h_3=5$ ($h_1/h_3=10$) and the parallel unit ratios $h_1/h_2=10$. Almost the same magnitude of pressure for both the units was obtained before the step after which a sharp fall could be observed for the parallel bore unit but further increase of the pressure after the step was noticed for the combined unit. Similar trend is illustrated in Figure 4.24(b) when drawing a copper wire except that it required almost twice the drawing speed for the parallel unit to produce the same pressure as that obtained when using the combined geometry pressure unit. Figure 4.25(a) and (b) shows pressure distribution curves for a combined geometry unit and a parallel bore unit of the same overall gap ratio. For the combined geometry gap ratio combinations of (h_1/h_2 , h_2/h_3) were changed keeping the overall gap ratio at 20 which is also the gap ratio for the parallel bore unit. The drawing speed is the same for all different units, namely, 0.1 m/sec and copper wire was drawn. It is evident from these Figures that the maximum pressure is considerably higher for all the combined geometry gap ratios when compared with the maximum pressure obtained for the parallel unit. Similar trend is evident from Figures 4.26(a) and (b) which shows results for two combined geometry units of gap ratio combinations ($h_1/h_2=6$, $h_2/h_3=5$) and ($h_1/h_2=10$, $h_2/h_3=3$) and for a parallel bore unit of gap ratio $h_1/h_2=h_1/h_3=30$, the wire materials being stainless steel and copper respectively drawn at 0.21 m/sec drawing speed.

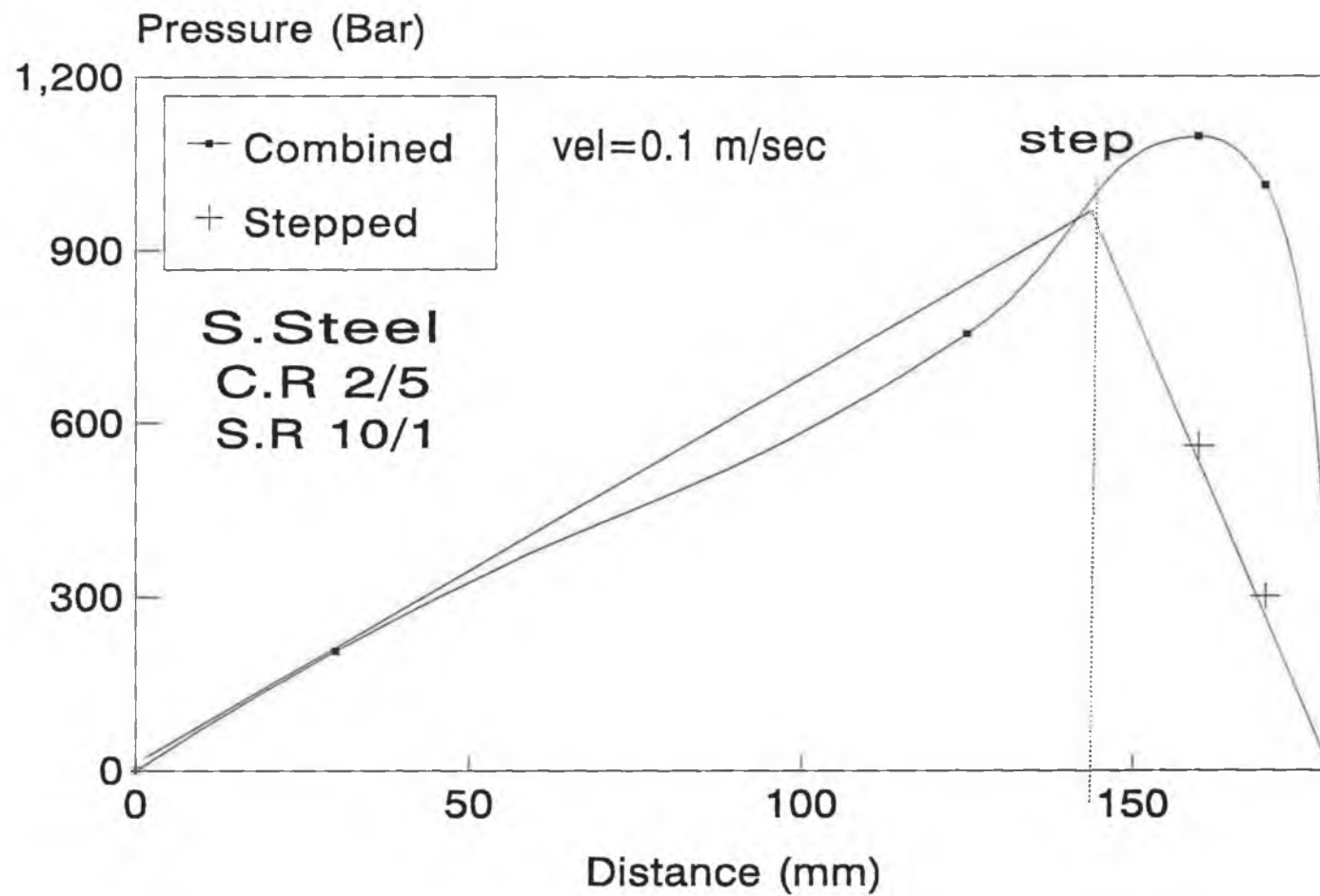


Fig. 4.24(a) Pressure distribution for combined unit

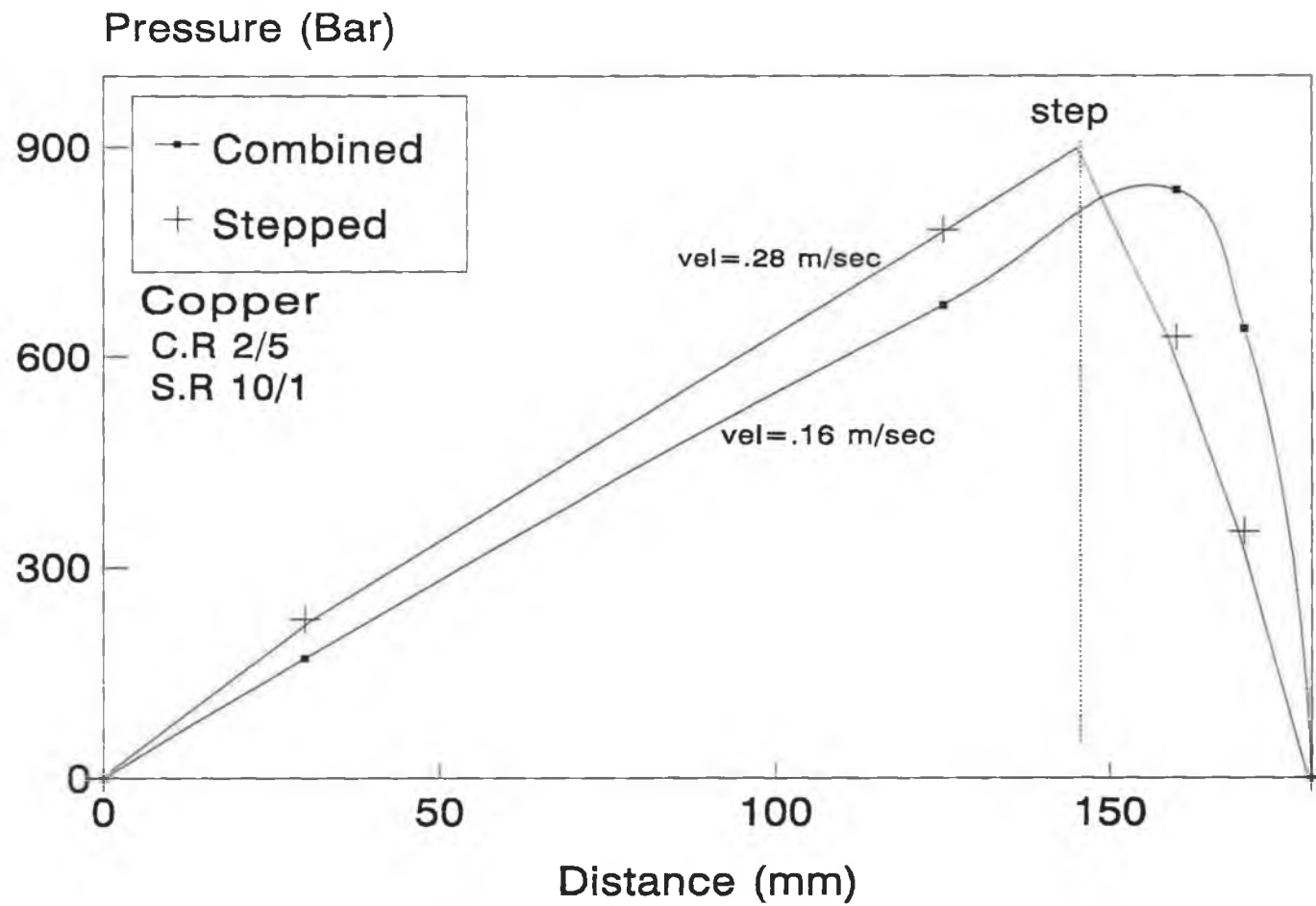


Fig. 4.24(b) Pressure distribution for combined unit

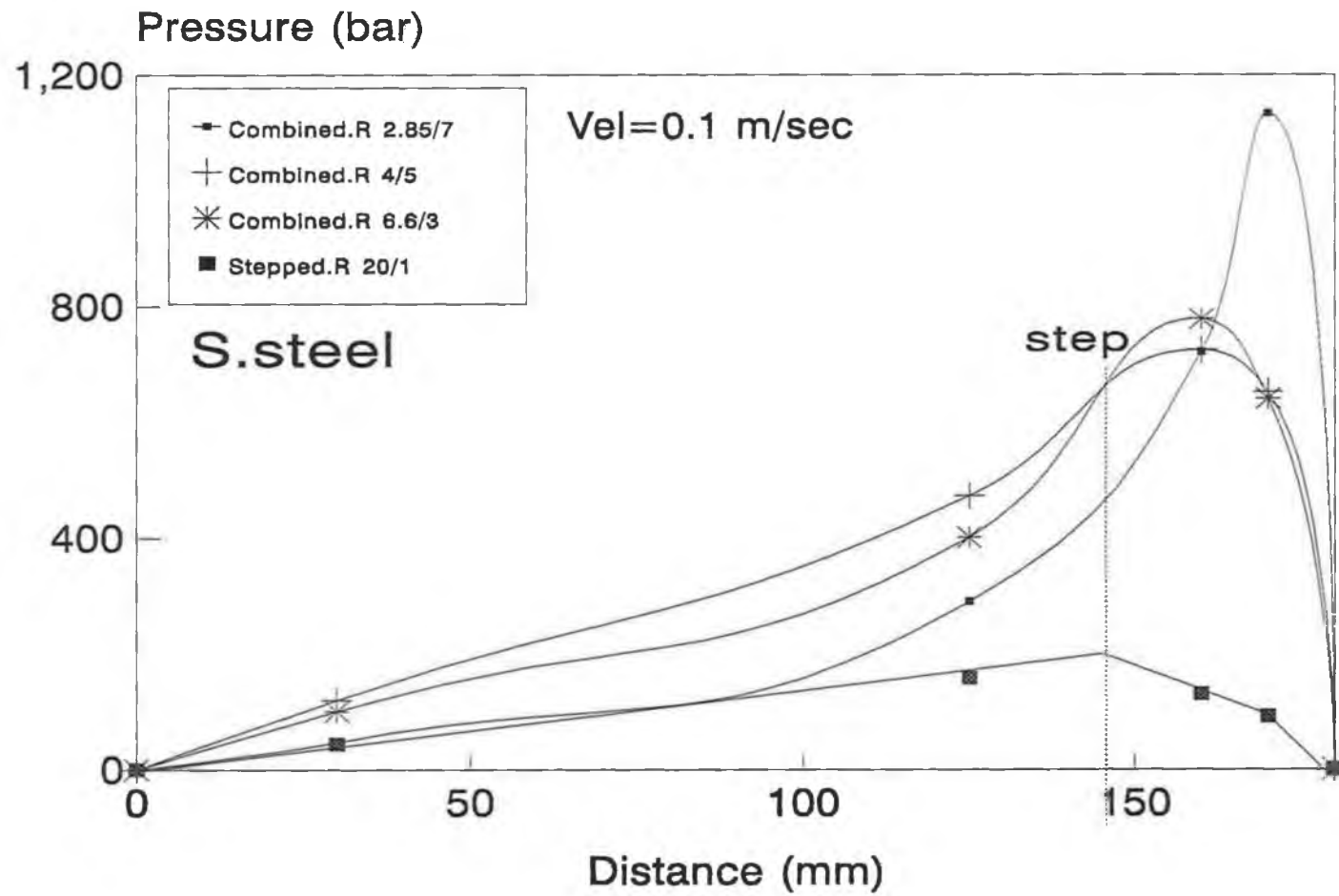


Fig. 4.25(a) Pressure distribution within combined unit

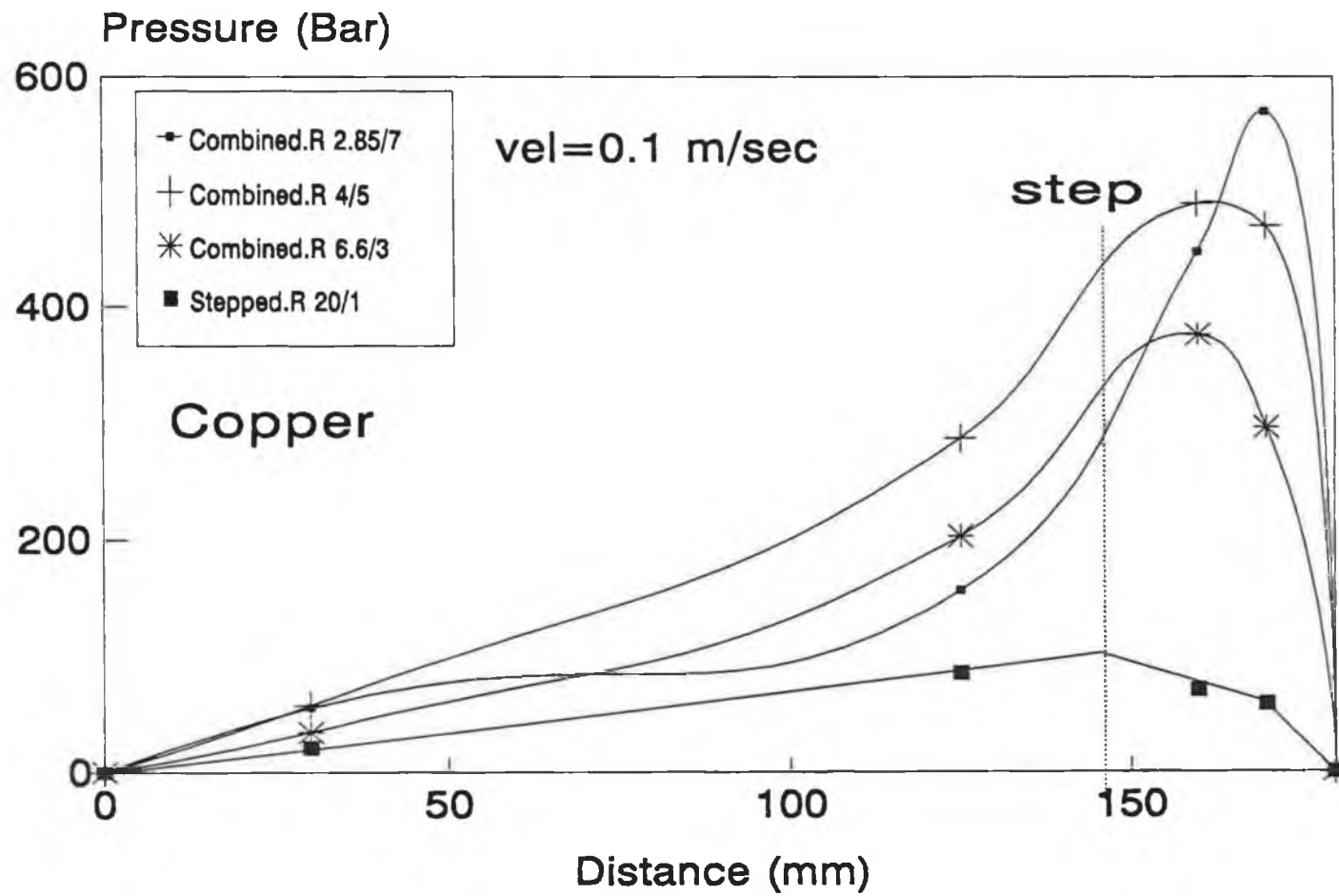


Fig. 4.25(b) Pressure distribution within combined unit

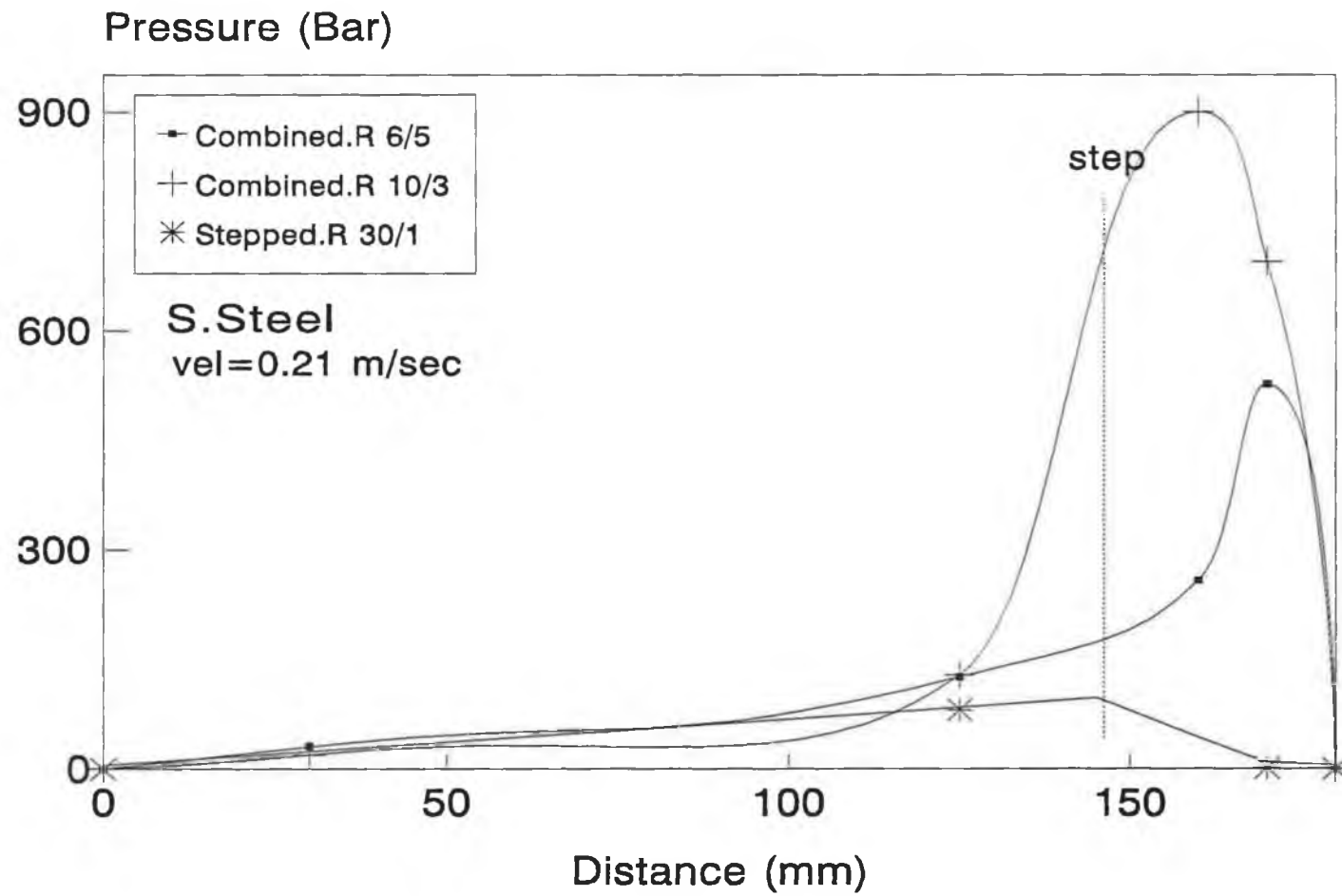


Fig. 4.26(a) Pressure distribution for combined unit

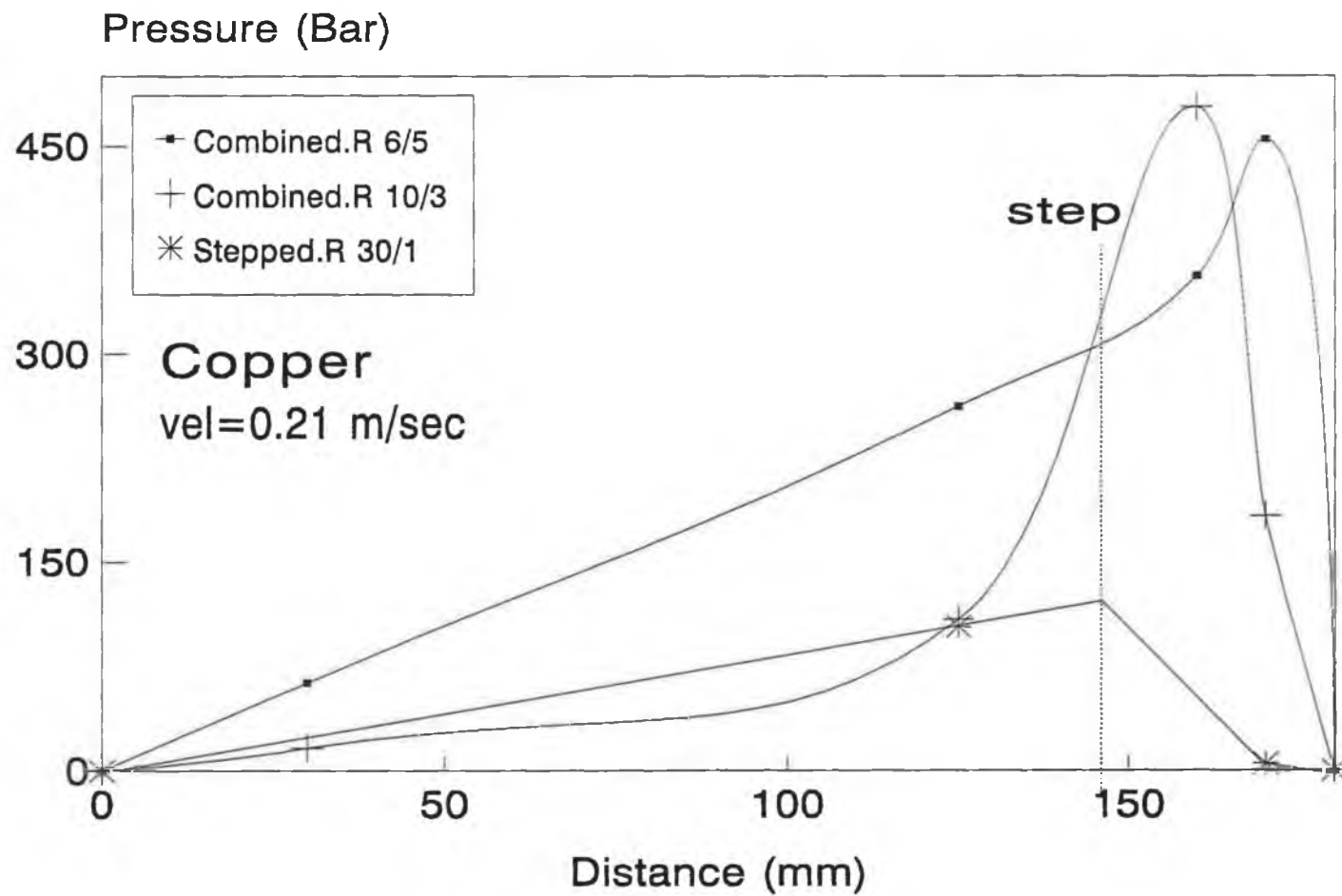


Fig. 4.26(b) Pressure distribution for combined unit

4.2.5- Results of maximum pressure

Experimental results were obtained in terms of the maximum pressure within the pressure unit. Experiments were carried out by varying h_1 and h_2 in a systematic manner keeping h_3 constant at 0.05 mm. For different drawing speeds of up to about 0.6 m/sec, the maximum pressure and drawing force were monitored for both materials. These results are presented in the following Figures. Figure 4.27 shows the effect of drawing speed on the maximum pressure generated within the unit when drawing copper and stainless steel wires for inlet gap ratio h_1/h_2 of 2 and outlet gap ratio h_2/h_3 of 5. The outlet gap, h_3 being equal to 0.05 mm. It is evident from this Figure that drawing of stainless steel wire generates higher maximum pressures than those when copper wire is drawn. For the same pressure unit the maximum pressure for a given drawing speed should be the same for different wire materials unless differing levels of elastic and plastic deformation take place in the wires. Any such deformation will increase h_3 and decrease the gap ratio h_2/h_3 , resulting in pressure loss.

In Figure 4.27 much lower maximum pressures are obtained for copper which suggests that the softer copper wire deformed more than the stainless steel wire possibly plastically.

Measurements on the drawn wires confirmed that the copper wire deformed plastically by about 0.2 percent reduction in diameter and virtually no deformation was noticed in steel wire. At drawing speed of 0.34 m/sec a maximum pressure of 2000 bar was generated when drawing stainless steel wire and only 1000 bar was obtained for the same speed when drawing the copper wire. This Figure also indicates that as the drawing speed increases the maximum pressure generated also increases.

Results were obtained by changing h_2 and keeping h_1 and h_3 constant at 0.5 and 0.05 mm respectively. Figures 4.28(a) and 4.28(b) demonstrate the effect of varying h_2 , on the

maximum pressure at different drawing speeds when drawing stainless steel and copper wire respectively. Figure 4.28(a) shows that for inlet gap ratio h_1/h_2 of 2, the maximum pressures are generally greater for all drawing speeds and that as this gap ratio is either decreased or increased the maximum pressure of reduced magnitudes are obtained. In Figure 4.28(b) similar trend is observed when drawing copper wire. It should be noted that change in h_2 changes both the h_1/h_2 and h_2/h_3 ratios.

The effect of varying the gap h_2 on the maximum pressure while h_1 and h_3 are kept constant as in Figure 4.28, but h_1 is 1.0 mm, is shown in Figure 4.29 for drawing stainless steel wires. This figure shows that for inlet gap ratio h_1/h_2 of 2.8 the maximum pressure was higher than for other gap ratios. Figures 4.28(a) and 4.28(b) also illustrate the effect of varying h_2 with constant h_1 and h_3 on the maximum pressure at different drawing speeds with inlet gap $h_1=1.5$ mm when drawing stainless steel and copper wires respectively. Figure 4.30(a) shows that for inlet gap ratio h_1/h_2 of 4.3 the maximum pressures are generally greater for all drawing speeds and increasing the gap ratio decreases the maximum pressure obtained. In Figure 4.30(b) similar trend could be observed when drawing a copper wire. The effect of varying the inlet gap h_1 while h_2 and h_3 are kept constant ($h_3=0.05$ mm), is demonstrated in Figures 4.31(a) and 4.31(b) again using stainless steel and copper wires respectively. Figure 4.31(a) shows that for inlet gap ratio h_1/h_2 of 3.3, the maximum pressures were greater for all drawing speeds and further increase to the gap ratio results in reduced magnitudes for the maximum pressure. The same trend is observed in Figure 4.31(b) which shows the results when copper wire was drawn. With a larger outlet gap ratio h_2/h_3 of 5, the effect of the variation in the inlet gap h_1 on the maximum pressure is shown in Figure 4.32 when drawing stainless steel wire. This Figure indicates that for an inlet gap ratio h_1/h_2 of 2 the maximum pressure was higher as compared to the maximum pressure for

the other gap ratios for all drawing speeds, higher gap ratios produce lower magnitudes of the maximum pressure. Figures 4.33(a) and 4.33(b) demonstrate the effect of changing the inlet gap h_1 for constant outlet gap ratio h_2/h_3 of 7 on the maximum pressure at different drawing speeds. In Figure 4.33(a) when drawing stainless steel wire, the inlet gap ratio h_1/h_2 of 2.86 produces higher magnitudes of maximum pressure for all drawing speeds and when this gap ratio is either decreased or increased the maximum pressure of lower magnitudes are obtained. In Figure 4.33(b) with copper wire, higher maximum pressures are obtained for h_1/h_2 ratio of 1.43.

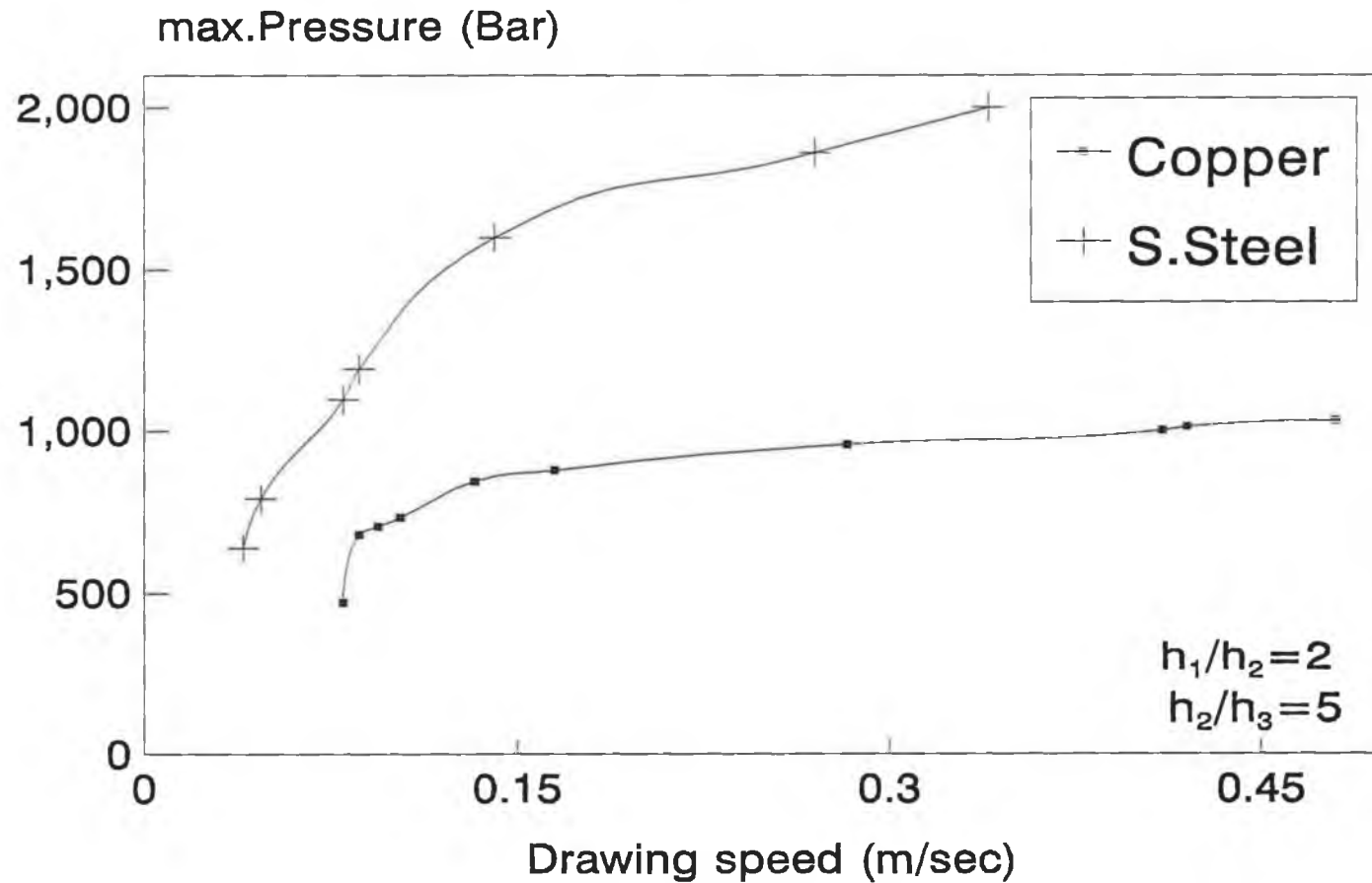


Fig. 4.27 Effect of drawing speed on maximum pressure for copper and stainless steel

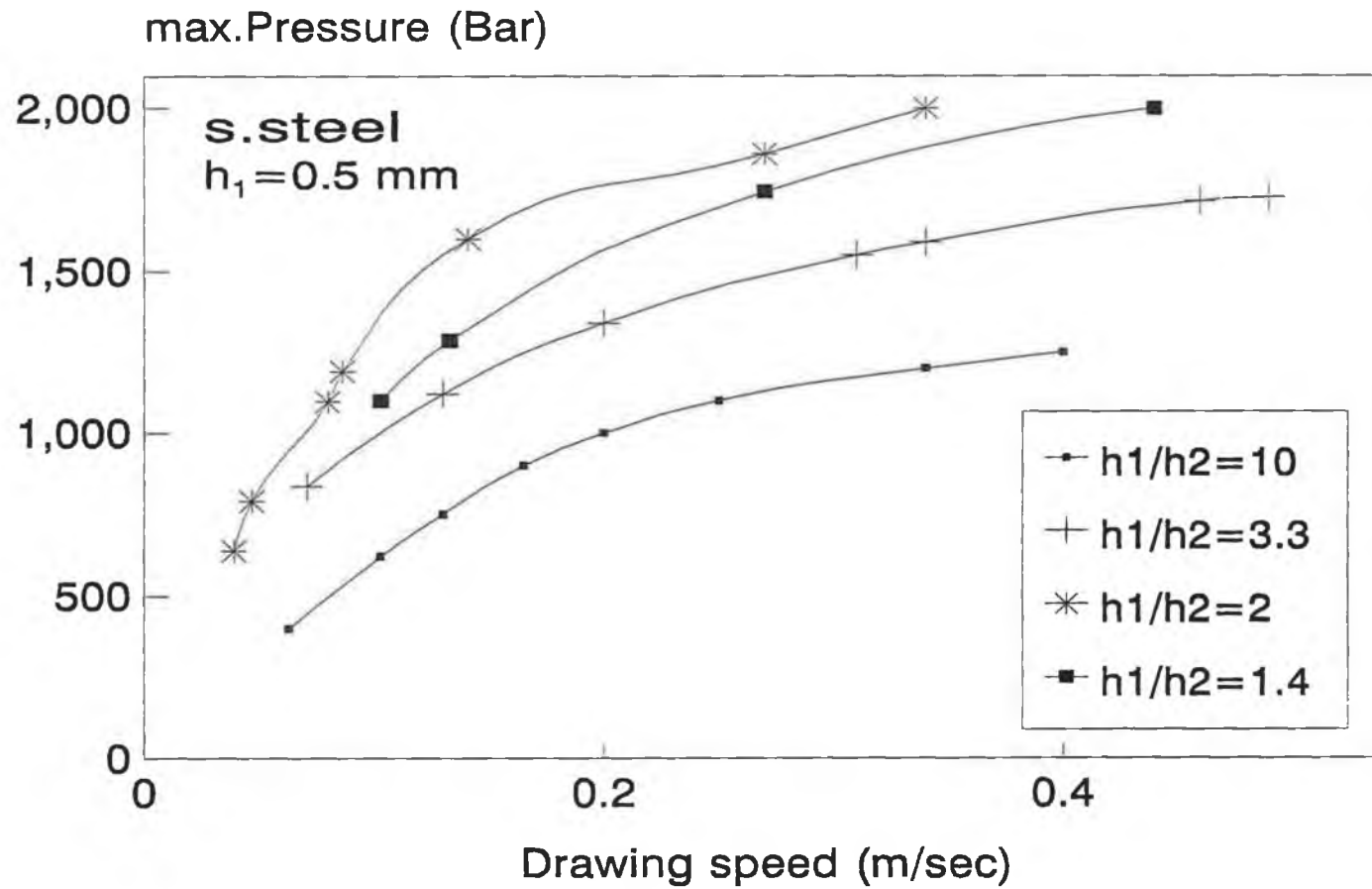


Fig. 4.28(a) Effect of changing h_2 on maximum pressure for constant h_1 and h_3 using stainless steel wire

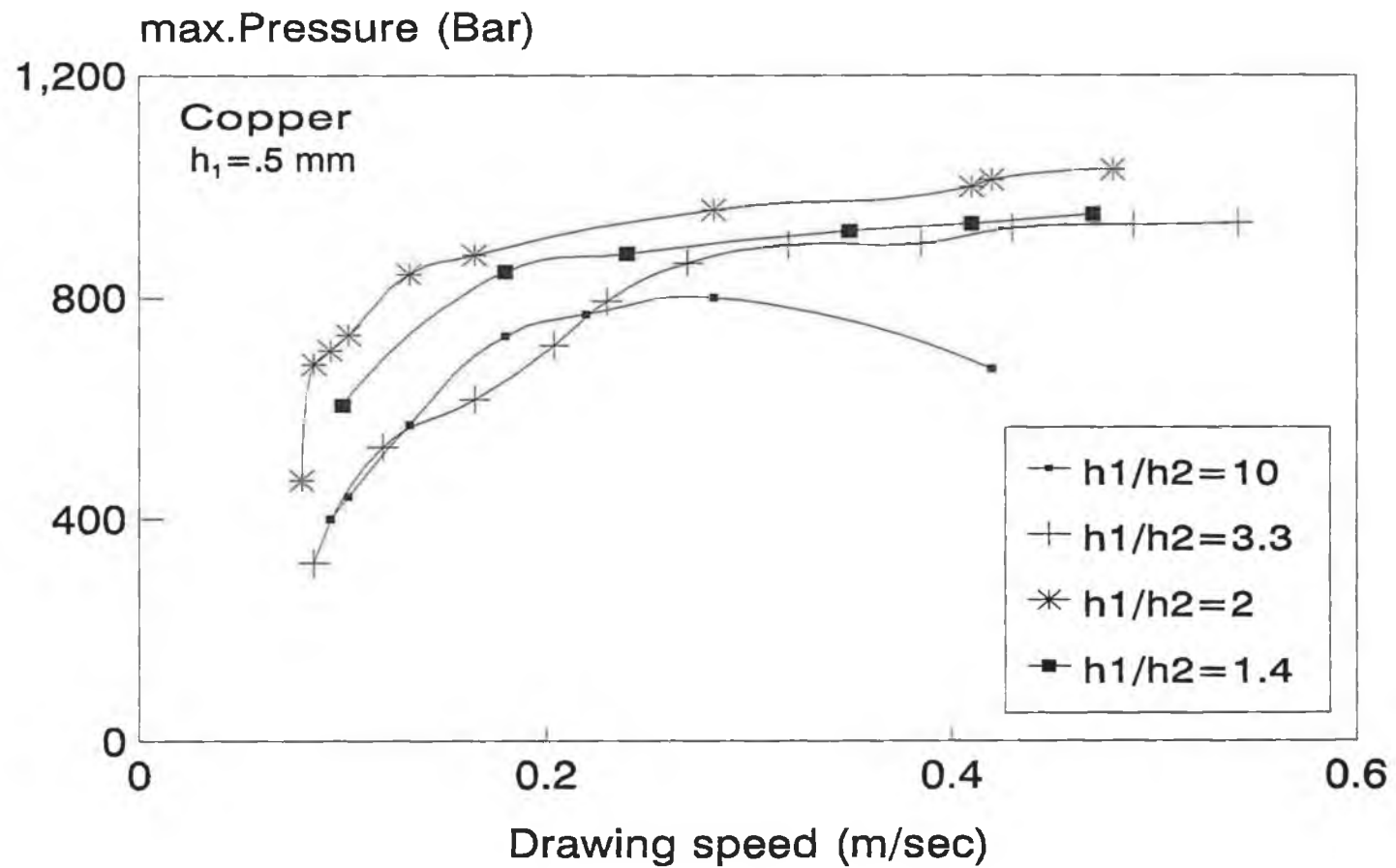


Fig. 4.28(b) Effect of changing h_2 on maximum pressure for constant h_1 and h_3 using copper wire

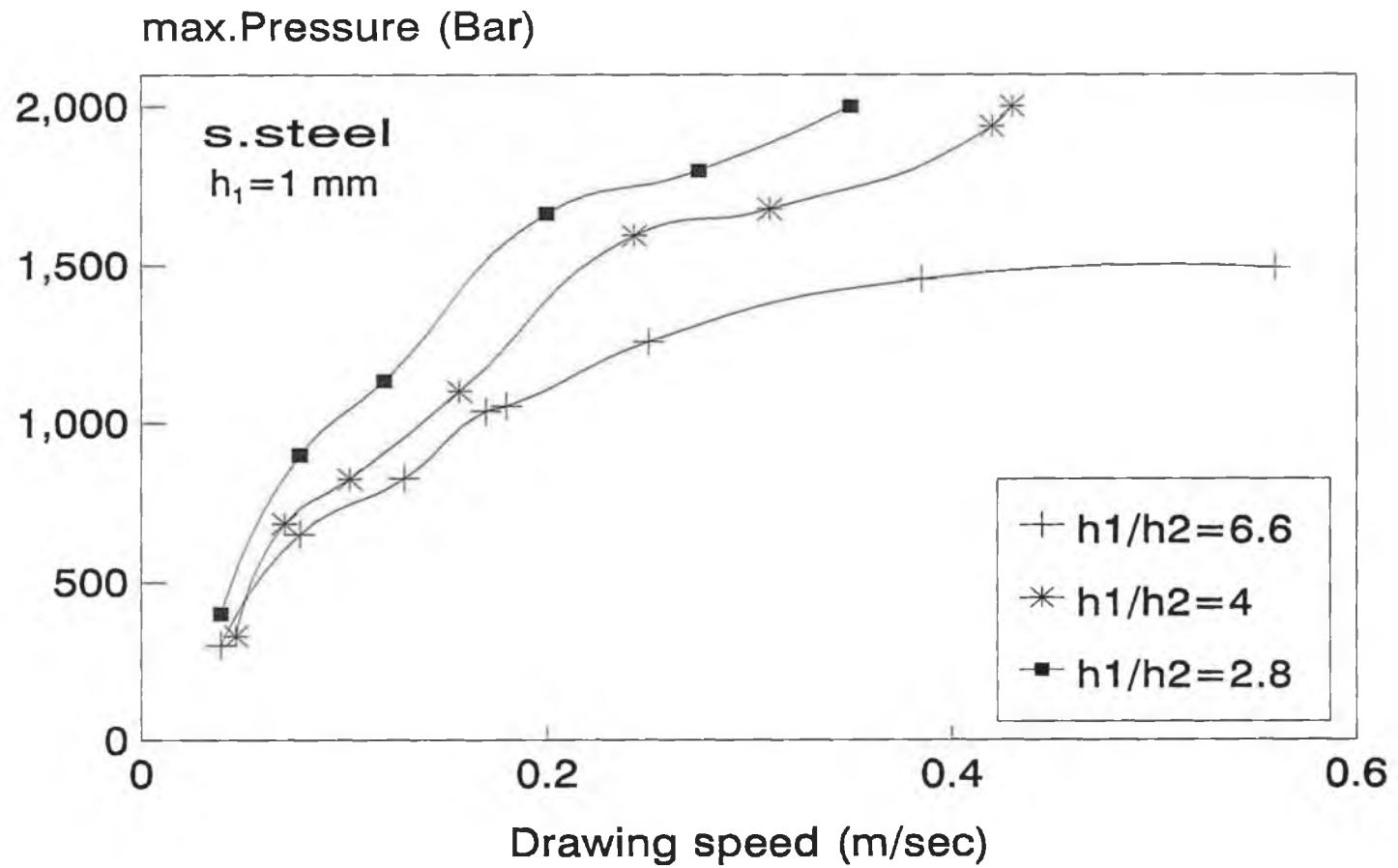


Fig. 4.29 Effect of changing h_2 on maximum pressure for constant h_1 and h_3 using stainless steel wire

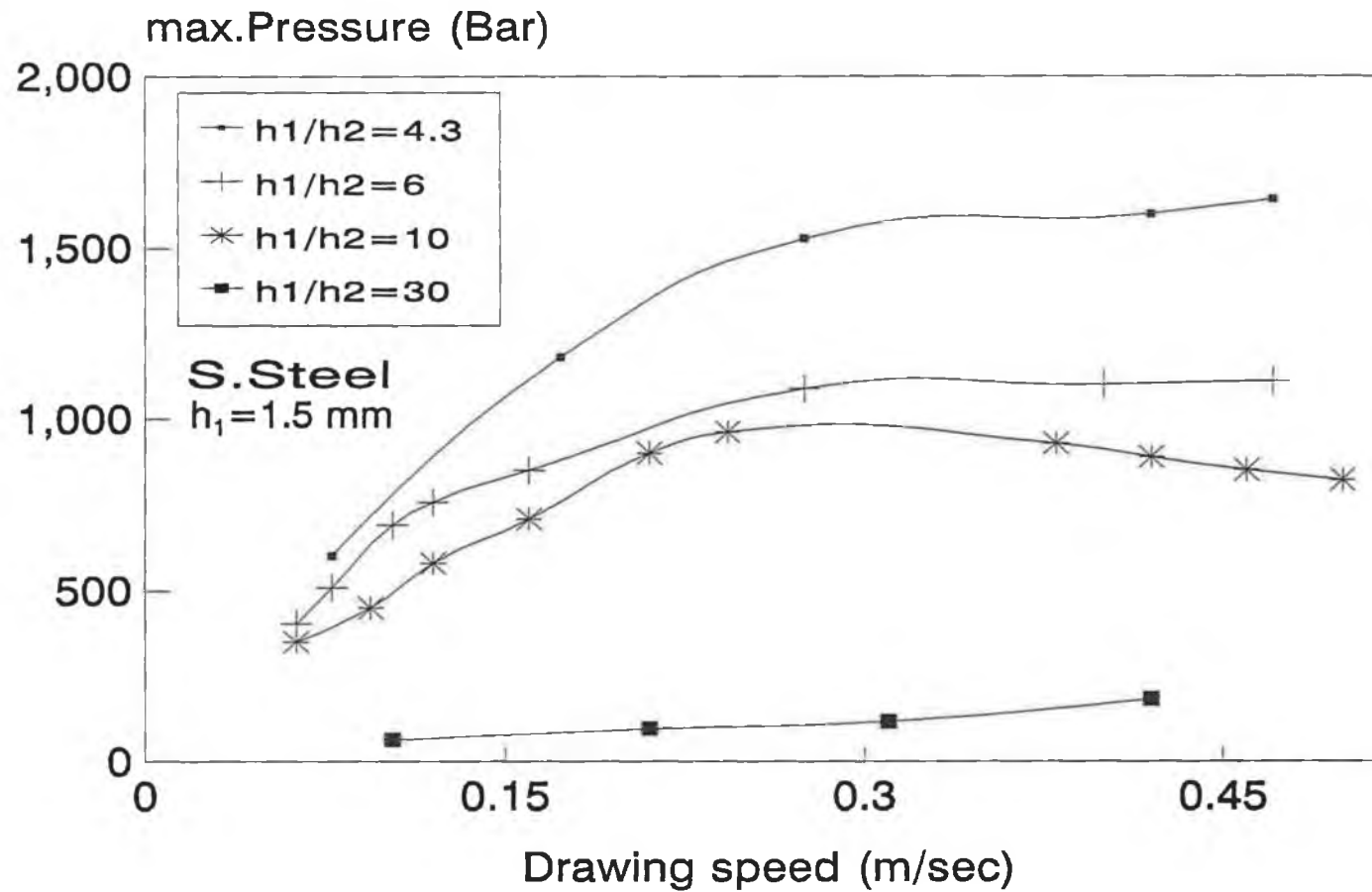


Fig. 4.30(a) Effect of changing h_2 on maximum pressure for constant h_1 and h_3 using stainless steel wire

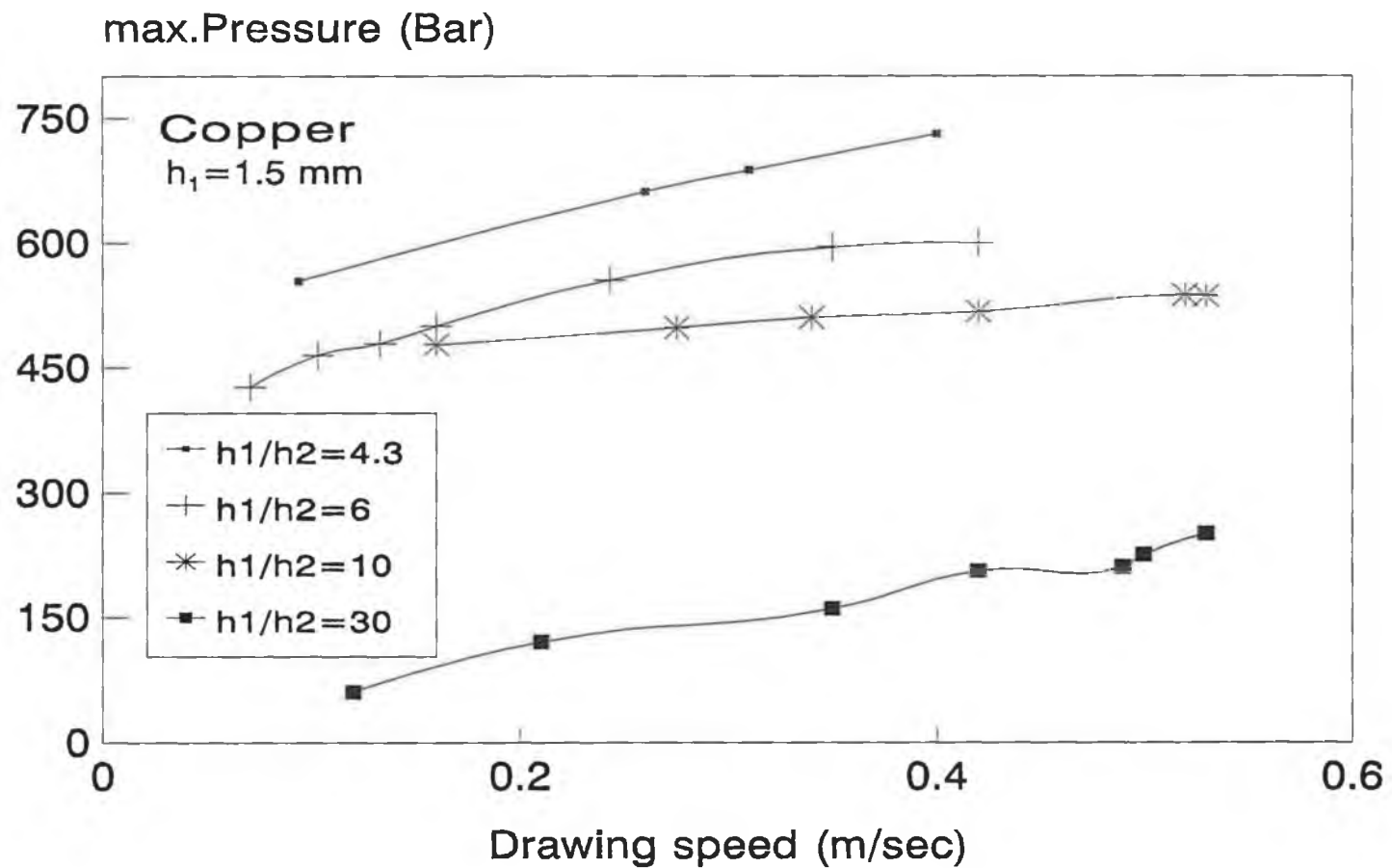


Fig. 4.30(b) Effect of changing h_2 on maximum pressure for constant h_1 and h_3 using copper wire

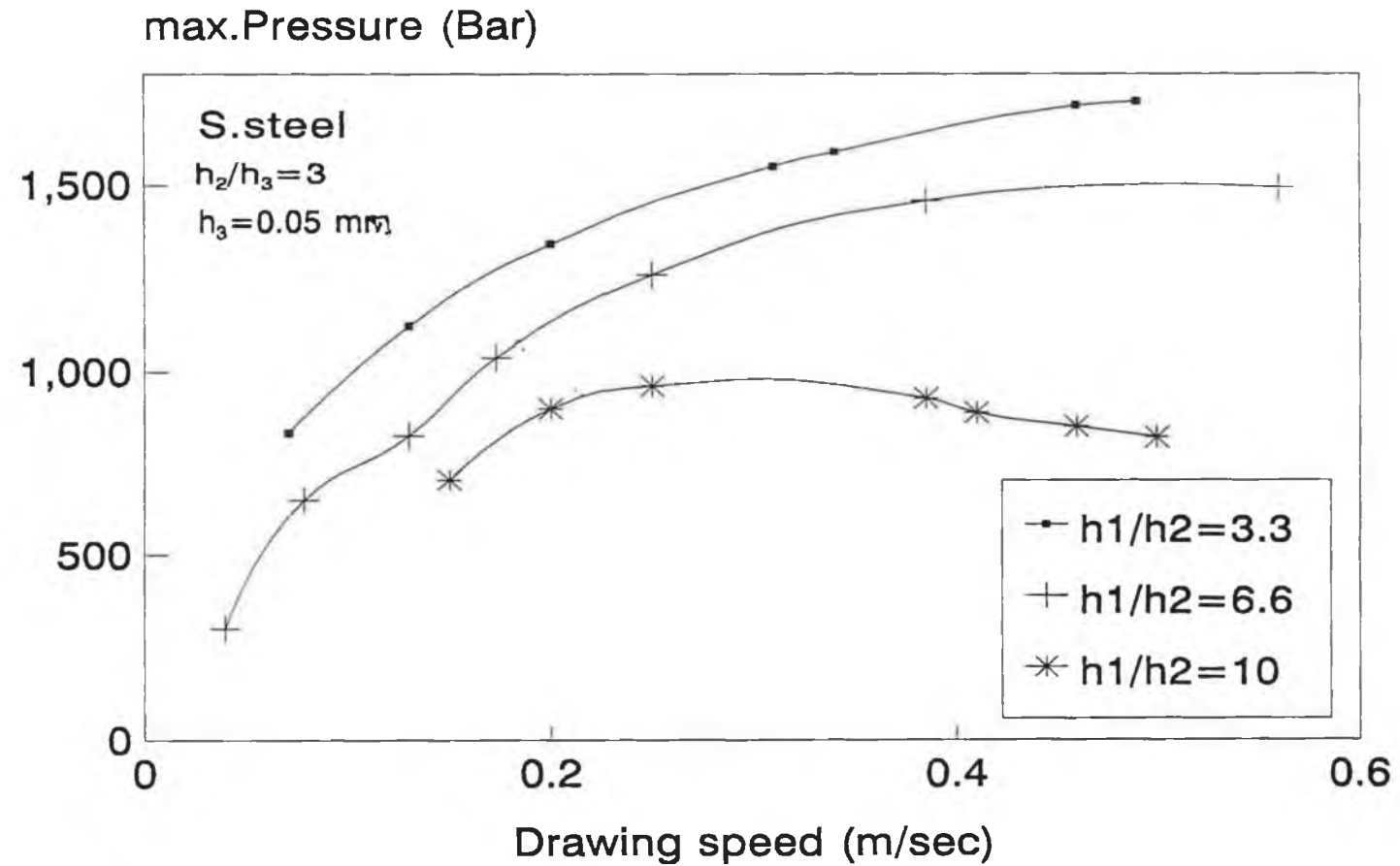


Fig. 4.31(a) Effect of drawing speed on maximum pressure for a combined unit

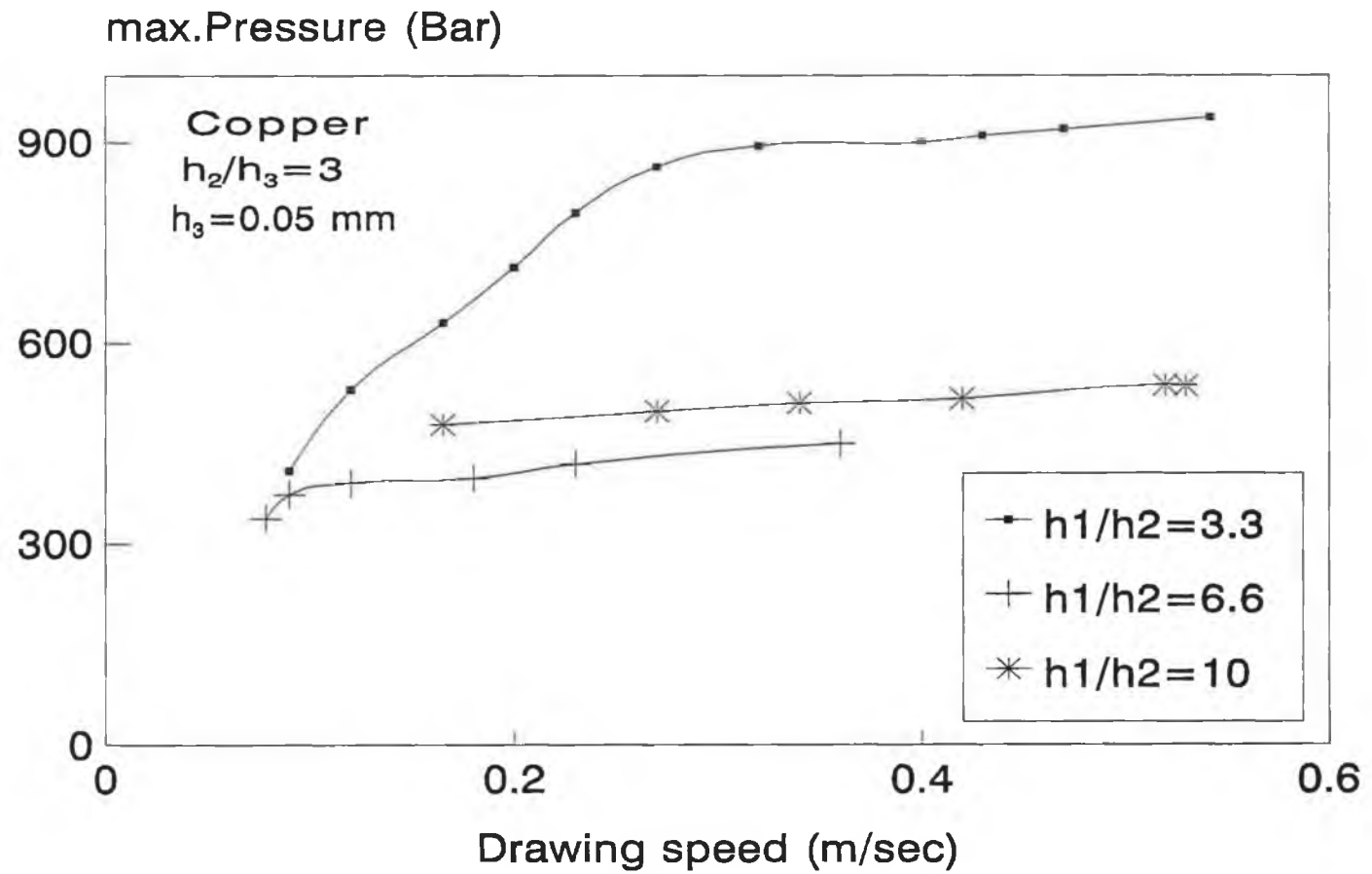


Fig. 4.31(b) Effect of drawing speed on maximum pressure for a combined unit

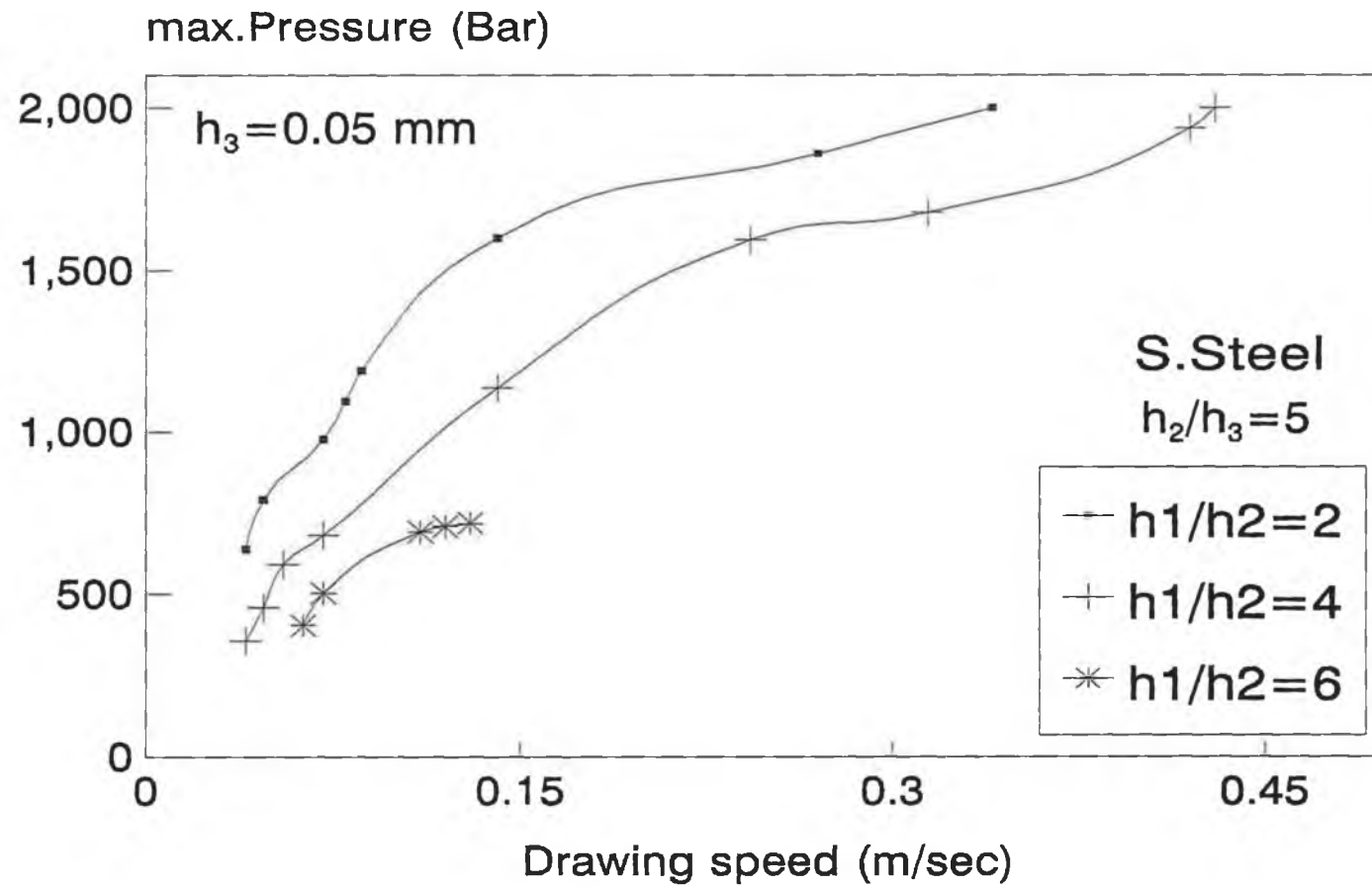


Fig. 4.32 Effect of drawing speed on maximum pressure for a combined unit

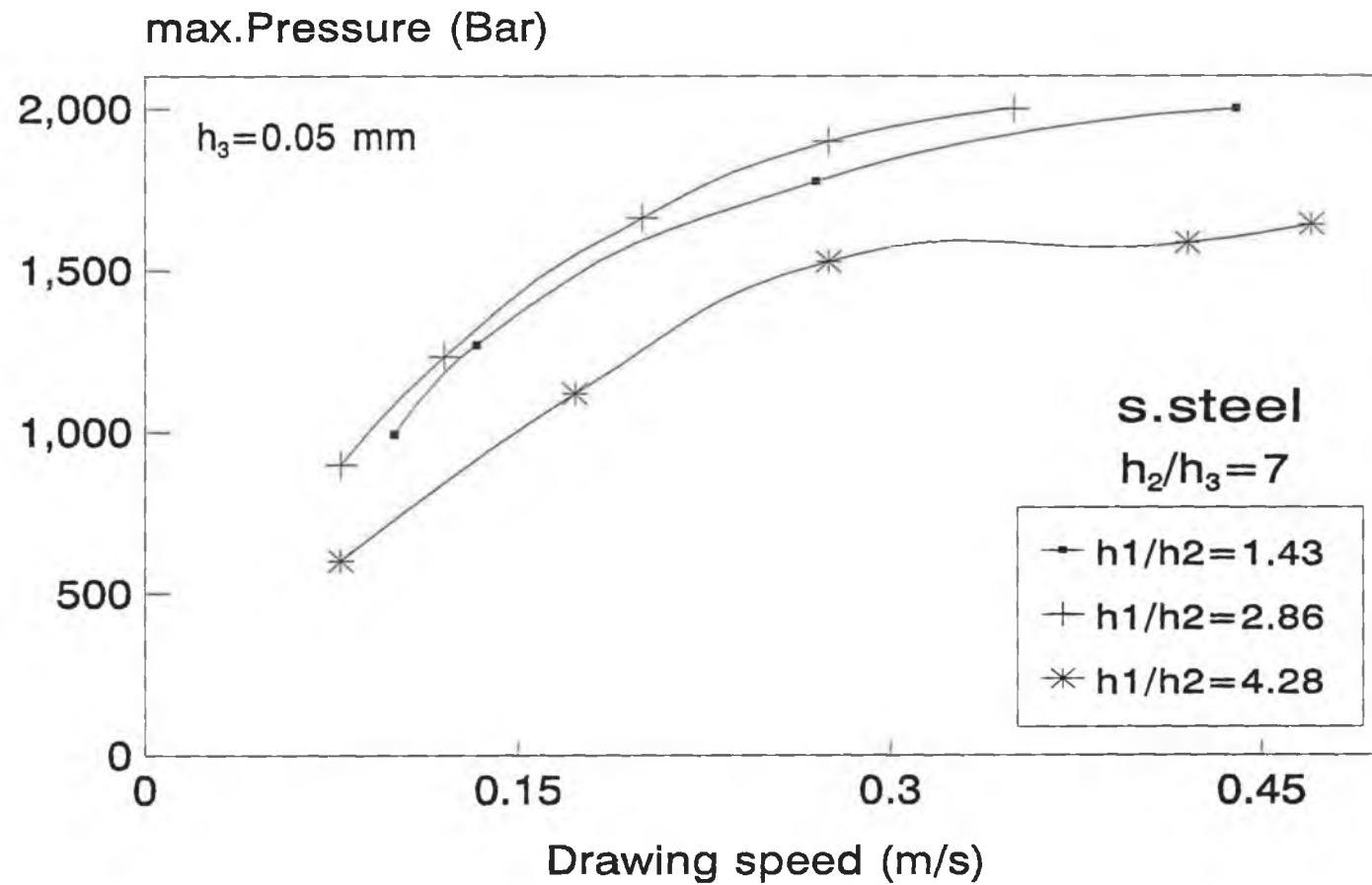


Fig. 4.33(a) Effect of drawing speed on maximum pressure for a combined unit

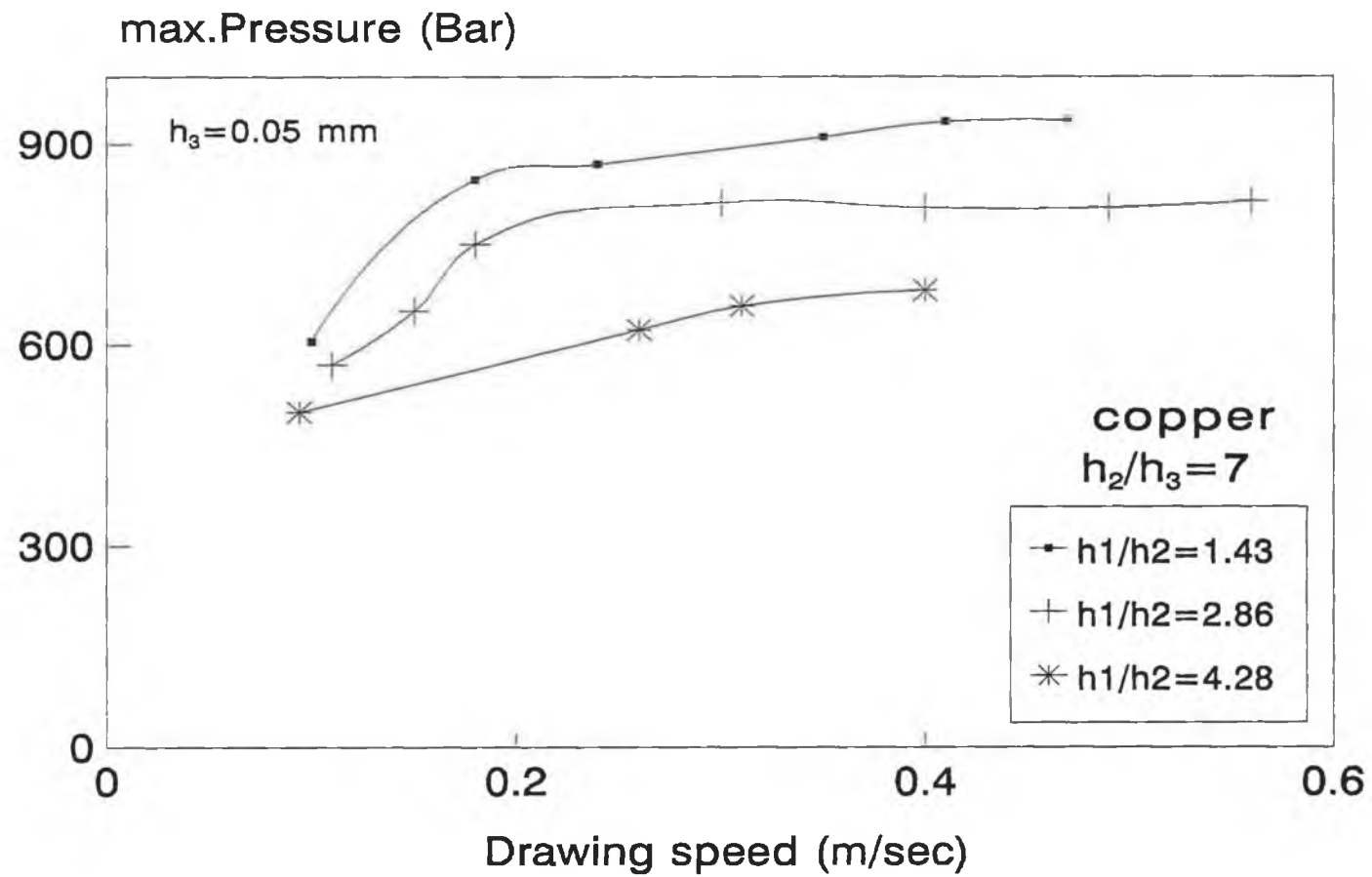


Fig. 4.33(b) Effect of drawing speed on maximum pressure for a combined unit

4.2.6- Results of drawing force

The drawing force generated when using the complex geometry pressure unit has been measured experimentally for both the stainless steel and copper wire materials for a range of drawing speed at different gap ratios and is given in this section.

In Figure 4.34 for a gap ratio combination of $h_1/h_2=2$ and $h_2/h_3=5$, the drawing force curves are presented for different wire materials for a range of drawing speed. It is evident from Figure 4.34(a) that for the range of drawing speed considered, higher magnitudes of drawing load was obtained when drawing stainless steel wire. For example, at drawing speed of 0.15 m/sec the drawing force for stainless steel wire was 55 N, whereas it is 40 N for the copper wire at the same drawing speed.

Figure 4.34(b) demonstrates the effect of the drawing speed on drawing force for inlet and outlet gap ratios of 2.85 and 7 respectively. Higher drawing force was obtained using the stainless steel wire than when using the copper wire for all drawing speeds.

Similar trend could be observed in Figure 4.34(c) for the gap ratios combination of 3.3 and 3. In order to compare the results for combined geometry and stepped parallel bore unit tests were carried out and the results are shown in Figure 4.34(d).

A higher drawing force was noticed when using stepped bore pressure unit as in Figure 4.34(d), a maximum drawing force of 65 N was obtained when drawing stainless steel wire. Experimental results were also obtained by varying h_1 and h_2 in a systematic manner keeping h_3 constant at 0.05, for different drawing speeds of up to 0.6 m/sec. The drawing force were monitored for both wire material. These results are presented in the following figures. Figure 4.35 shows the effect of drawing speed on the drawing force generated within the unit when drawing stainless steel and copper wires for inlet gap $h_1=0.5$ mm and outlet gap of $h_3=0.05$ mm. Figure 4.35(a) shows that for inlet ratio h_1/h_2 of 2, the drawing loads obtained were

generally higher for all drawing speeds and that as this gap ratio is either increased or decreased the drawing loads of reduced magnitudes are obtained. In Figure 4.35(b) similar trend is observed when drawing copper wire. It should be noted that change in h_2 changes both h_1/h_2 and h_2/h_3 ratios. For inlet gap of $h_1=1$ mm and outlet gap of $h_3=0.05$ mm experiments was carried out varying h_2 for drawing stainless steel wire, for the given gap thicknesses a generally higher drawing force was obtained for inlet gap ratio of $h_1/h_2=4$. Either decreasing or increasing this gap ratio results in lower magnitudes of drawing force as it could be observed in Figure 4.36.

Figure 4.37 shows the effect of varying h_2 for constant $h_1=1.5$ mm and $h_3=0.05$ mm for both stainless steel and copper wires. Figure 4.37(a) shows that for inlet gap ratio $h_1/h_2=6$, a generally higher magnitudes of drawing force was obtained and that as this gap ratio is either increased or decreased, drawing load of reduced magnitudes was obtained. Similar trend could be observed in Figure 4.37(b) when drawing copper wire.

For a constant outlet gap ratio $h_2/h_3=3$ ($h_3=0.05$ mm), the effect of varying the inlet gap ratio h_1/h_2 (by changing h_1) is shown in Figure 4.38 for stainless steel and copper wires respectively.

In Figure 4.38(a) for the given outlet gap a generally higher magnitudes of drawing load were obtained for the inlet gap ratio of $h_1/h_2=6.7$; lower magnitudes of drawing load were obtained by either decreasing or increasing this gap ratio. Similar observation could be noticed in Figure 4.38(b) when drawing copper wire.

Results were also obtained using a parallel bore unit, (Figure 4.39) drawing copper wire for the range of inlet gap ratios considered, a generally high drawing load was obtained for inlet gap ratio of 10 (which also the overall gap ratio).

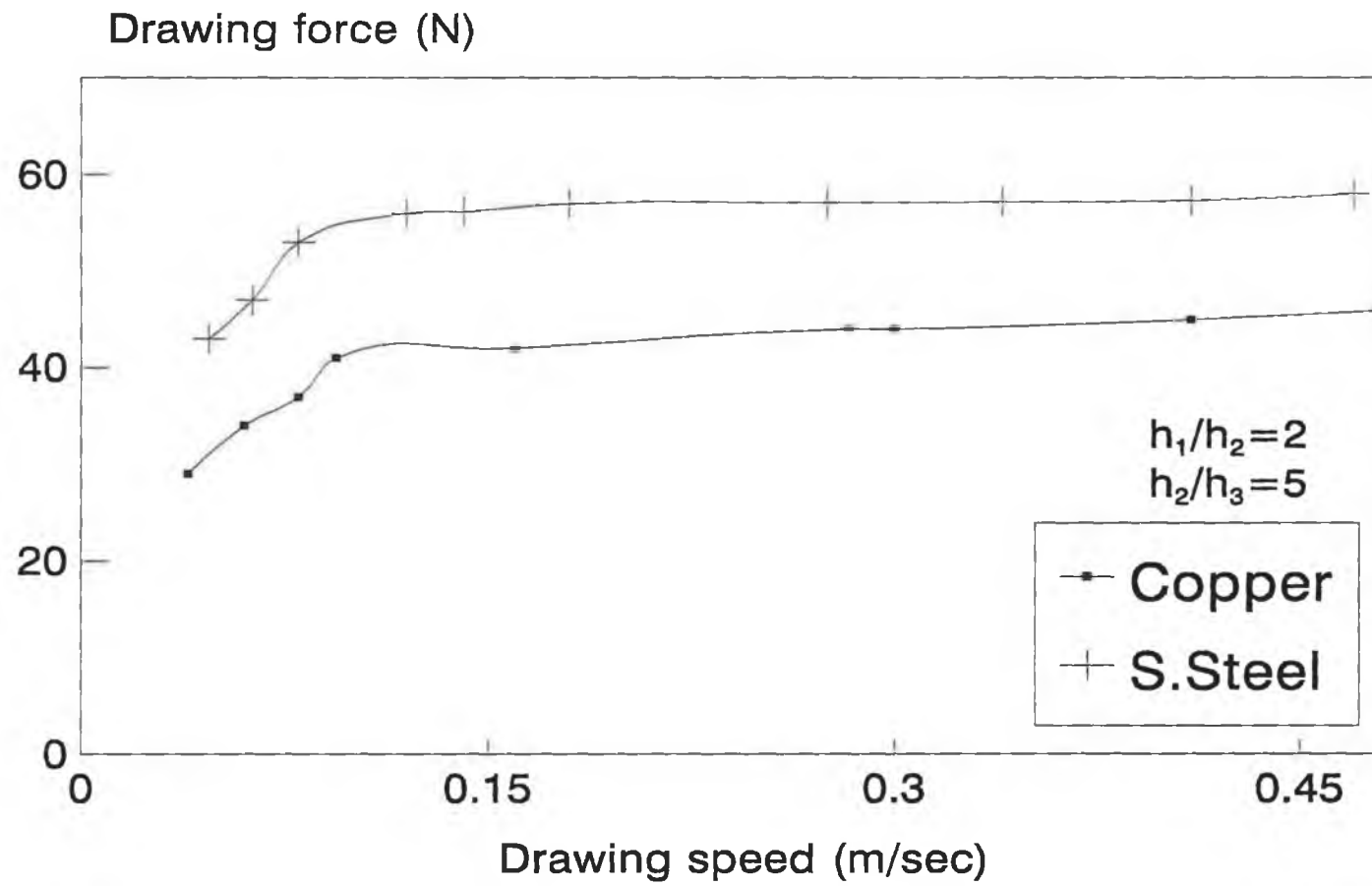


Fig. 4.34(a) Effect of the drawing speed on drawing force for combined unit

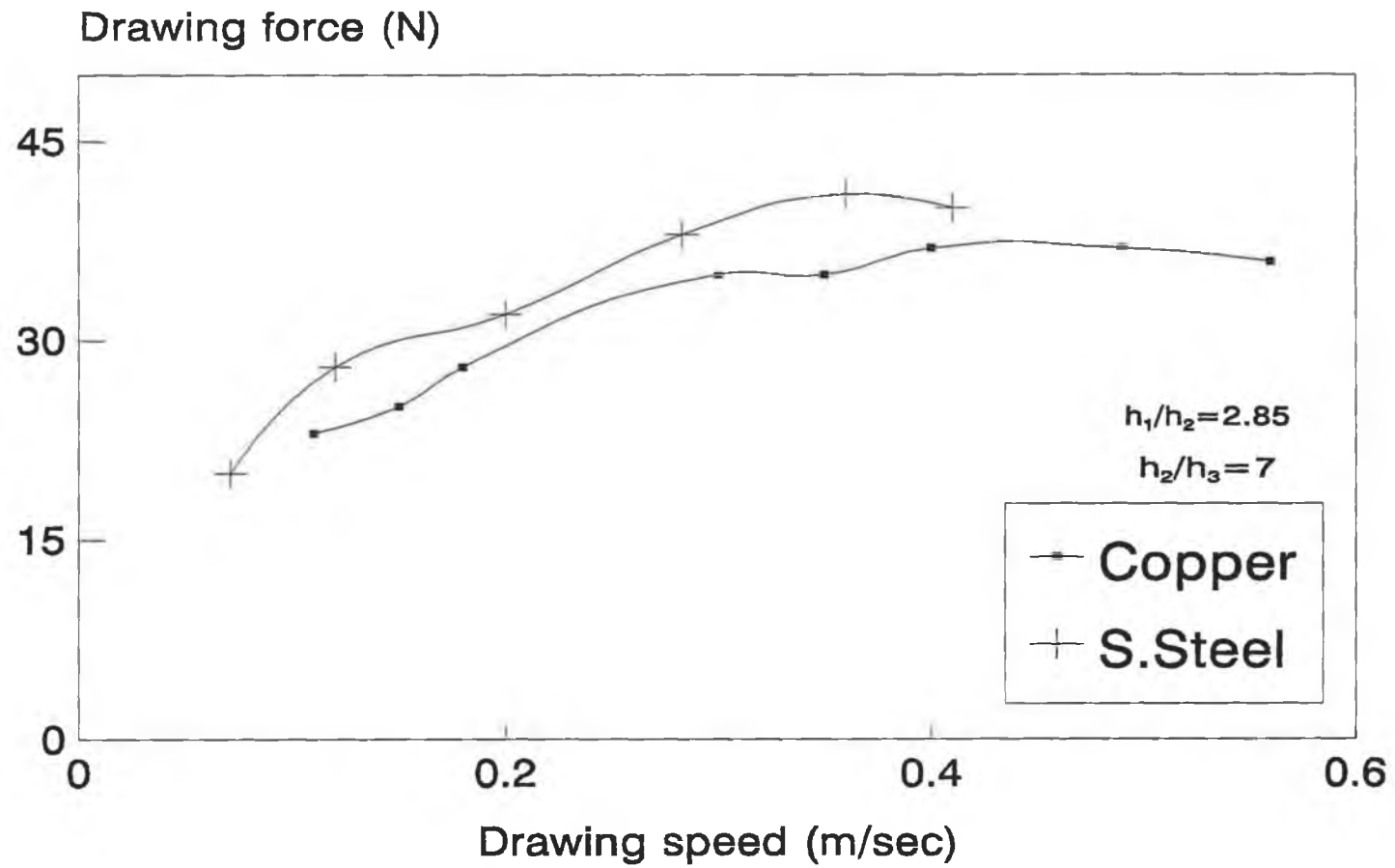


Fig. 4.34(b) Effect of the drawing speed on drawing force for combined unit

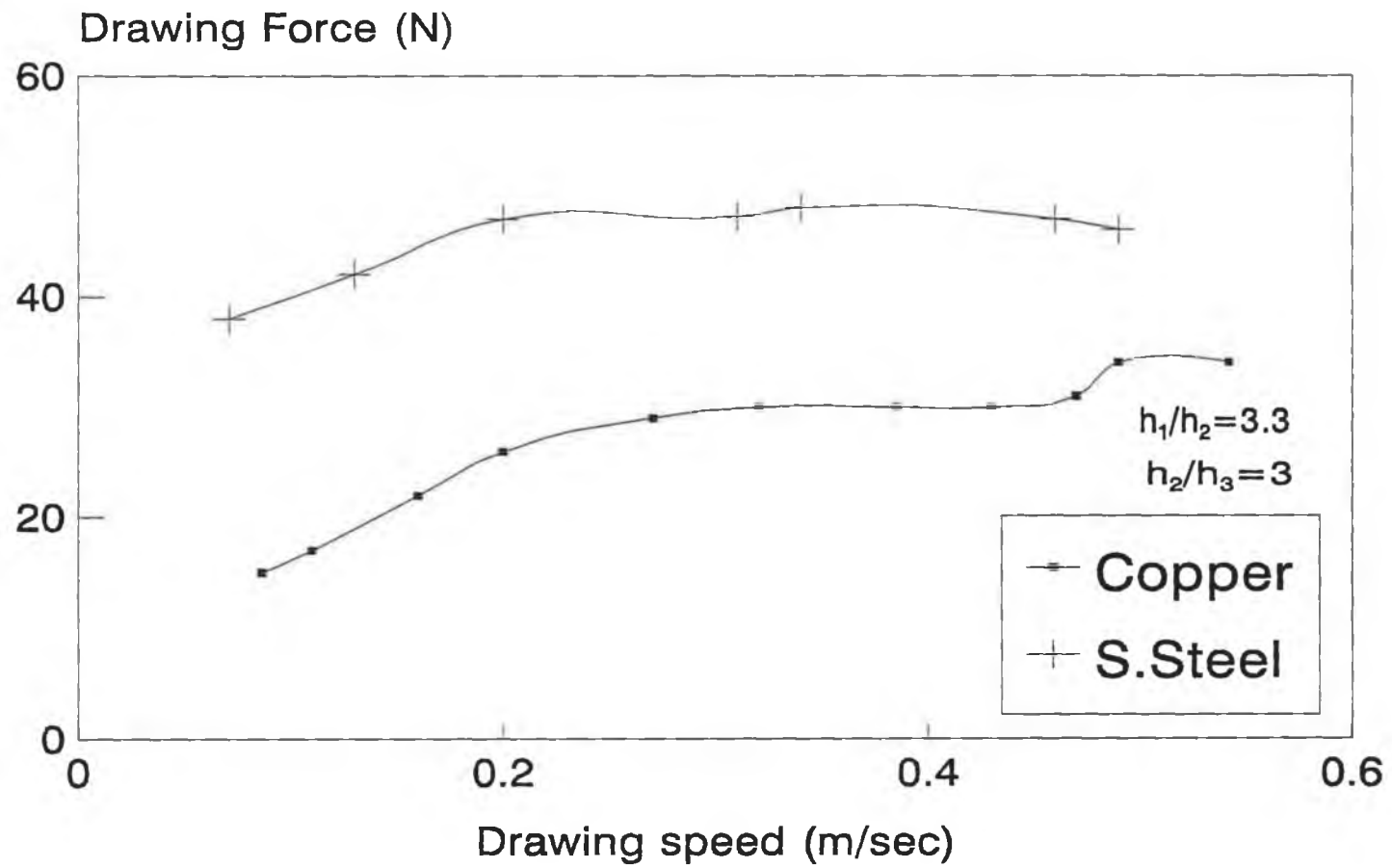


Fig. 4.34(c) Effect of drawing speed on drawing force for combined unit

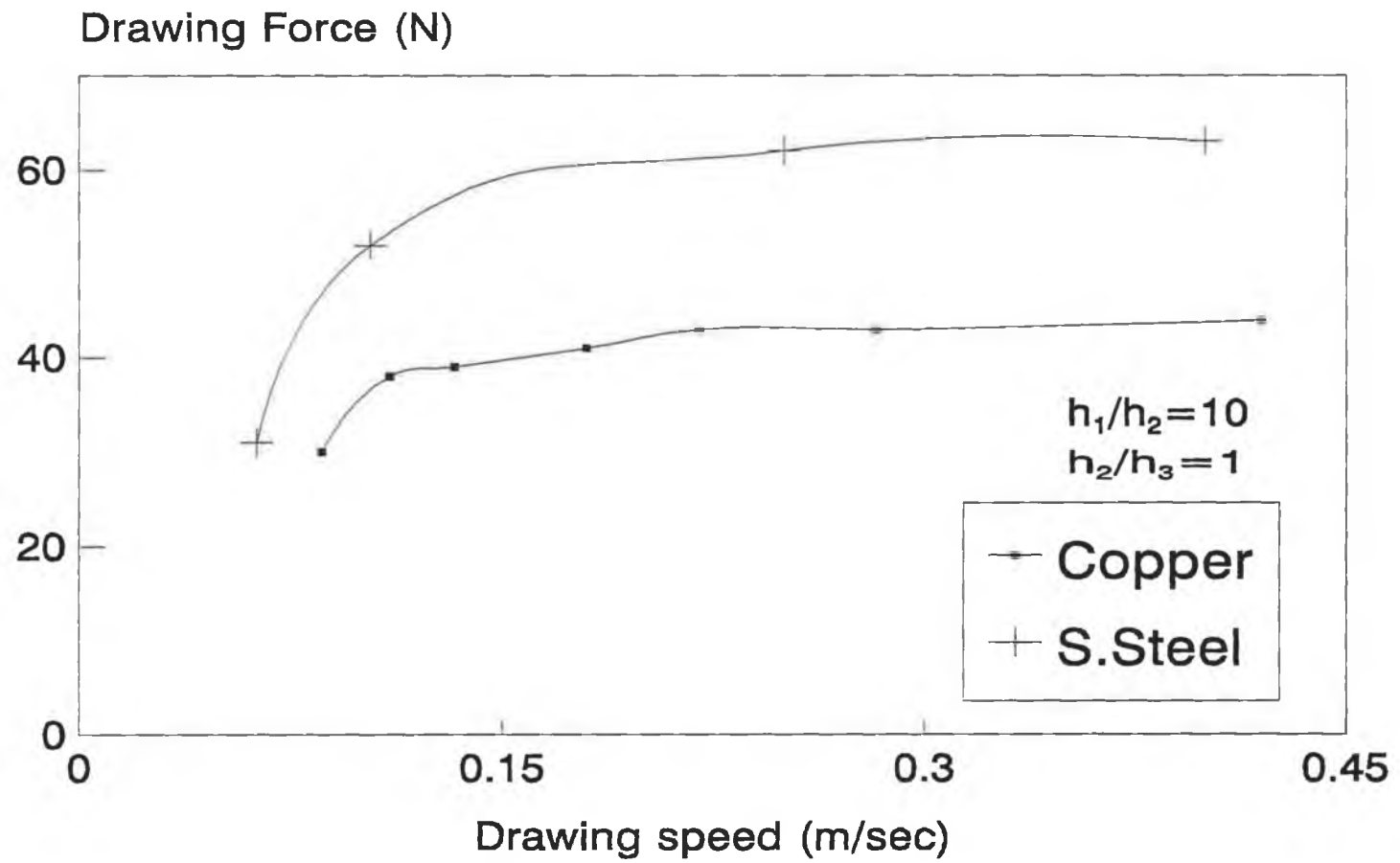


Fig. 4.34(d) Effect of drawing speed on drawing force for combined unit

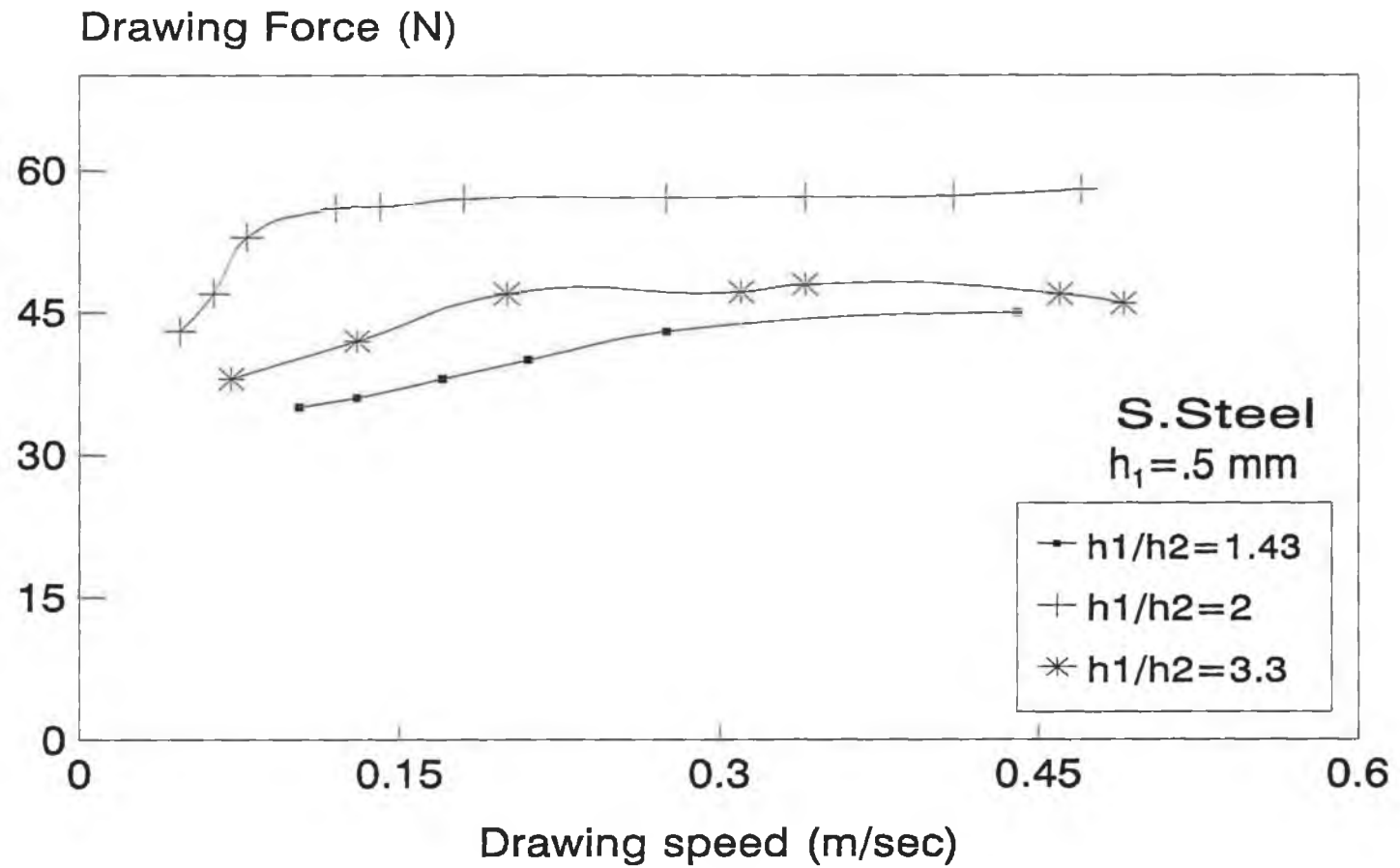


Fig. 4.35(a) Effect of changing h_2 on drawing force for constant h_1 and h_3

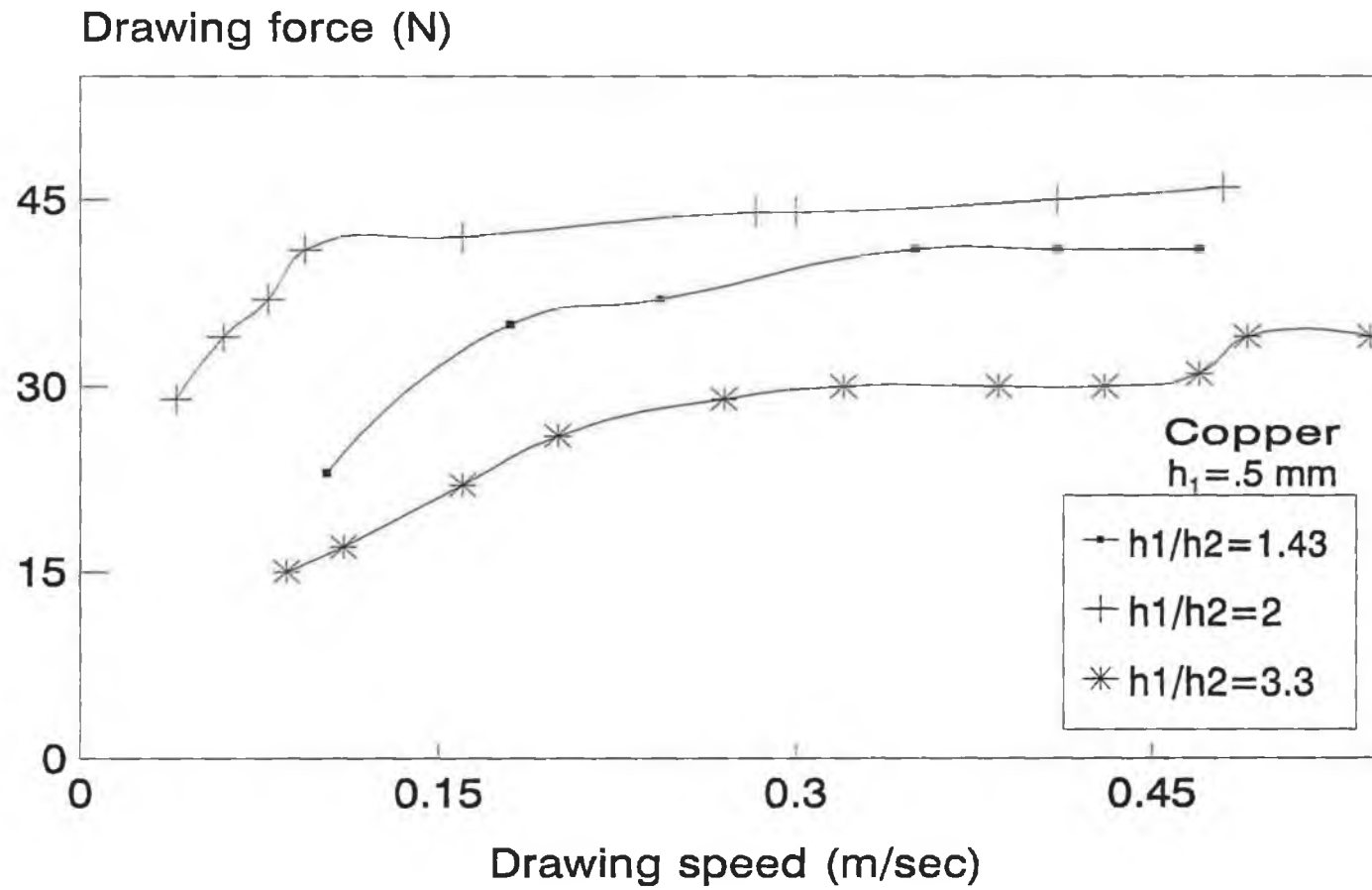


Fig. 4.35(b) Effect of changing h_2 on drawing force for constant h_1 and h_3

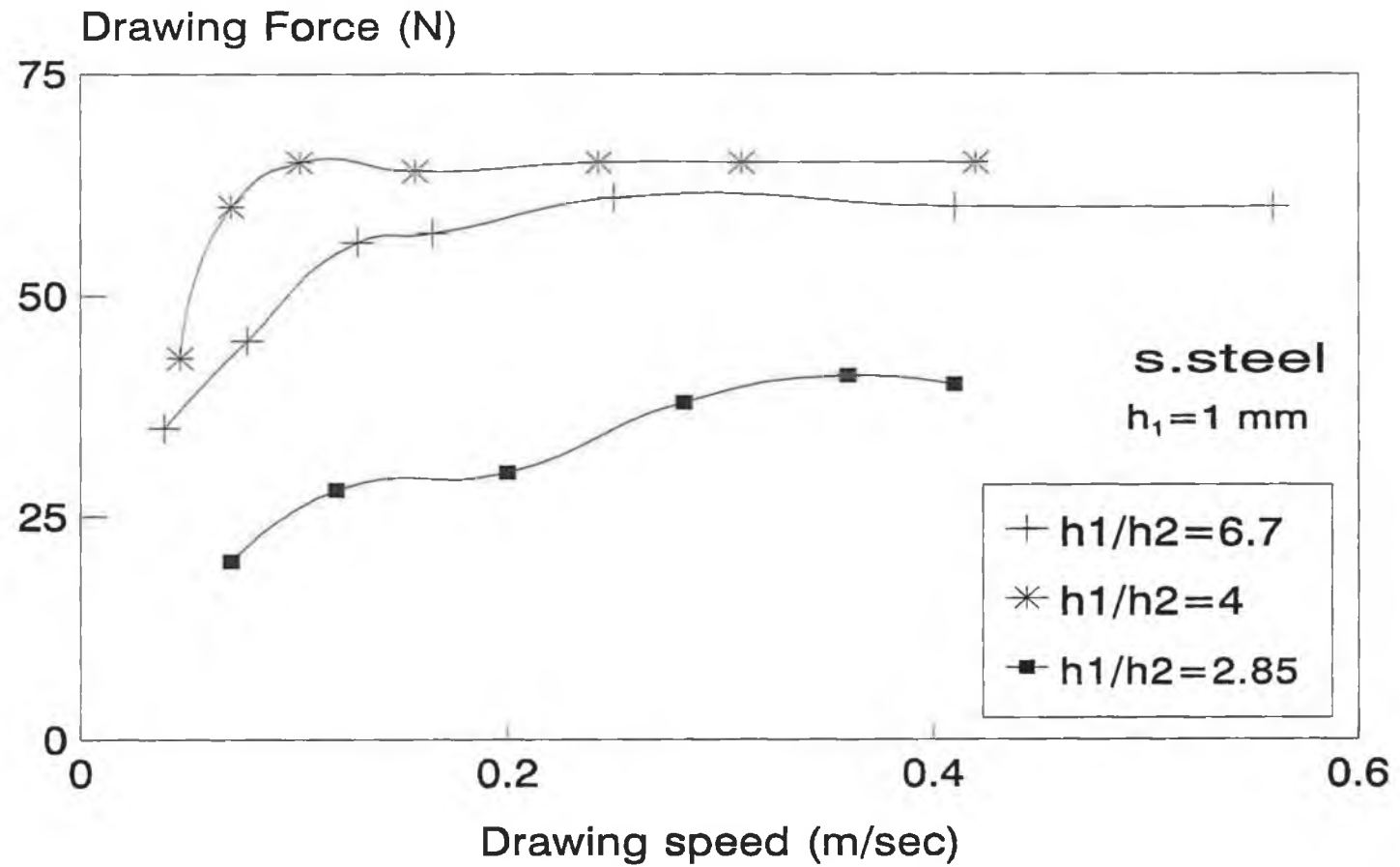


Fig. 4.36 Effect of changing h_2 on drawing force for constant h_1 and h_3

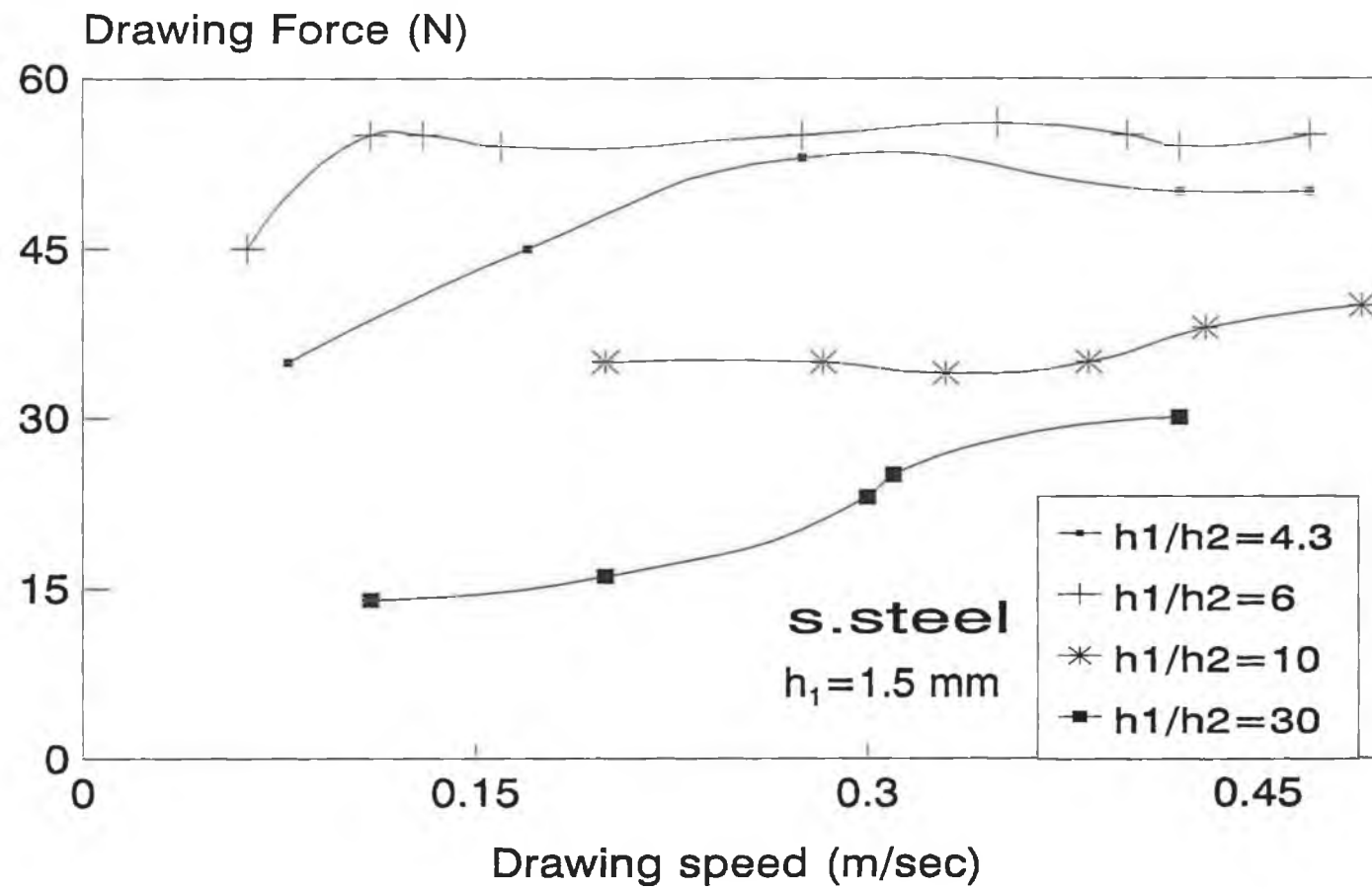


Fig. 4.37(a) Effect of changing h_2 on drawing force for constant h_1 and h_3

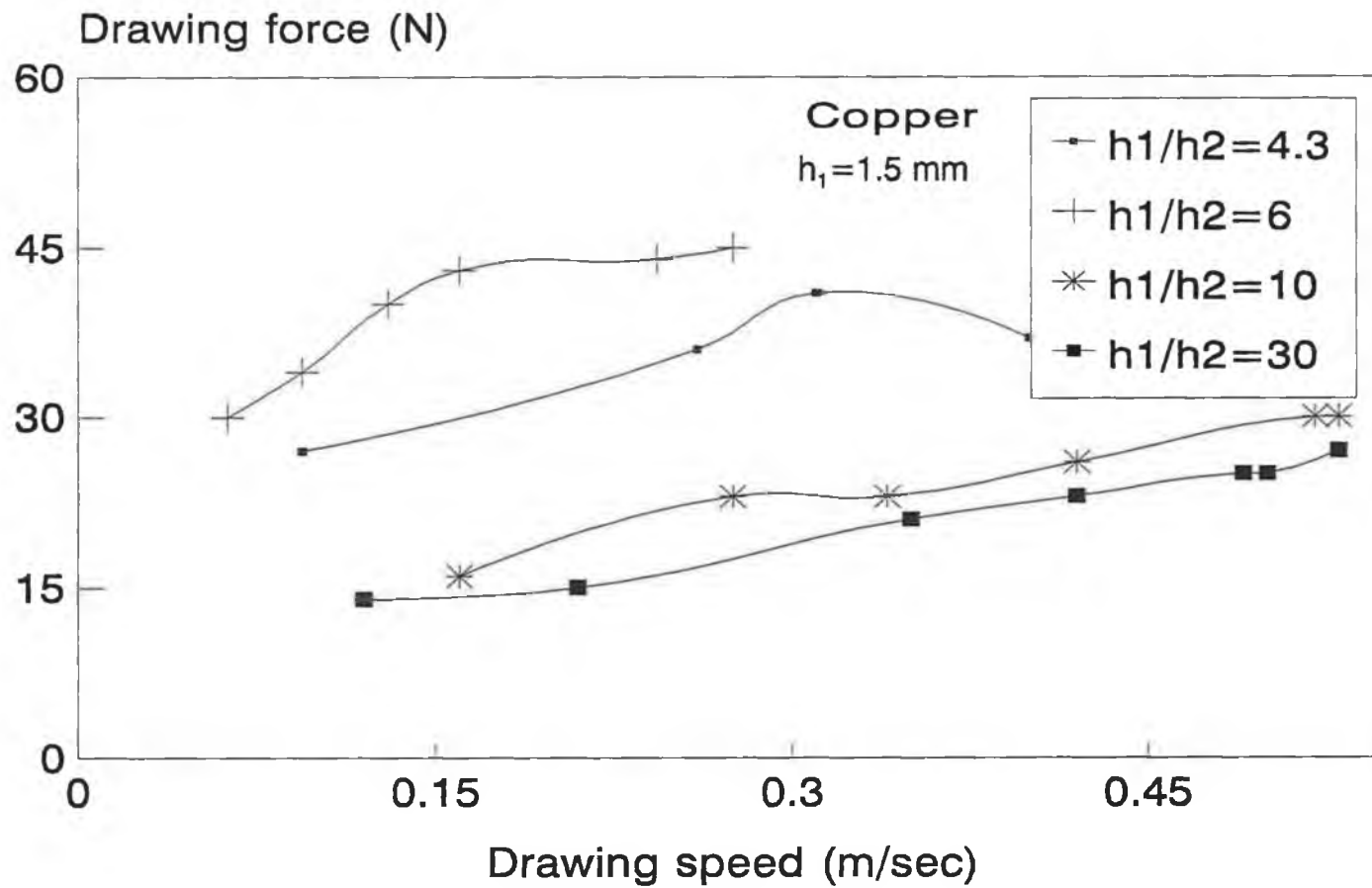


Fig. 4.37(b) Effect of changing h_2 on drawing force keeping h_1 and h_3 are constant

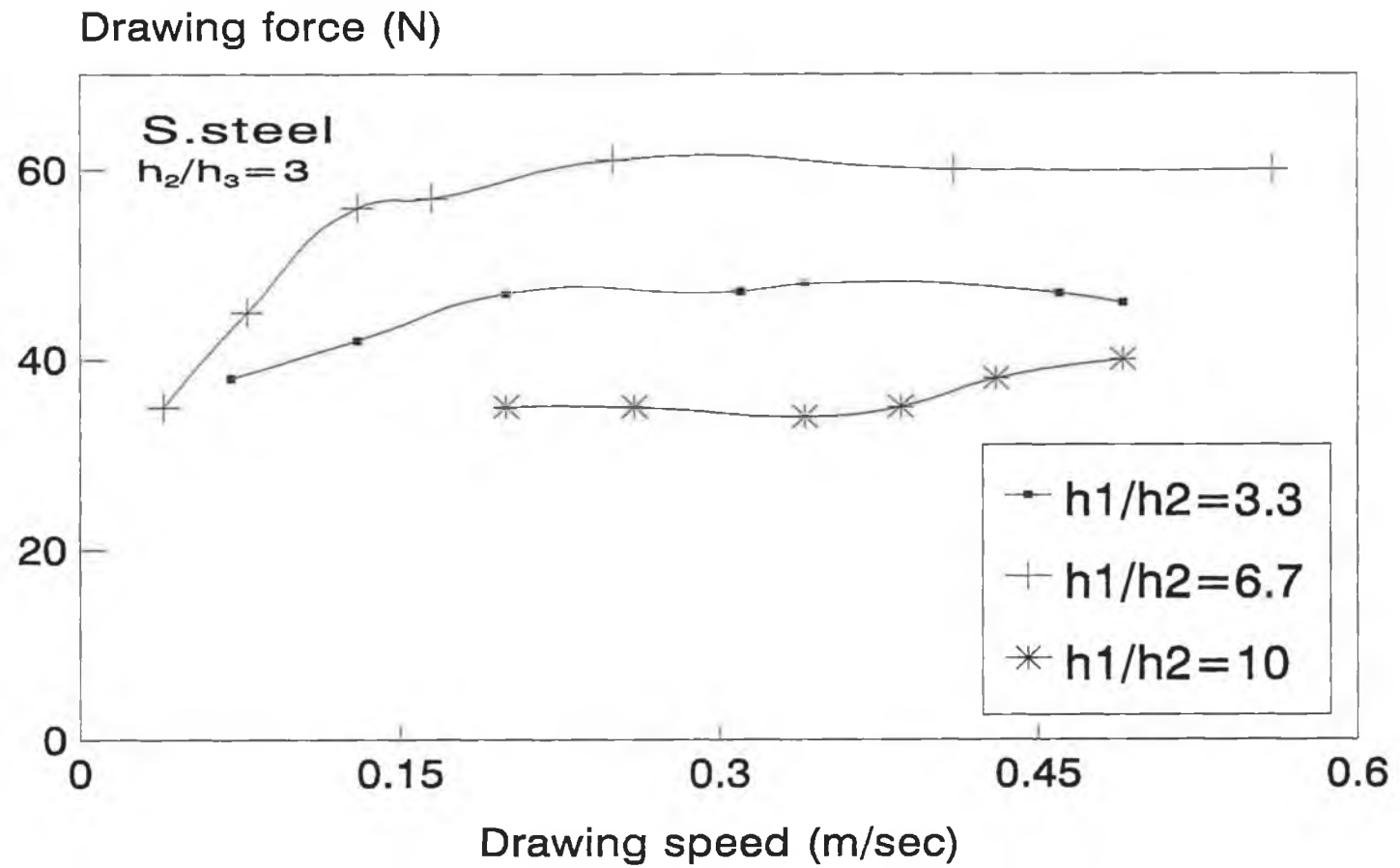


Fig. 4.38(a) Effect of drawing speed on drawing force combined unit using S. steel wire

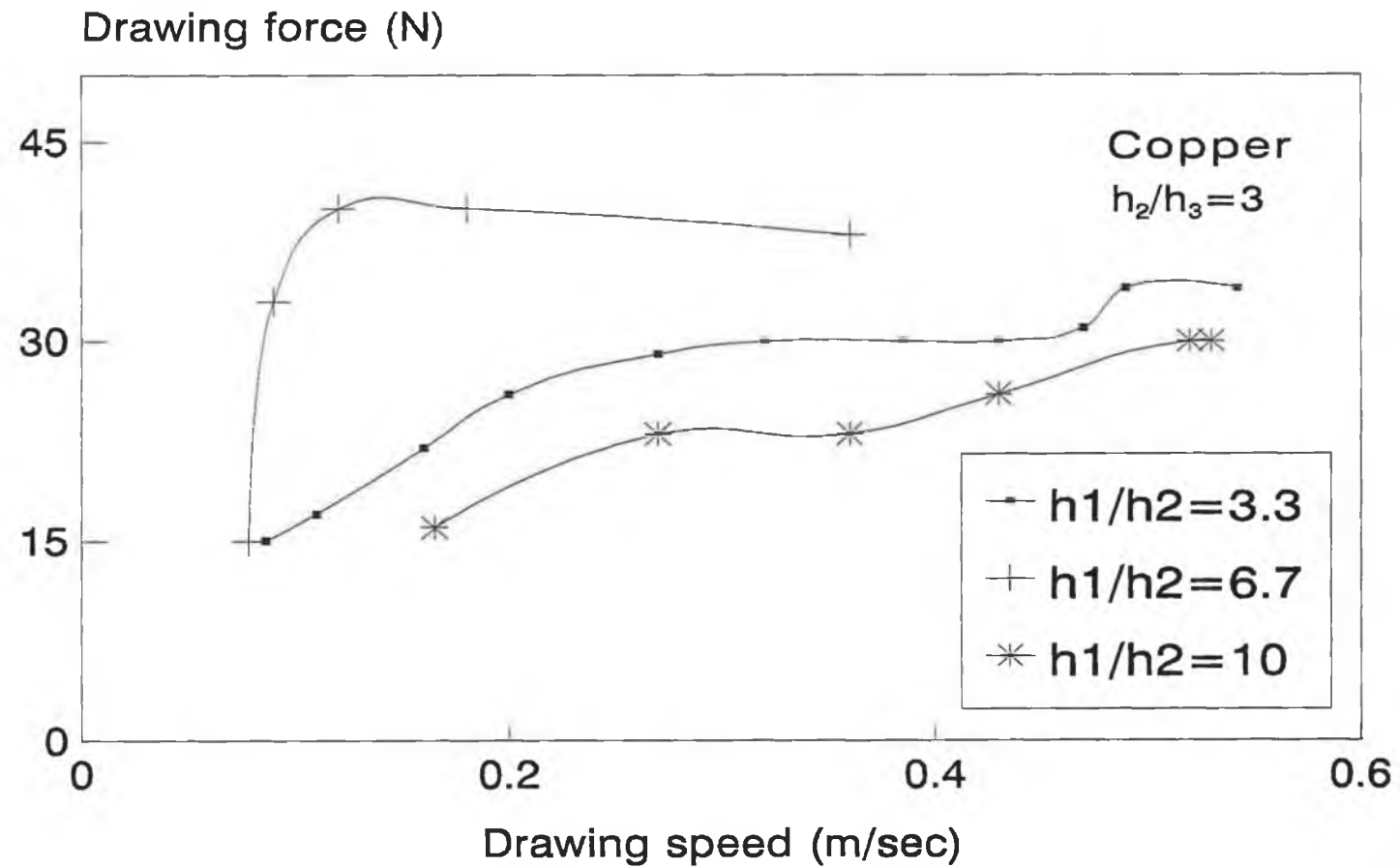


Fig. 4.38(b) Effect of drawing speed on drawing force for a combined unit using a copper wire

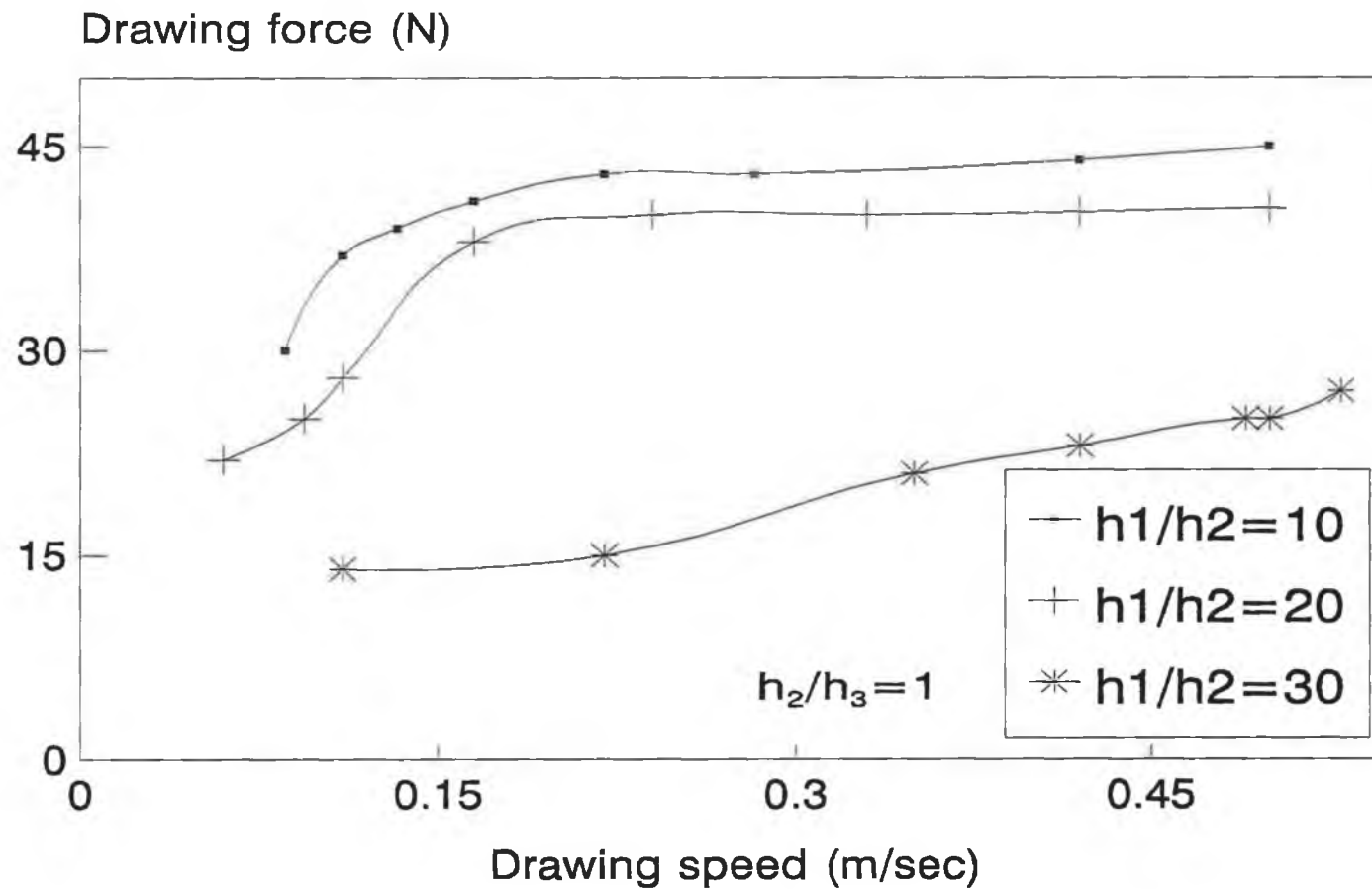


Fig. 4.39 Effect of drawing speed on drawing force using a copper wire at different gap ratios

CHAPTER- FIVE

RESULTS FROM THE TAPERED UNIT

5.1- Theoretical Results

5.1.1- Introduction

An extensive theoretical study was carried out on the simple tapered unit assuming the pressure medium to behave as non-Newtonian fluid for which the viscosity is dependent on the pressure generated within the unit. Theoretical results were calculated on the basis of equations derived in the theoretical analysis in section 3.2.4 . The shear stress was assumed to be constant for a given drawing speed.

The results presented in this section were calculated using the following standard values of the parameters shown;

Reference viscosity $\mu_0 = 50 \text{ N.sec/m}^2$

Gap at the inlet of the unit $h_1 = 0.25 \text{ mm}$

Gap at the exit of the unit $h_2 = 0.05 \text{ mm}$

Length of the unit $L = 180 \text{ mm}$

Diameter of the wire $D = 2 \text{ mm}$

In order to study the manner in which the pressure distribution, the maximum pressure and the drawing load are affected, the magnitudes of some of the above parameters were varied systematically.

5.1.2- Theoretical Pressure

5.1.2.A- Drawing speed effect

The magnitude of the gap h_1 was varied to obtain different h_1/h_2 gap ratios and the

resulting theoretical pressure distributions are shown in Figure 5.1(a) to (c). Figure 5.1(a) shows the effect of drawing speed on the pressure distribution for a range of drawing speeds and gap ratio of $h_1/h_2=3$. It is predicted that only marginally higher magnitudes of pressure are predicted for drawing speeds of considerably higher magnitudes. For example, a peak pressure of 1500 bar is predicted for the drawing speed of 0.32 m/sec whereas 1400 bar is predicted for 0.094 m/sec drawing speed which is more than three times greater.

Similar trend is observed in Figure 5.1(b) for a higher gap ratio of 5 in which even higher magnitudes of pressure (compared to those in Figure 5.1(a)) are predicted for the same drawing speed. The effect of the drawing speed on the peak pressure is again only marginal. Figure 5.1(c) demonstrates the pressure distribution curves for a gap ratio of 10. The trend is very similar as in Figures 5.1(a) and (b). Figure 5.2 illustrates the effect of varying the gap ratio on the pressure distribution for a given drawing speed of 0.5 m/sec.

It is evident from this figure that as the gap ratio h_1/h_2 is increased, The magnitude of the peak pressure increases and then levels off at $h_1/h_2=10$. It is also evident that the location at which the pressure is maximum shifts towards the exit end of the pressure unit as the gap ratio increases.

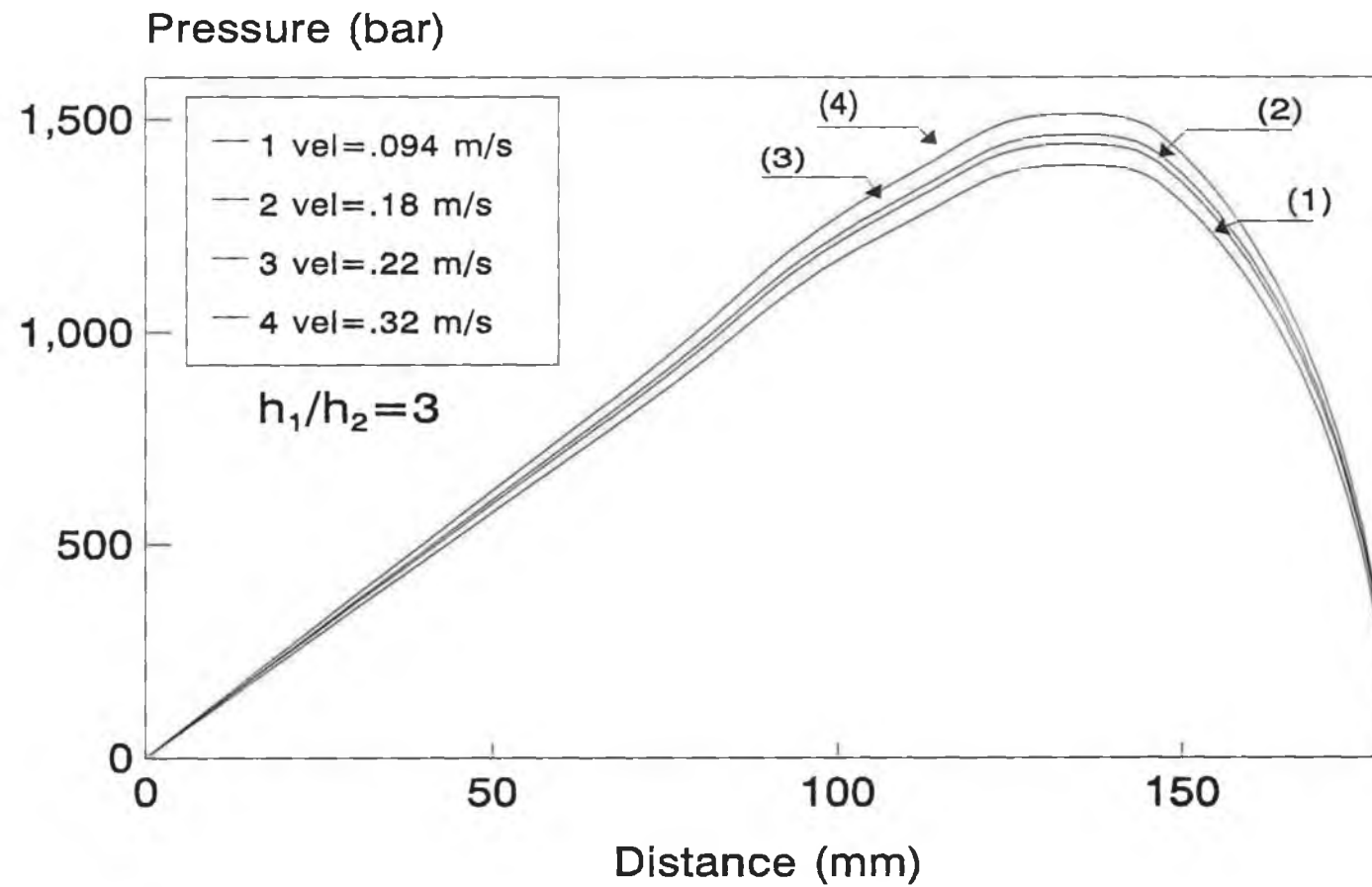


Fig. 5.1(a) Theoretical effect of drawing speed on pressure distribution

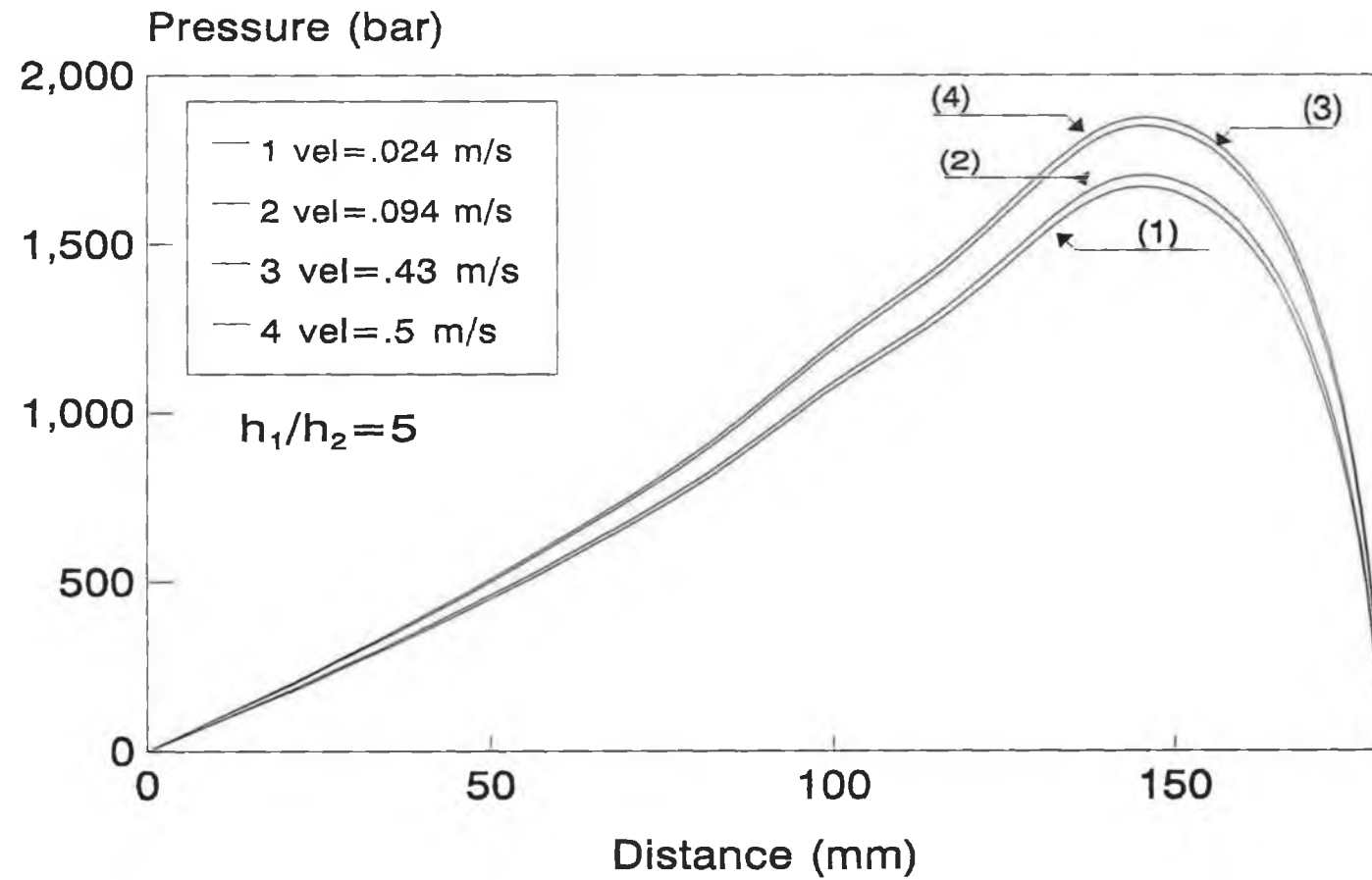


Fig. 5.1(b) Theoretical effect of drawing speed on pressure distribution

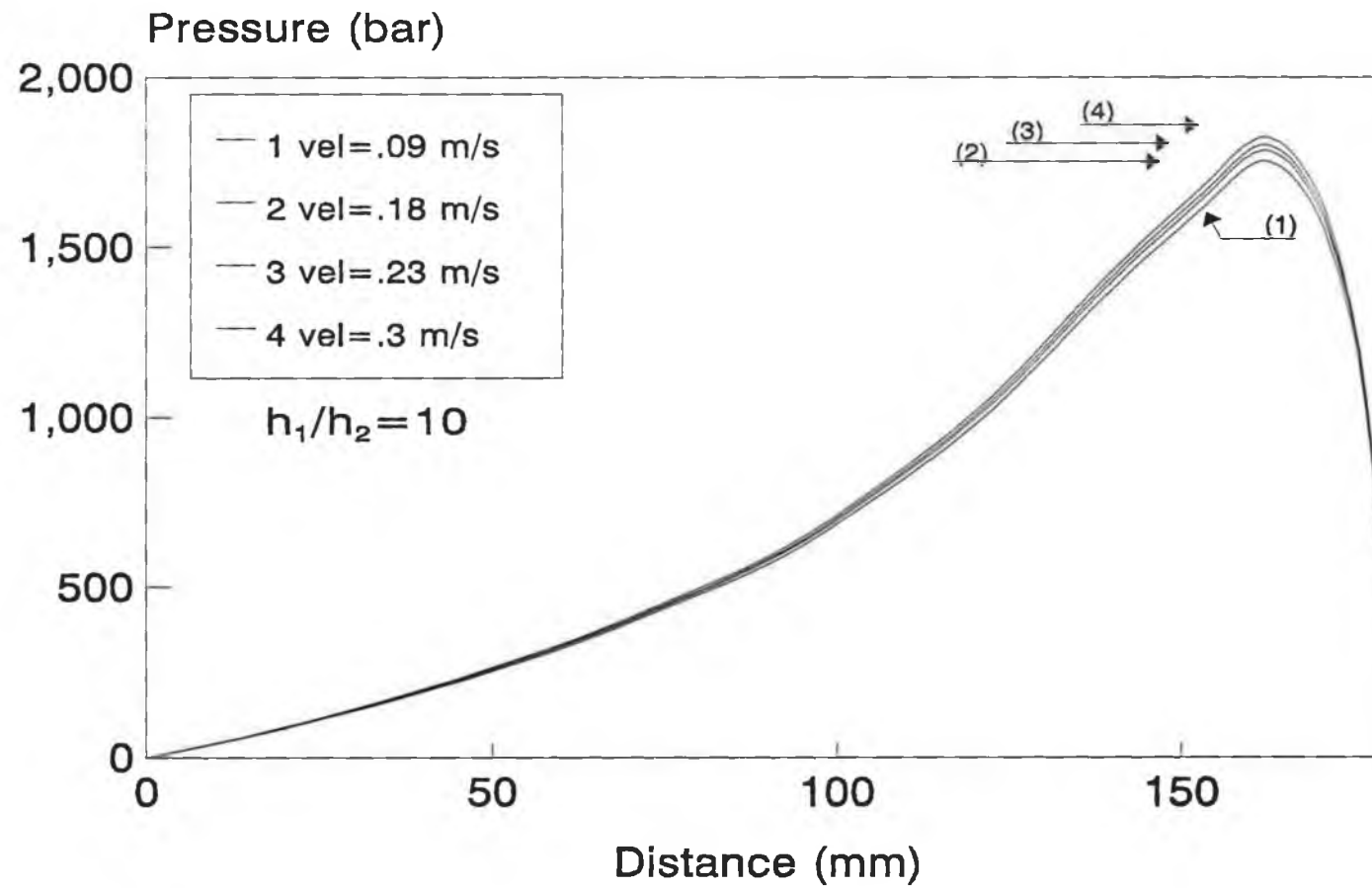


Fig. 5.1(c) Theoretical effect of drawing speed on pressure distribution

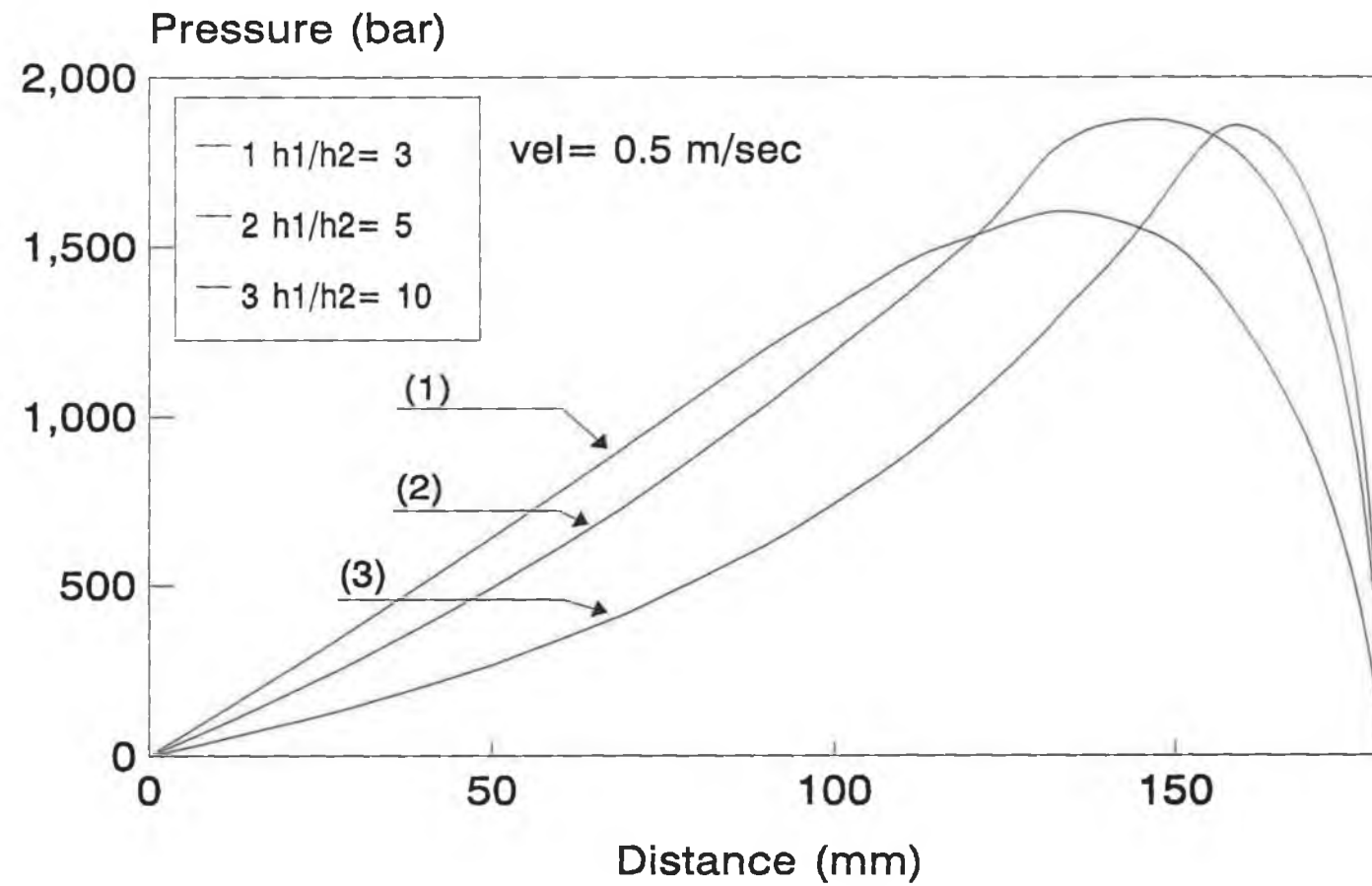


Fig. 5.2 Theoretical effect of the gap ratio on the pressure distribution

5.1.2.B- Gap ratio effect

In order to study the manner in which the maximum pressure is affected the magnitude of a number of parameters was varied systematically. In Figure 5.3(a) the inlet gap h_1 was varied keeping h_2 constant of 0.05 mm in order to obtain different gap ratios and the resulting maximum pressures show that for h_1/h_2 ratio of 6 the magnitude of the maximum pressures for all drawing speeds reaches its peak at the gap ratio of about 6 and then it remains fairly constant.

Theoretical results of the effect of the gap ratio on the maximum pressure were also obtained assuming Newtonian characteristics of the pressure fluid and presented as in Figure 5.3(b). This Figure suggests that for the same initial viscosity and given unit length, increase in the drawing speed results in higher magnitudes of maximum pressure. The figure also shows that the optimum h_1/h_2 ratio for maximum pressure do not change with the speed. The effect of the gap ratio on the average pressure was plotted in Figure 5.4 which indicates that for h_1/h_2 ratio of 5 the average pressure is generally higher and increasing or decreasing this gap ratio results in lower magnitudes of the average pressure.

For h_1/h_2 ratio of 5 the effect of the length of the pressure unit on the maximum pressure at different drawing speed is shown in Figure 5.5 which indicates that a higher magnitude of maximum pressure could be obtained using longer pressure unit and a combination of both the unit length and the drawing speed increase results in higher magnitudes of maximum pressure.

Figure 5.6 shows the effect of the drawing speed on the maximum pressure for different gap ratios which indicates that higher magnitudes of maximum pressure could be obtained with higher drawing speed.

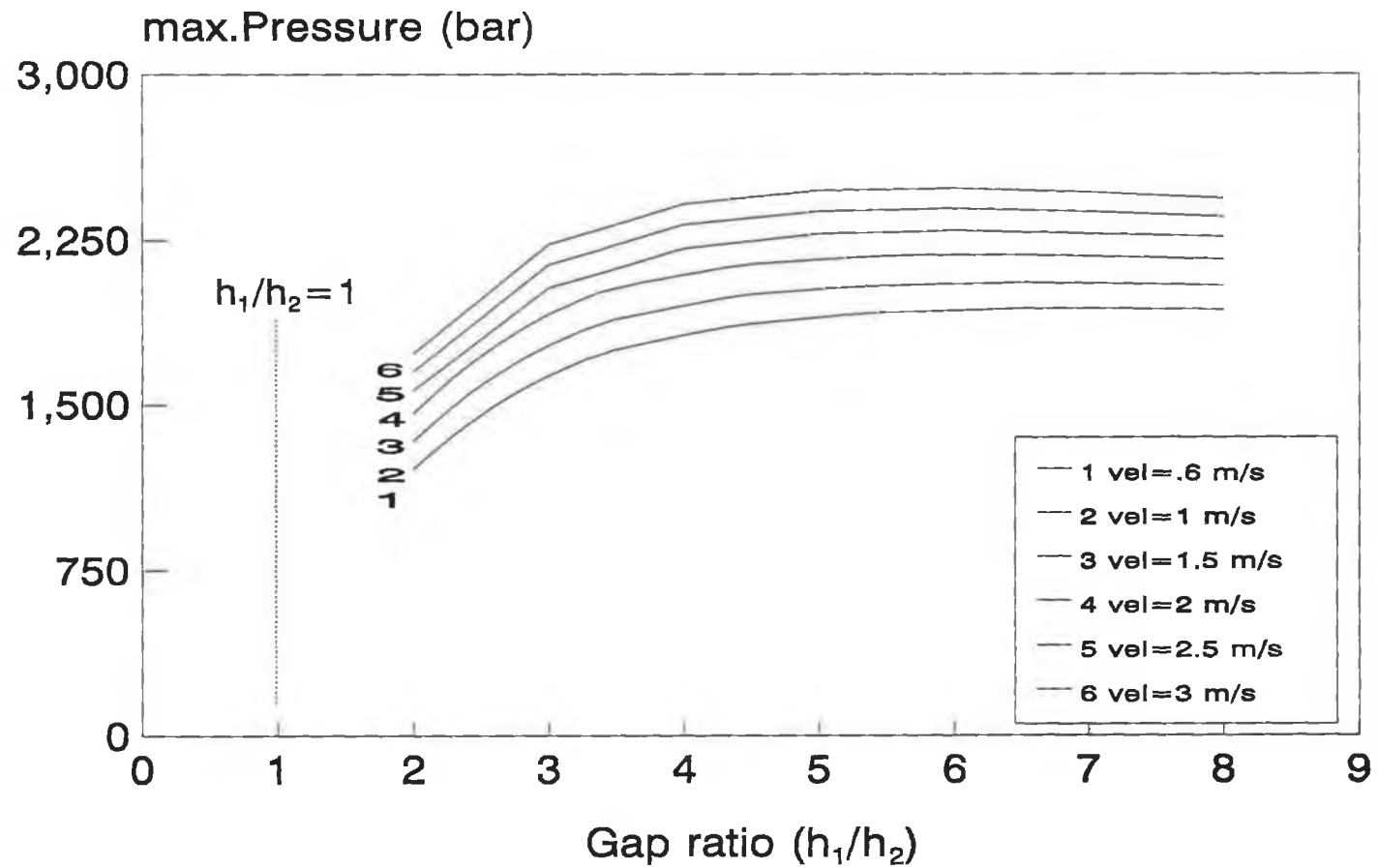


Fig. 5.3(a) Theoretical effect of gap ratio on maximum pressure

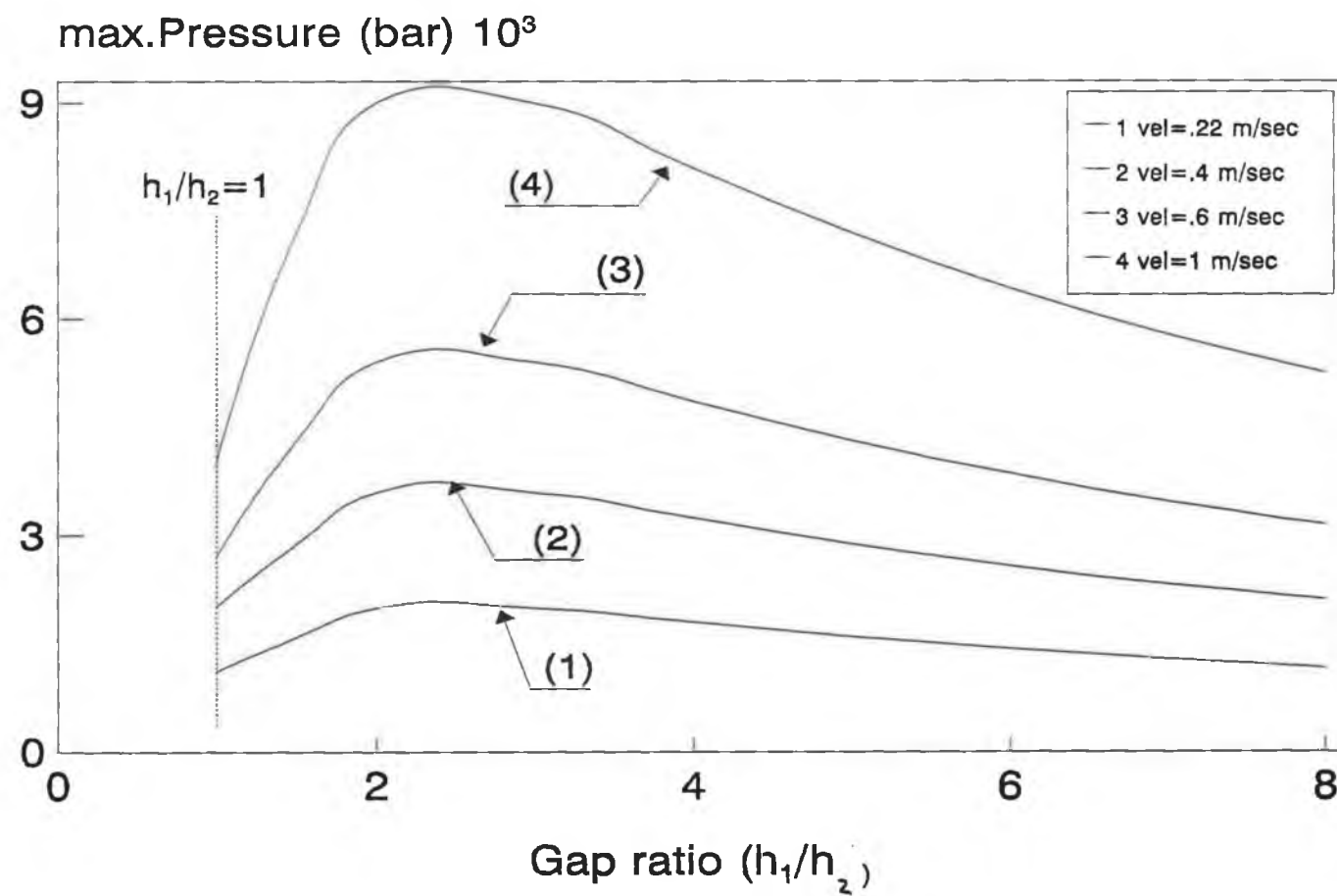


Fig. 5.3(b) Theoretical effect of the gap ratio on the maximum pressure "Newtonian solution"

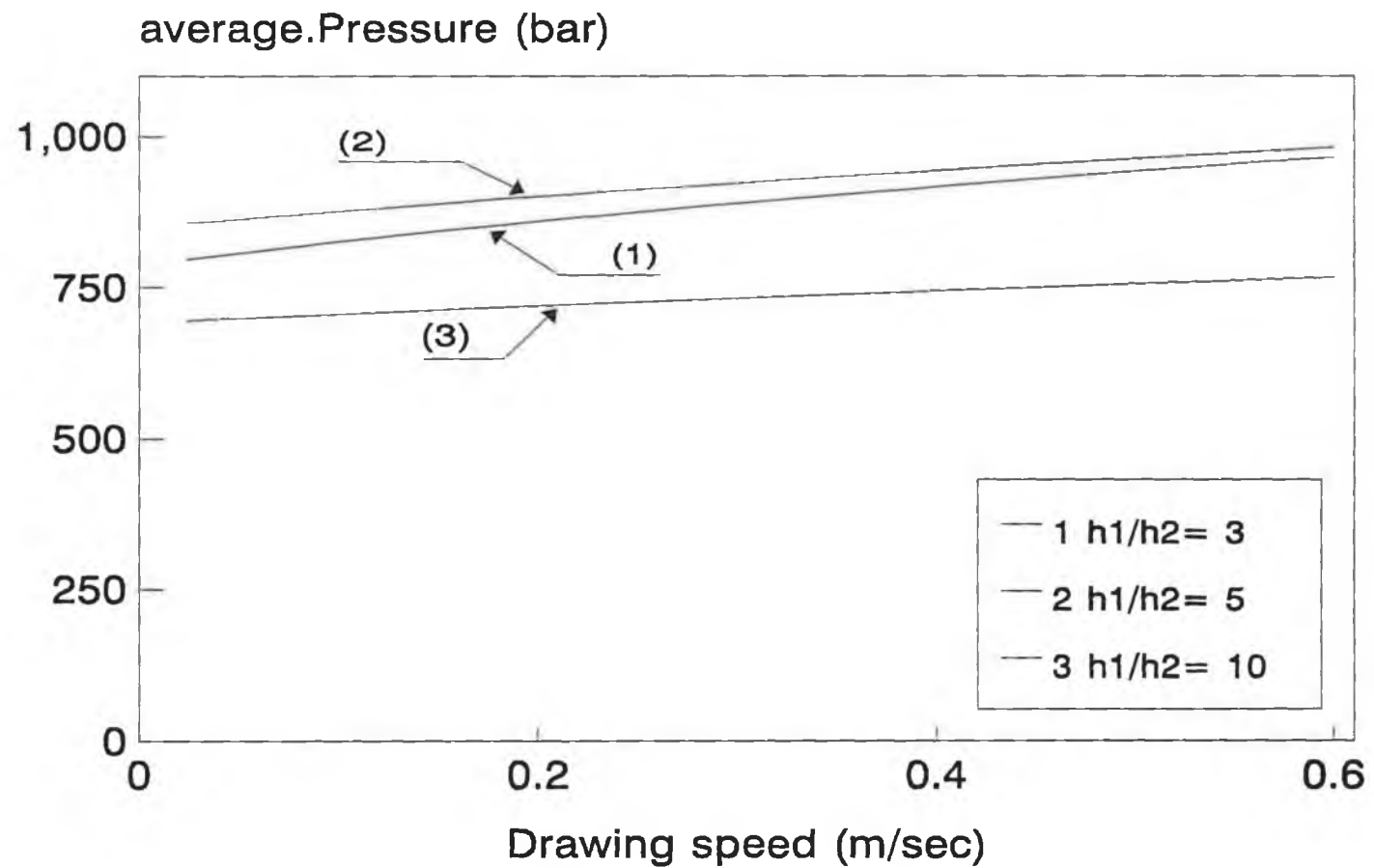


Fig. 5.4 Theoretical effect of the drawing speed on average pressure

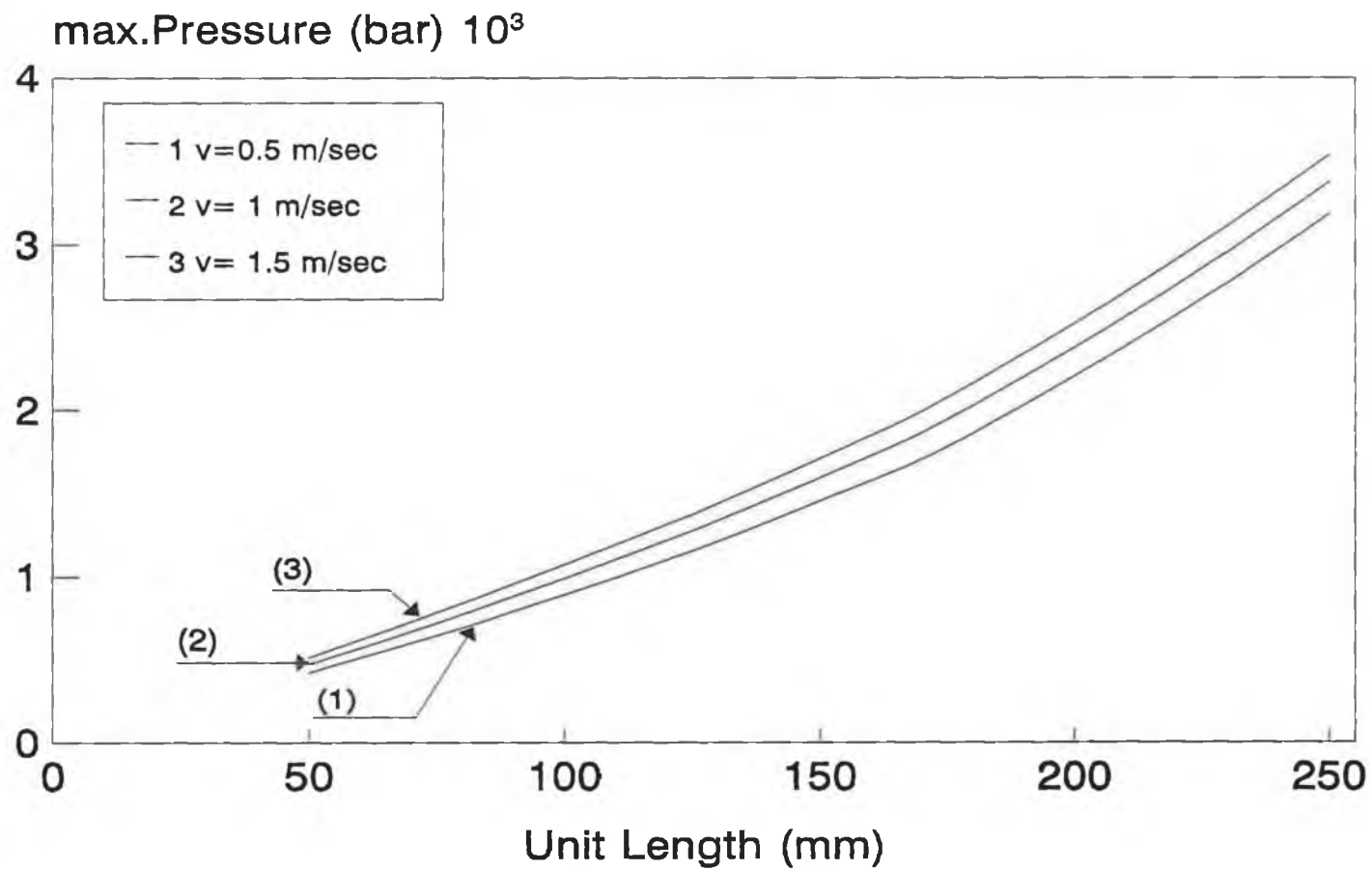


Fig. 5.5 Theoretical effect of the unit length on maximum pressure

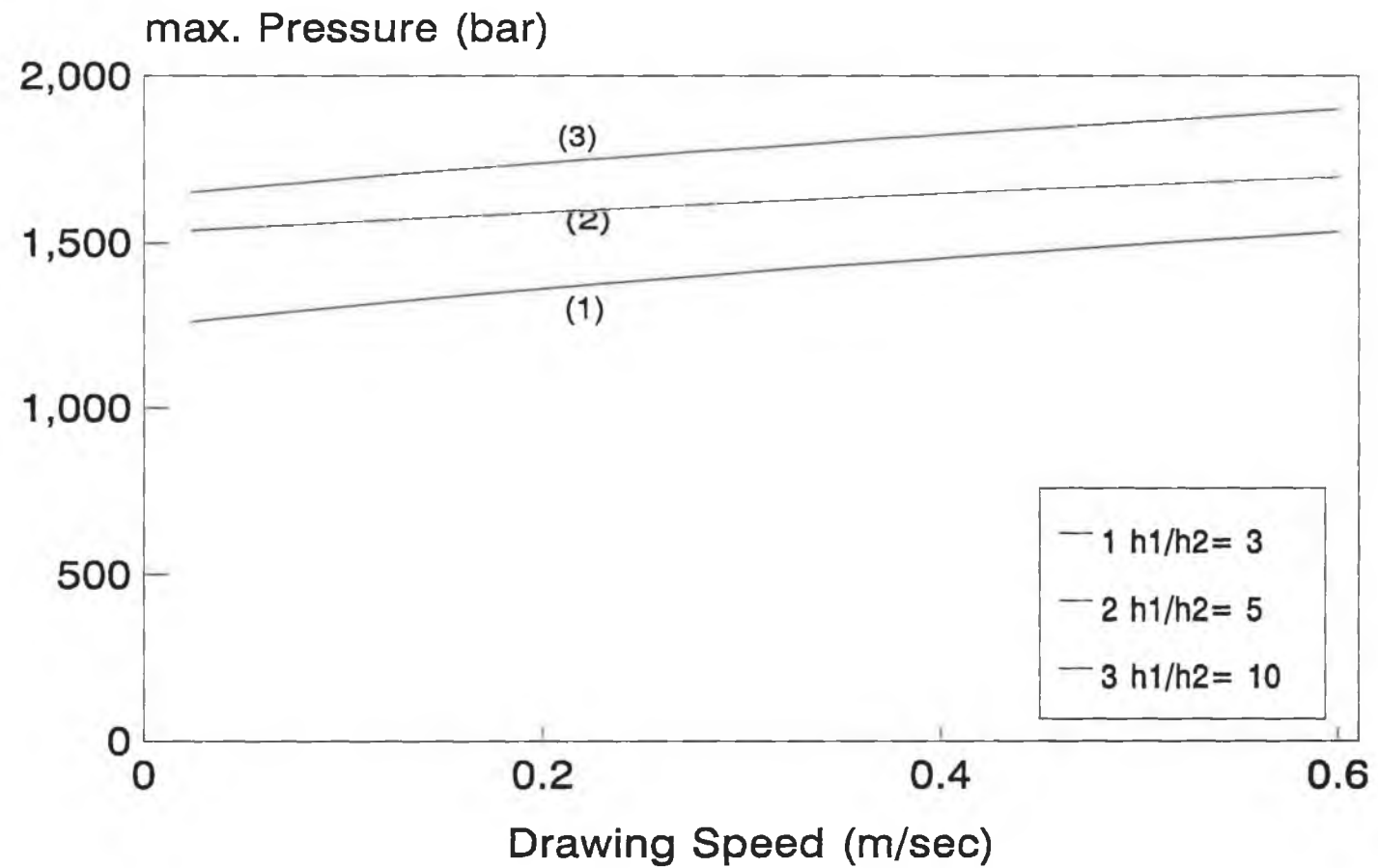


Fig. 5.6 Theoretical effect of drawing speed on maximum pressure

5.1.2.C- Viscosity effect

The effect of the geometrical configuration of the unit on the viscosity of the pressure fluid is illustrated in Figures 5.7(a) to (c). Figure 5.7(a) demonstrates the effect of gap ratio on the viscosity at different drawing speeds. It is evident from this figure that the viscosity increases for higher h_1/h_2 ratios and lower drawing speeds. For higher drawing speeds of more than 0.6 m/sec the viscosity is almost the same for all the considered gap ratios.

The effect of varying the inlet gap thickness h_1 on viscosity is shown in Figure 5.7(b), which indicates that a higher viscosity could be obtained with a higher inlet gap (greater h_1/h_2 ratio).

The effect of the length of the unit on the viscosity is illustrated in Figure 5.7(c) which suggests that a longer pressure unit produces higher viscosity.

The effect of the reference viscosity on the maximum pressure is shown in Figure 5.8, for h_1/h_2 ratio of 5, which indicates that a higher reference viscosity results in higher magnitudes of maximum pressure.

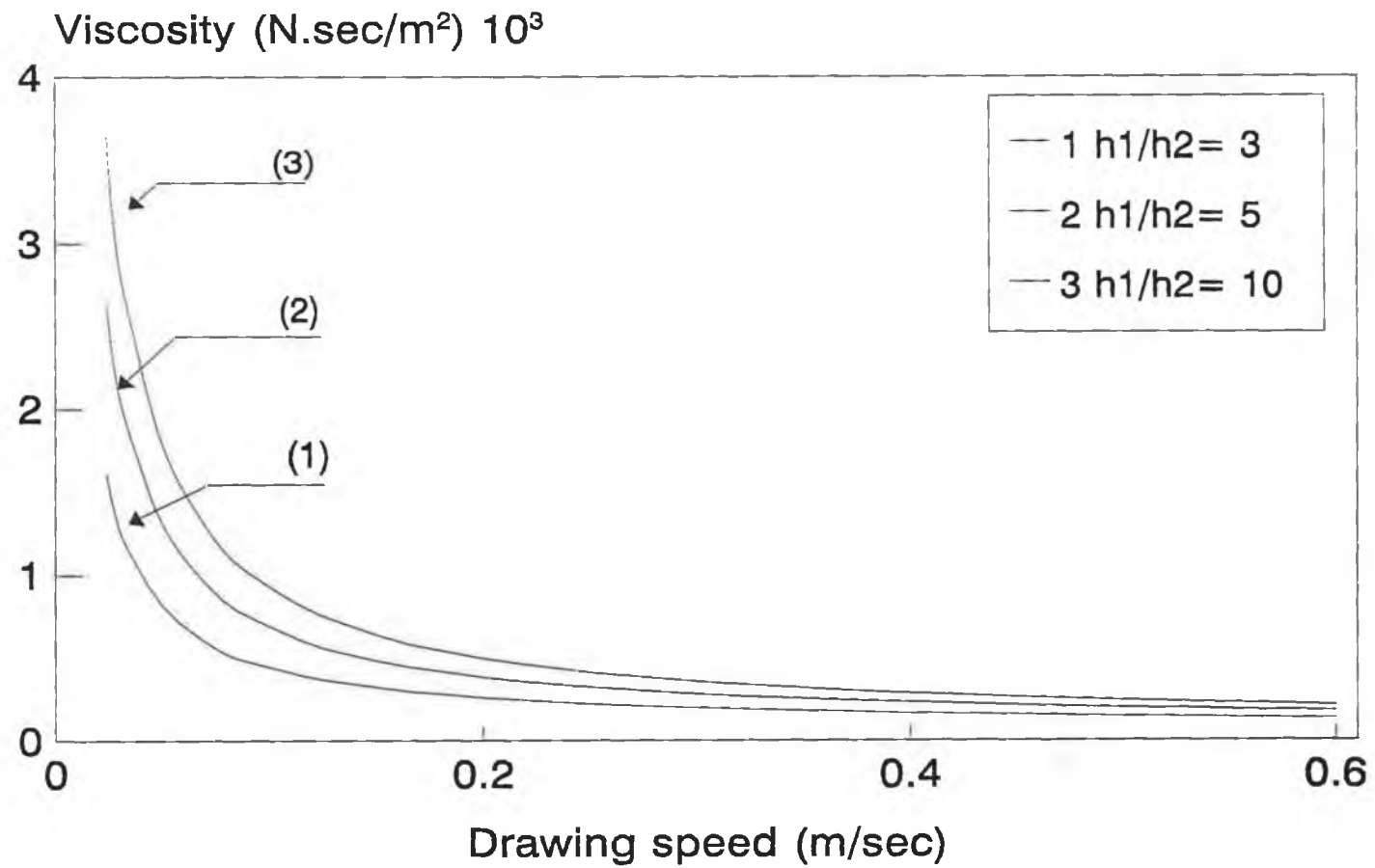


Fig. 5.7(a) Theoretical effect of drawing speed on viscosity

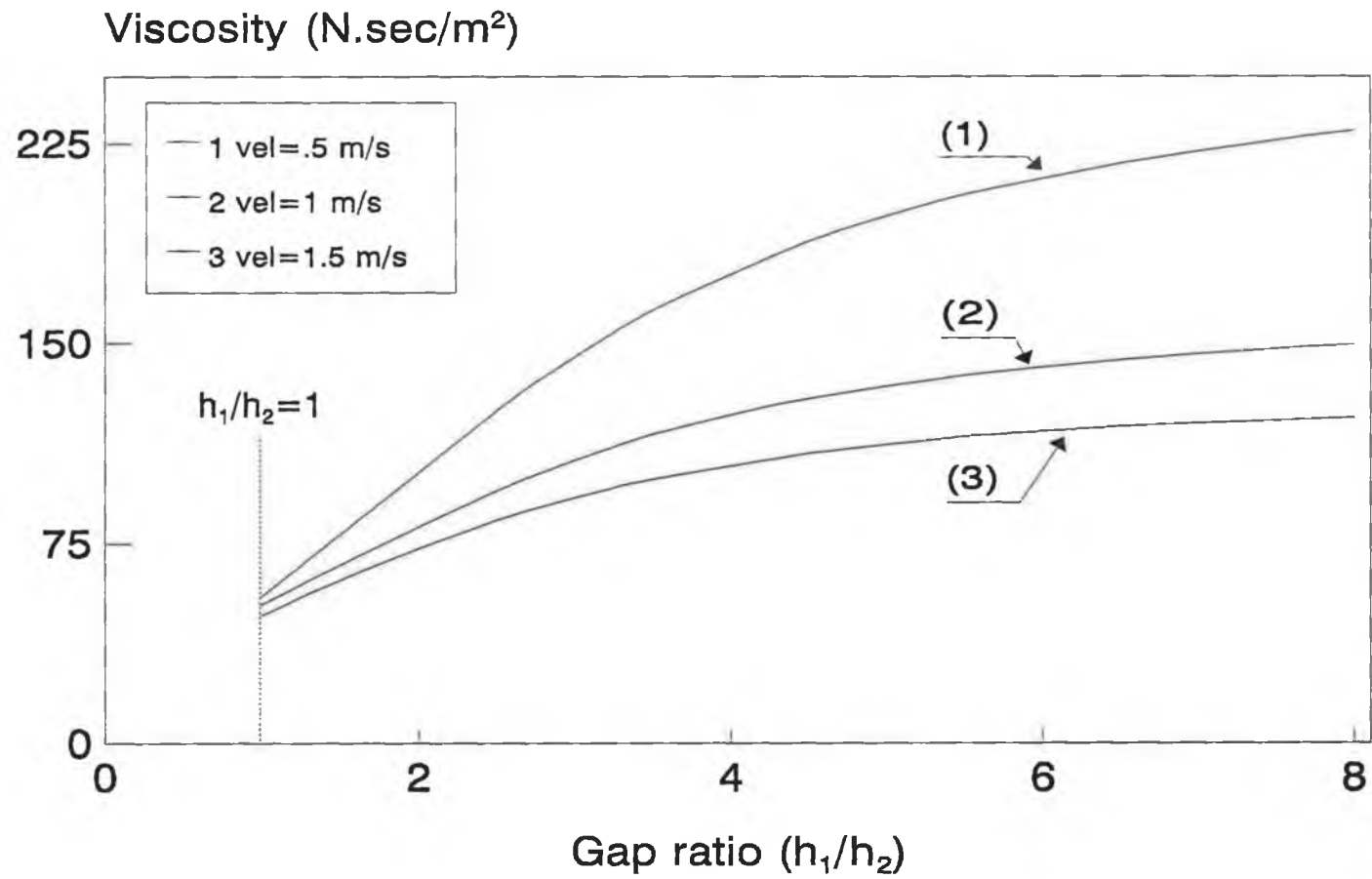


Fig. 5.7(b) Theoretical effect of the gap ratio on viscosity

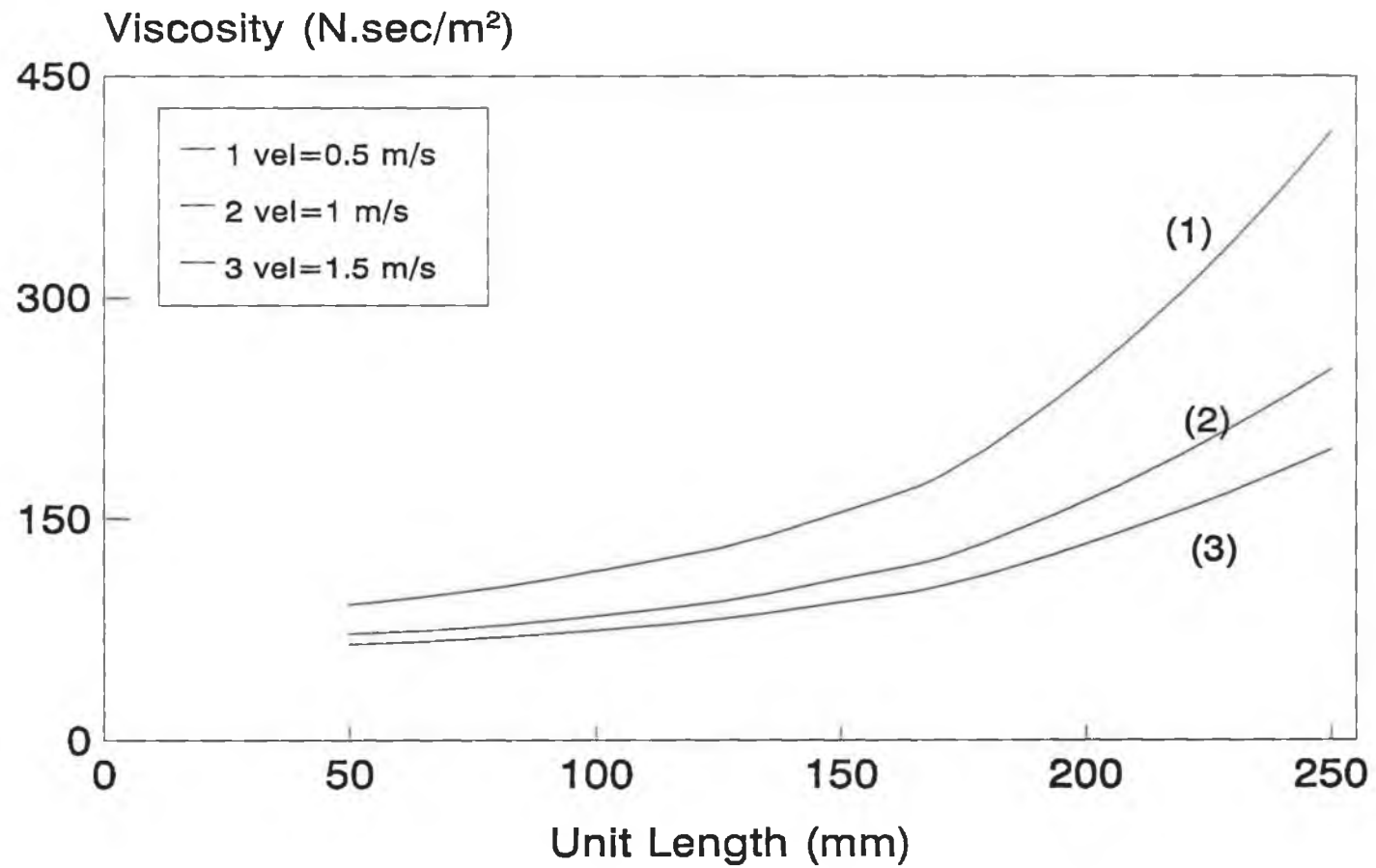


Fig. 5.7(c) Theoretical effect of the unit length on viscosity

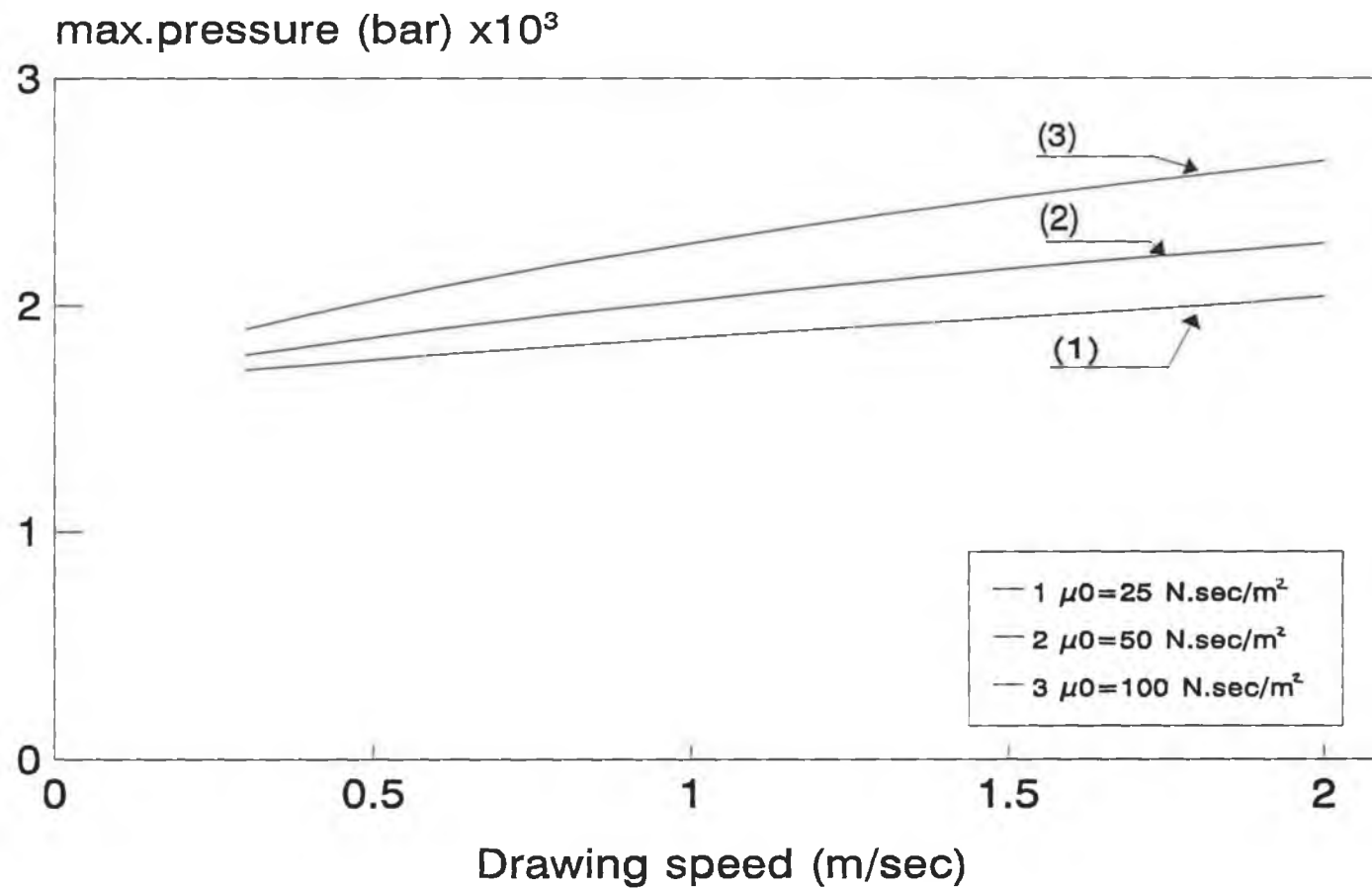


Fig. 5.8 Theoretical effect of reference viscosity change on the maximum pressure

5.1.3- Drawing Stress

Theoretical results were also obtained in terms of drawing load, drawing stress and shear stress which are shown in Figures 5.9(a) to 5.9(e). Figure 5.9(a) illustrates the effect of the drawing speed on the drawing load for different gap ratios, a linear increase to the drawing force with the increase in the drawing speed for all gap ratios could be observed. This Figure also suggests that for a lower gap ratio the drawing force obtained was generally higher for all the drawing speed and any increase in the gap ratio results in reduced magnitudes of drawing force. In Figure 5.9(b) similar trend is observed for the shear stress versus the drawing speed. The effect of the drawing speed on the drawing stress distribution is shown in Figure 5.9(c) for h_1/h_2 ratio of 5, where a linear drawing stress distribution within the unit could be observed.

For drawing speed of 0.1 m/sec the theoretical effect of the gap ratio on the drawing stress was investigated, Figure 5.9(d) suggests that the h_1/h_2 ratio has very little effect on the stress within the unit.

Figure 5.9(e) demonstrates the effect of the length of the pressure unit on the drawing stress using different gap ratios for a given drawing speed of 0.1 m/sec and it indicates that a relatively higher magnitudes of drawing stresses were obtained as the length of the unit is increased.

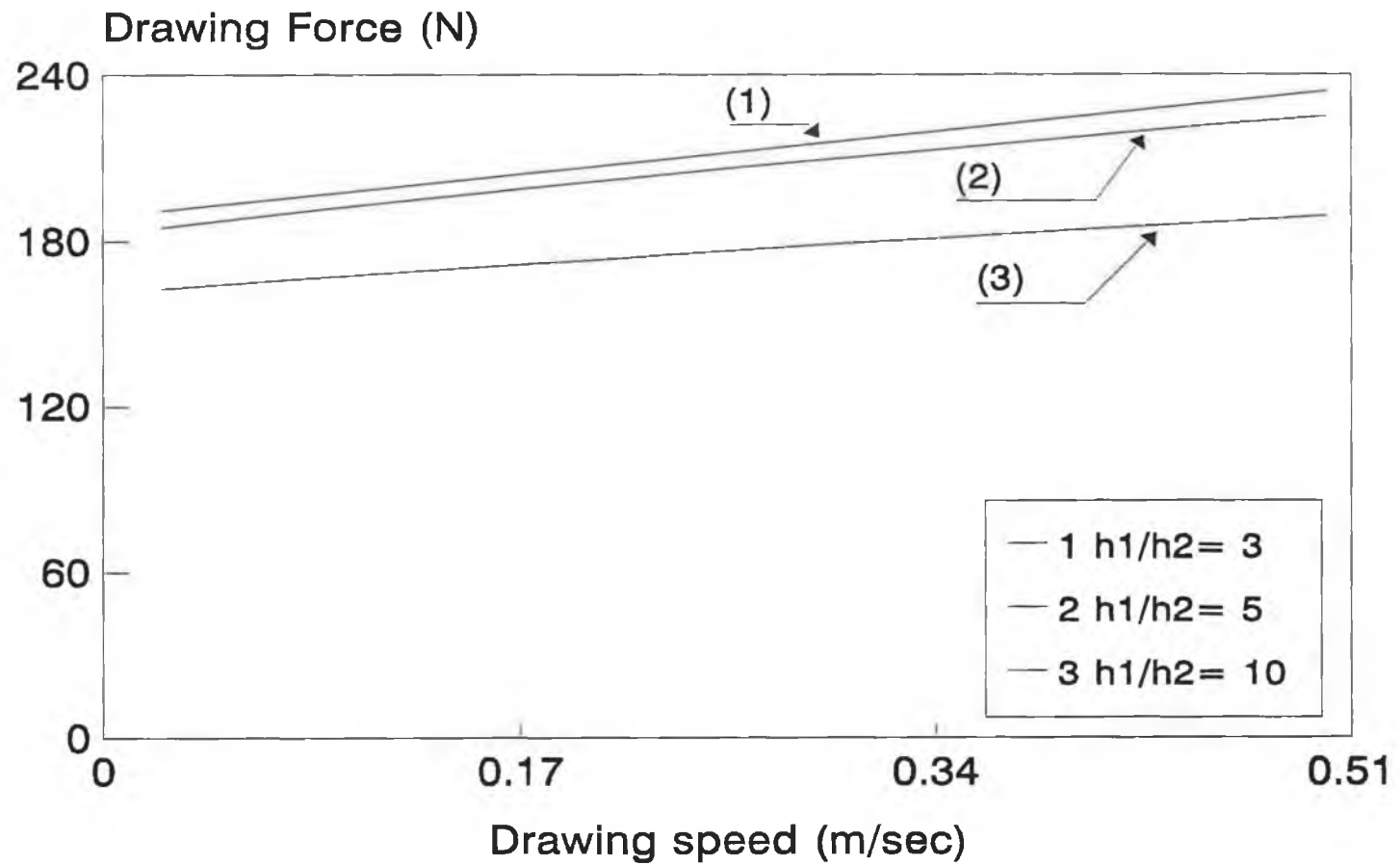


Fig. 5.9(a) Theoretical effect of drawing speed on drawing force

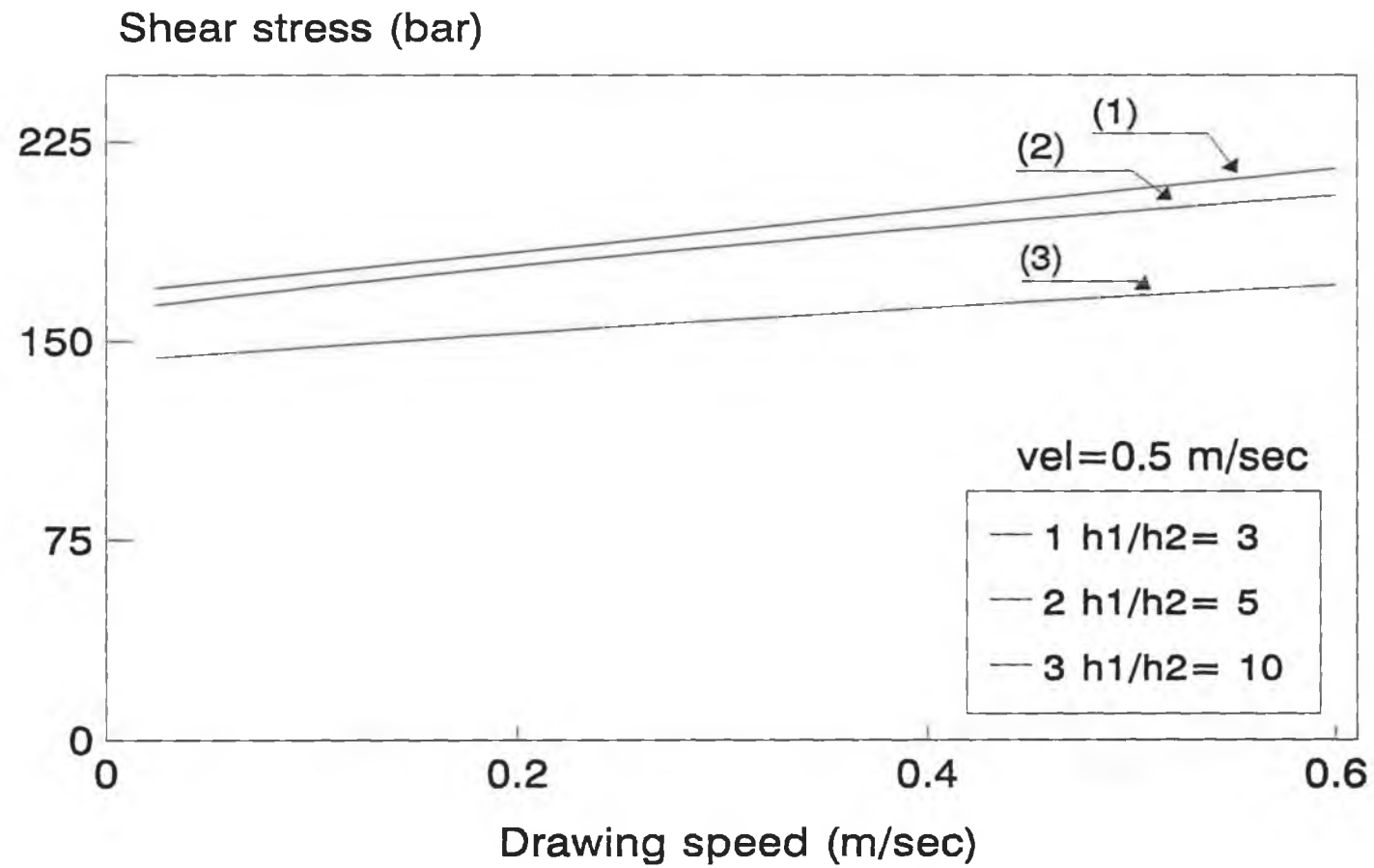


Fig 5.9(b) Theoretical effect of drawing speed on shear stress

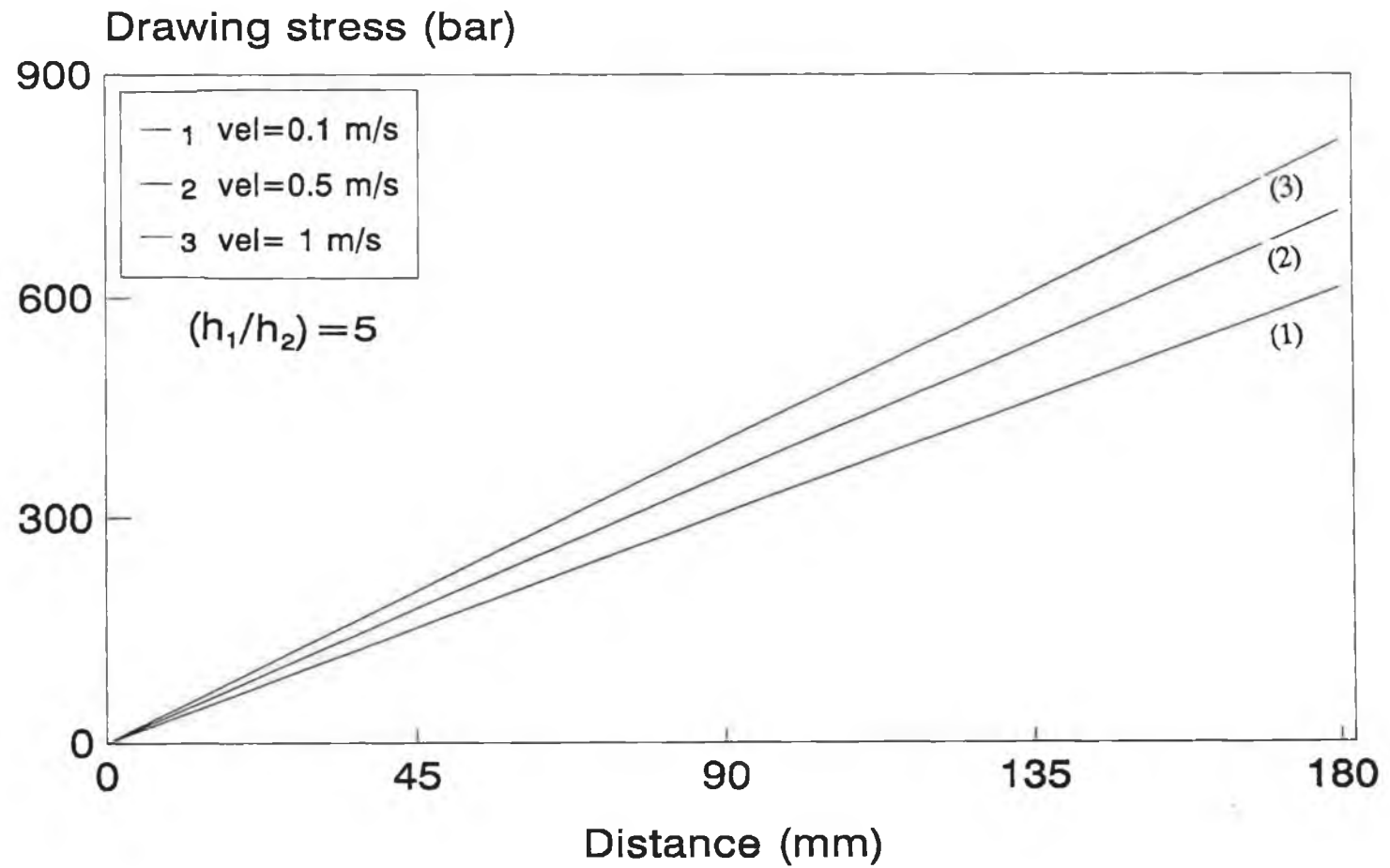


Fig 5.9(c) Theoretical effect of the drawing speed on the drawing stress distribution

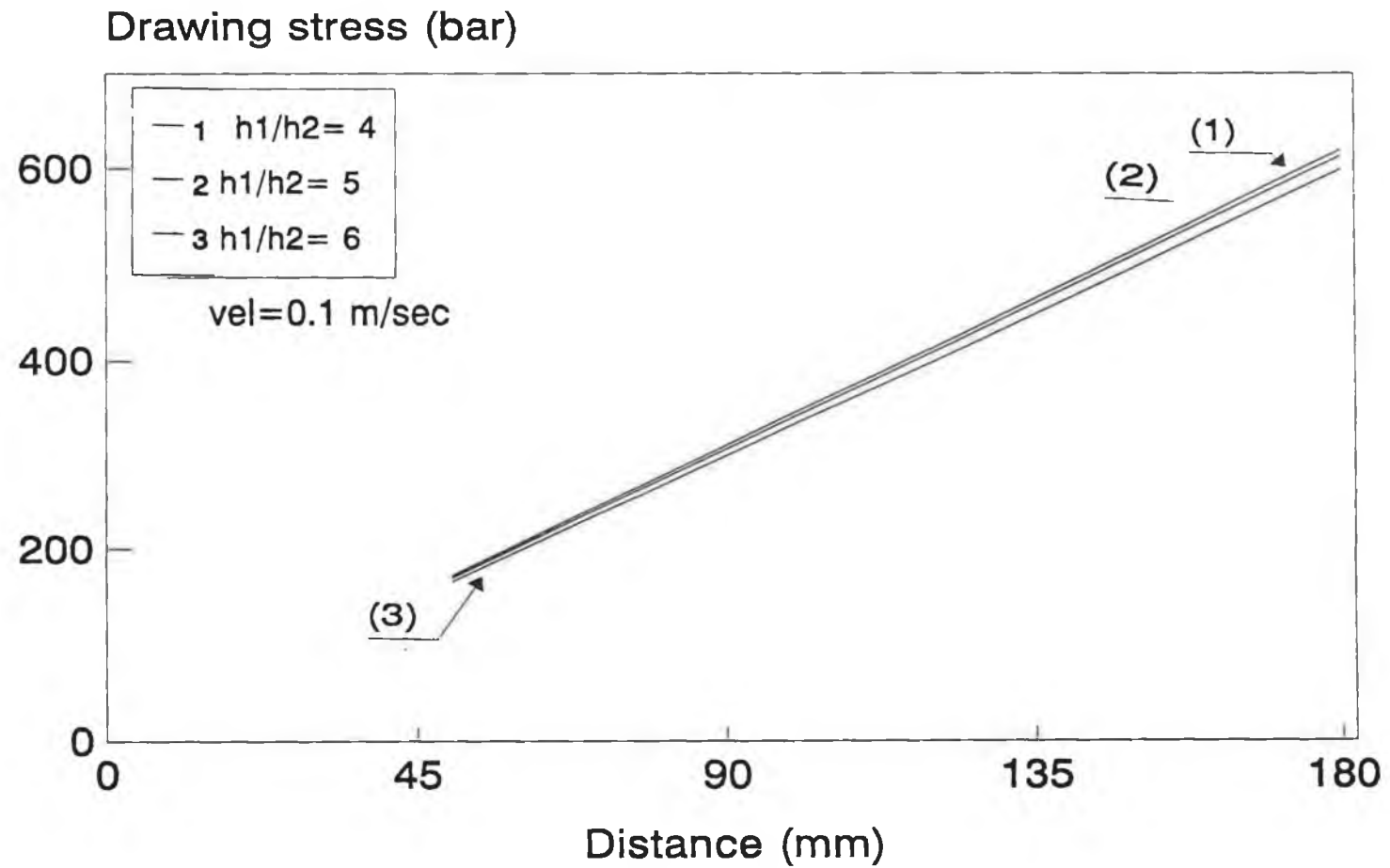


Fig 5.9(d) Theoretical effect of the gap ratio (h_1/h_2) on the drawing stress distribution

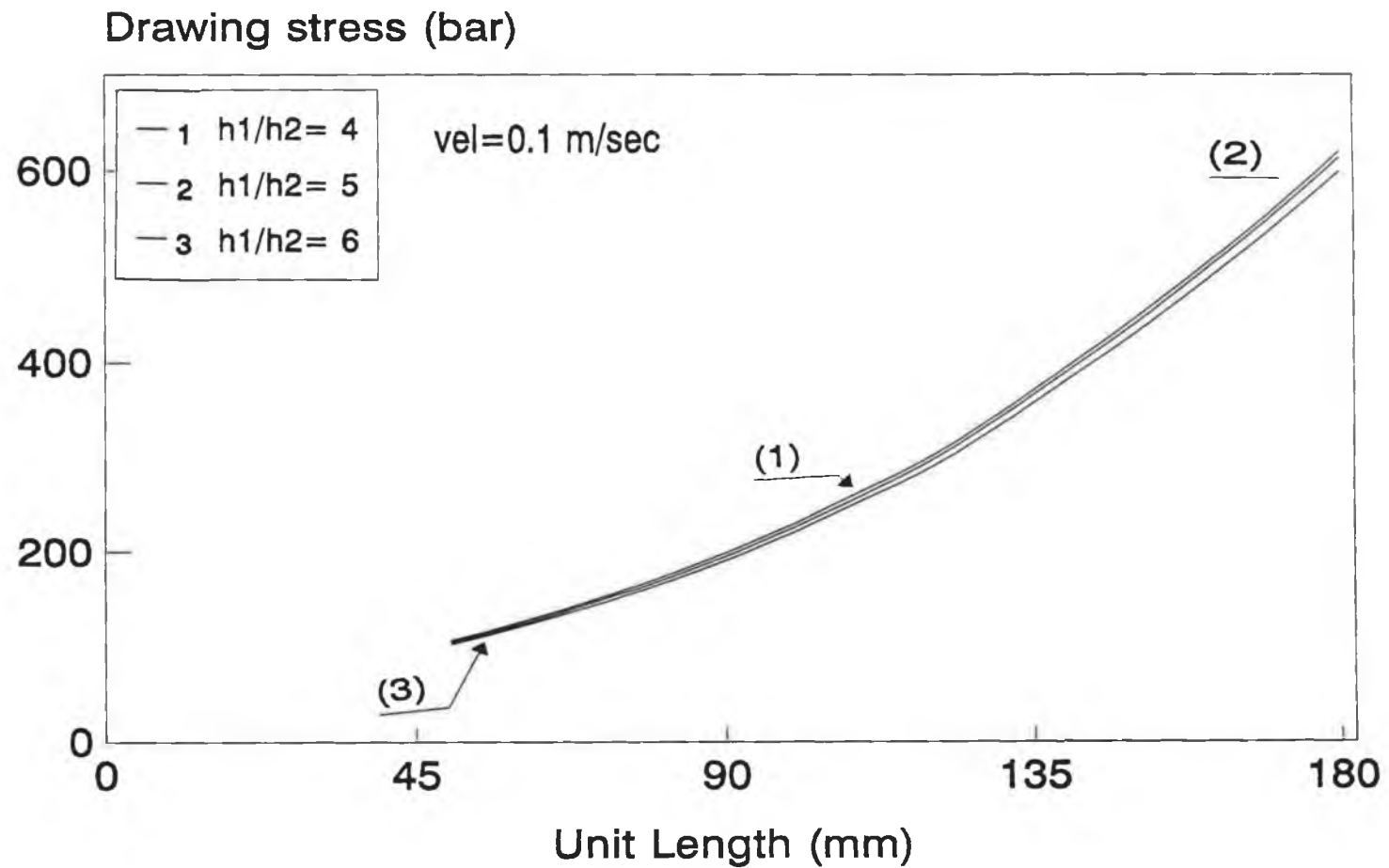


Fig 5.9(e) Theoretical effect of the unit length on the drawing stress

5.2- Experimental Results

5.2.1- Introduction

An extensive experimental study was under taken to investigate the performance of the tapered bore pressure unit in which a considerable amount of data was obtained and presented in this section in graphical form for convenience.

In order to study the manner in which the pressure distribution, the maximum pressure and the drawing load are affected, the magnitudes of some of the parameters given below were varied systematically while using copper and stainless steel wire.

Gap at the entry of the unit $h_1=0.25$ mm

Gap at the exit of the unit $h_2=0.05$ mm

Length of the unit $L=180$ mm

Wire diameter $D=2$ mm

The temperature at which the tests where carried out was 110 ± 5 °C.

The stress strain properties of the stainless steel and copper wires were given in appendix [DD] and the yield stresses for the wires are 456 MPa for stainless steel and 304 MPa for the copper.

5.2.2- Pressure distribution

Experimental results were obtained in terms of pressure distribution when drawing stainless steel and copper wires. Experiments were carried out by varying the inlet gap h_1 in a systematic manner keeping the outlet gap $h_2=0.05$ mm constant, in order to obtain different gap ratios. For each combination of h_1/h_2 , drawing speed ranging between about 0.05 m/sec to about 0.7 m/sec were used for both of the stainless steel and the copper wires.

The pressure distribution within the unit based on experimentally measured pressure at three different points, have been obtained and plotted for the gap ratio of $h_1/h_2=3$, and are

presented for different drawing speeds in Figures 5.10.(a) and 5.10.(b) for stainless steel and copper respectively. In Figure 5.10(a) for the range of drawing speed considered, the drawing speed increase results in higher magnitudes of pressure; for example a peak pressure of almost 1500 bar was obtained with drawing speed of 0.13 m/sec whereas, the peak pressure obtained at drawing speed of 0.06 m/sec was 500 bar. Similar trend could be observed when drawing a copper wire as shown in Figure 5.10(b) except that the magnitudes of the peak pressure are lower. Figure 5.11(a) illustrates the pressure distribution curves for a gap ratio of $h_1/h_2=5$ at different drawing speeds, a maximum pressure of 1500 bar was obtained when drawing stainless steel wire at speed of 0.1 m/sec. The location of the peak pressure as the Figures suggest is in the last third of the pressure unit. This is also true for the pressure distribution obtained using copper wire as shown in Figure 5.11(b), except the magnitudes of the peak pressure are generally much lower for copper wire for comparable drawing speeds of stainless steel wire.

For the same geometrical parameter of the pressure unit and same wire diameter and drawing speed, the pressure distribution curve and the magnitude of the peak pressure in the unit should be the same for drawing wires of different materials provided that their elasto-plastic deformation properties are identical. In the present case, the copper wire is much softer than the stainless steel wire, 0.2 percent of reduction in diameter of copper wire was obtained when carrying the tests. This would cause the pressure to be lower. This point has been discussed in the section dealing with the combined geometry unit.

A higher gap ratio of h_1/h_2 was used in order to plot the pressure distribution curves for both the stainless steel and copper wires respectively. Figure 5.12(a) shows the effect of the drawing speed on pressure distribution for stainless steel wire, a peak pressure of 1600 bar was obtained with a drawing speed of 0.23 m/sec which is low as compared to that in Figure

5.11(a).

Similar trend could be observed in Figure 5.12(b) for drawing copper wire with $h_1/h_2=10$.

The effect of the gap ratios for a given drawing speed on the pressure distribution for both stainless steel and copper wires could be observed in Figures 5.13(a) and 5.13(b) respectively. In Figure 5.13(a) the magnitude of peak pressure was almost equally higher for h_1/h_2 ratios of 5 and 10; decreasing this gap ratio produces a lower magnitude of the peak pressures. However, this is not the same drawing copper as seen in Figure 5.13(b) in which the peak pressure is maximum for $h_1/h_2=5$.

However, for h_1/h_2 ratios greater or smaller than 5 give lower magnitudes of the peak pressure.

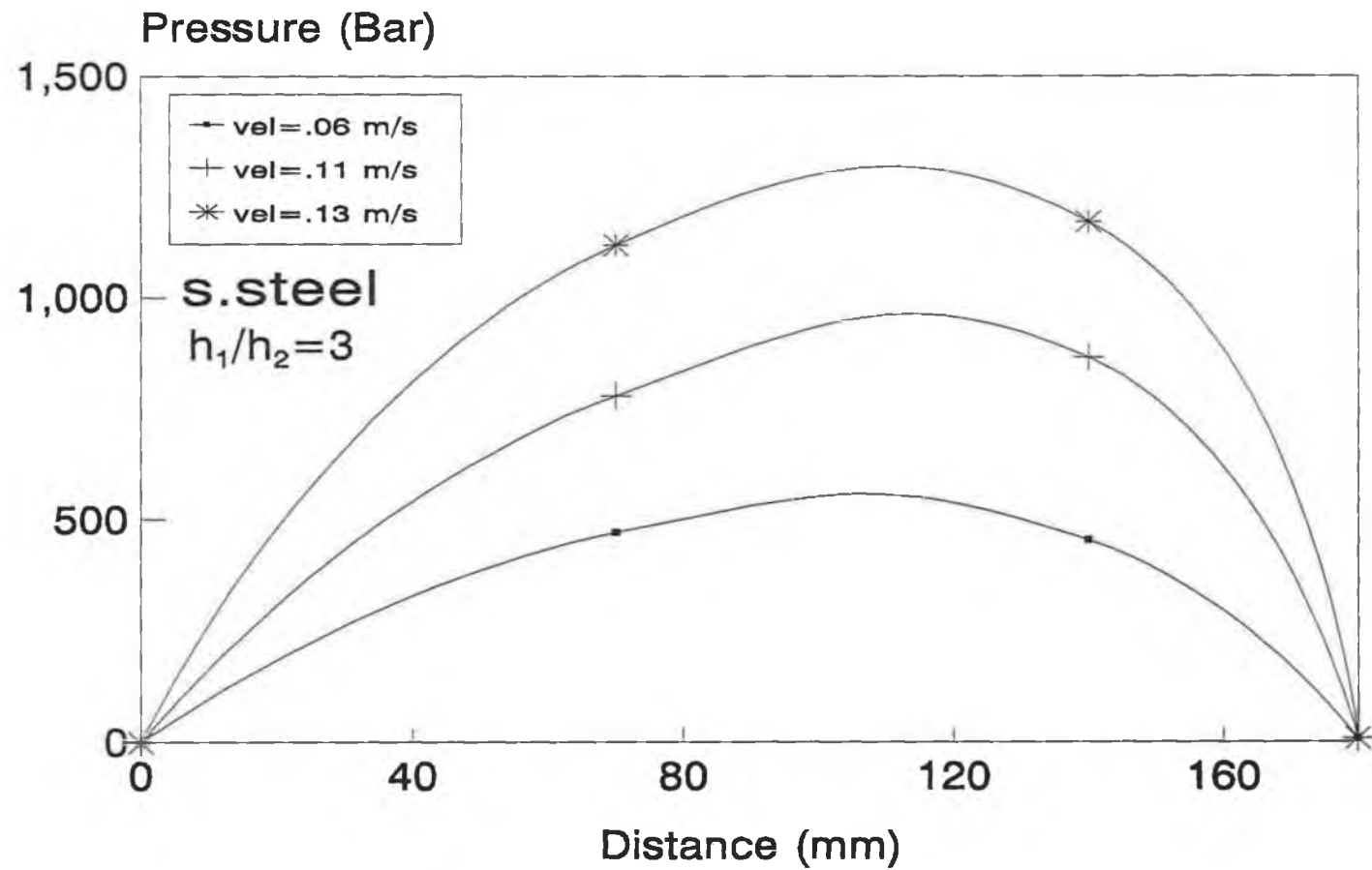


Fig. 5.10(a) Effect of drawing speed on pressure distribution

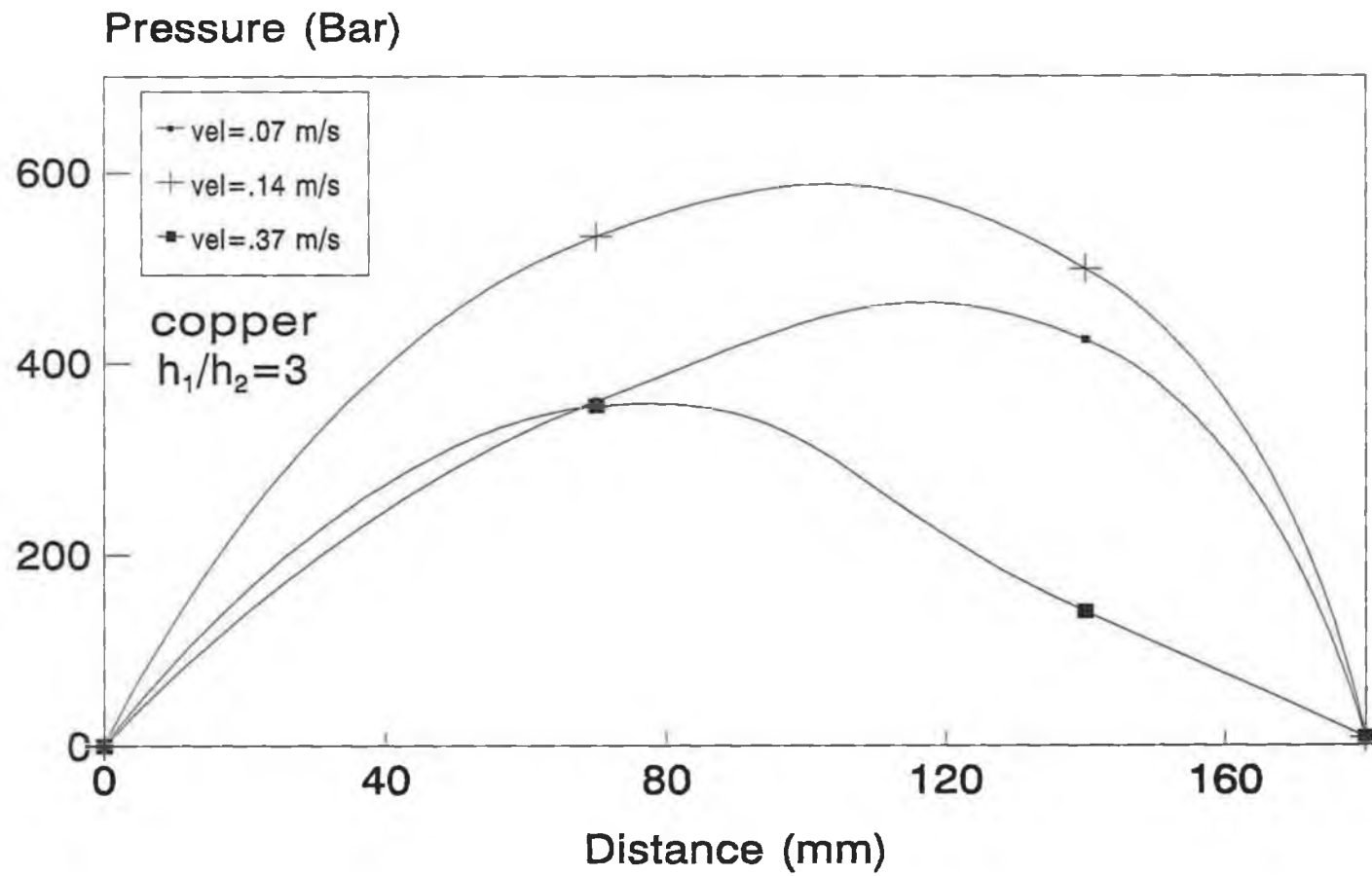


Fig. 5.10(b) Effect of drawing speed on pressure distribution

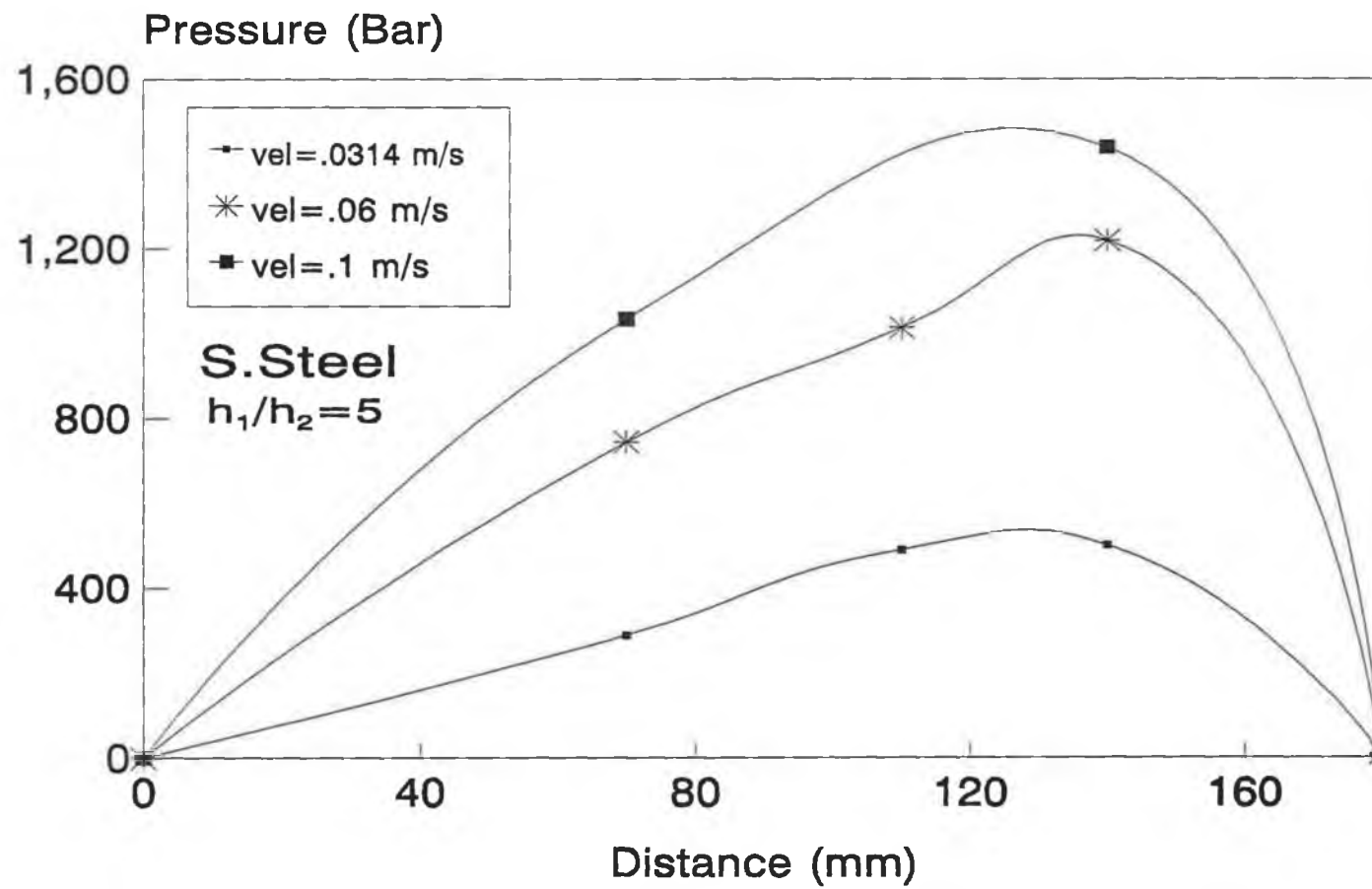


Fig. 5.11(a) Effect of drawing speed on pressure distribution

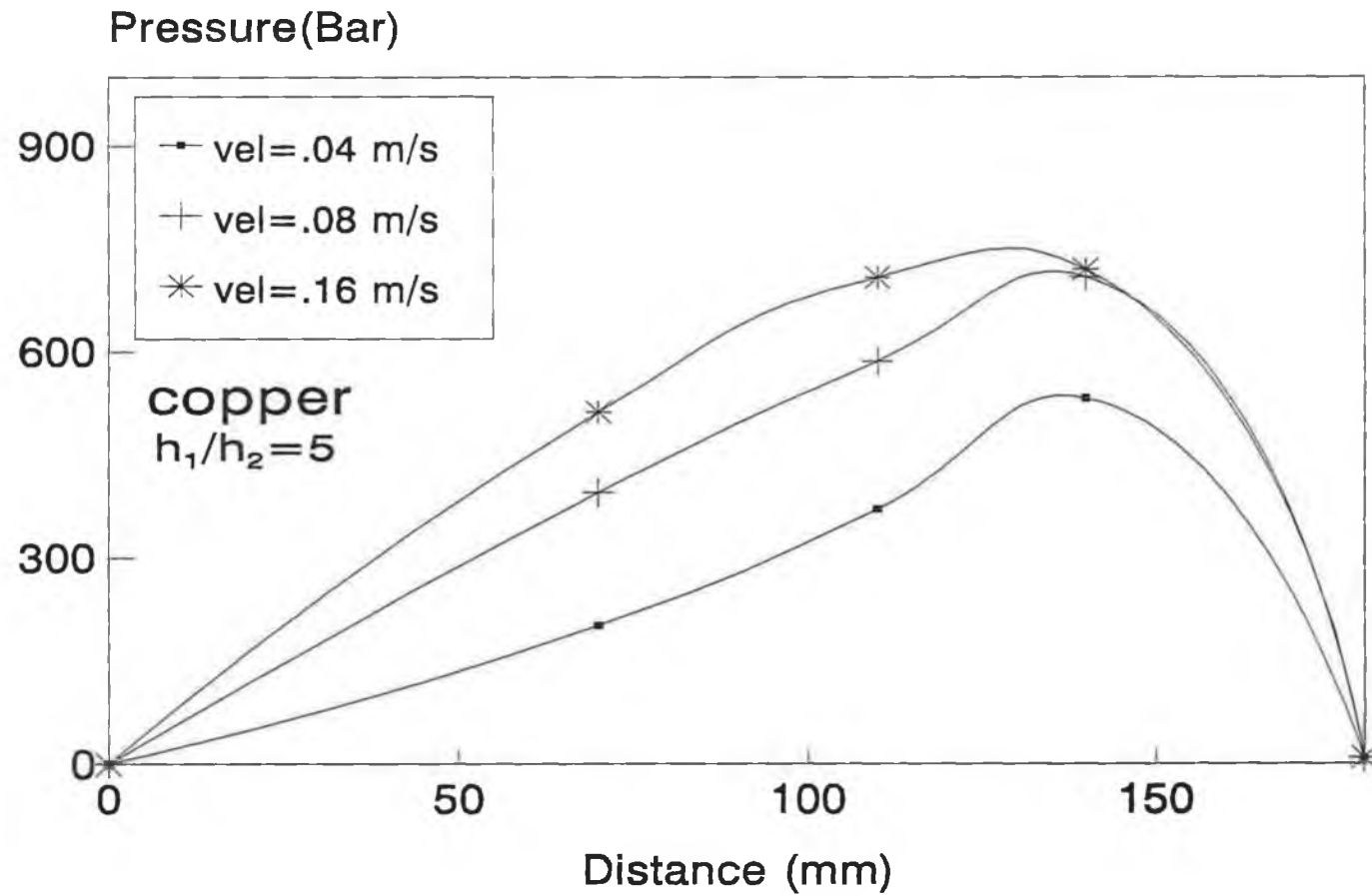


Fig. 5.11(b) Effect of drawing speed on pressure distribution

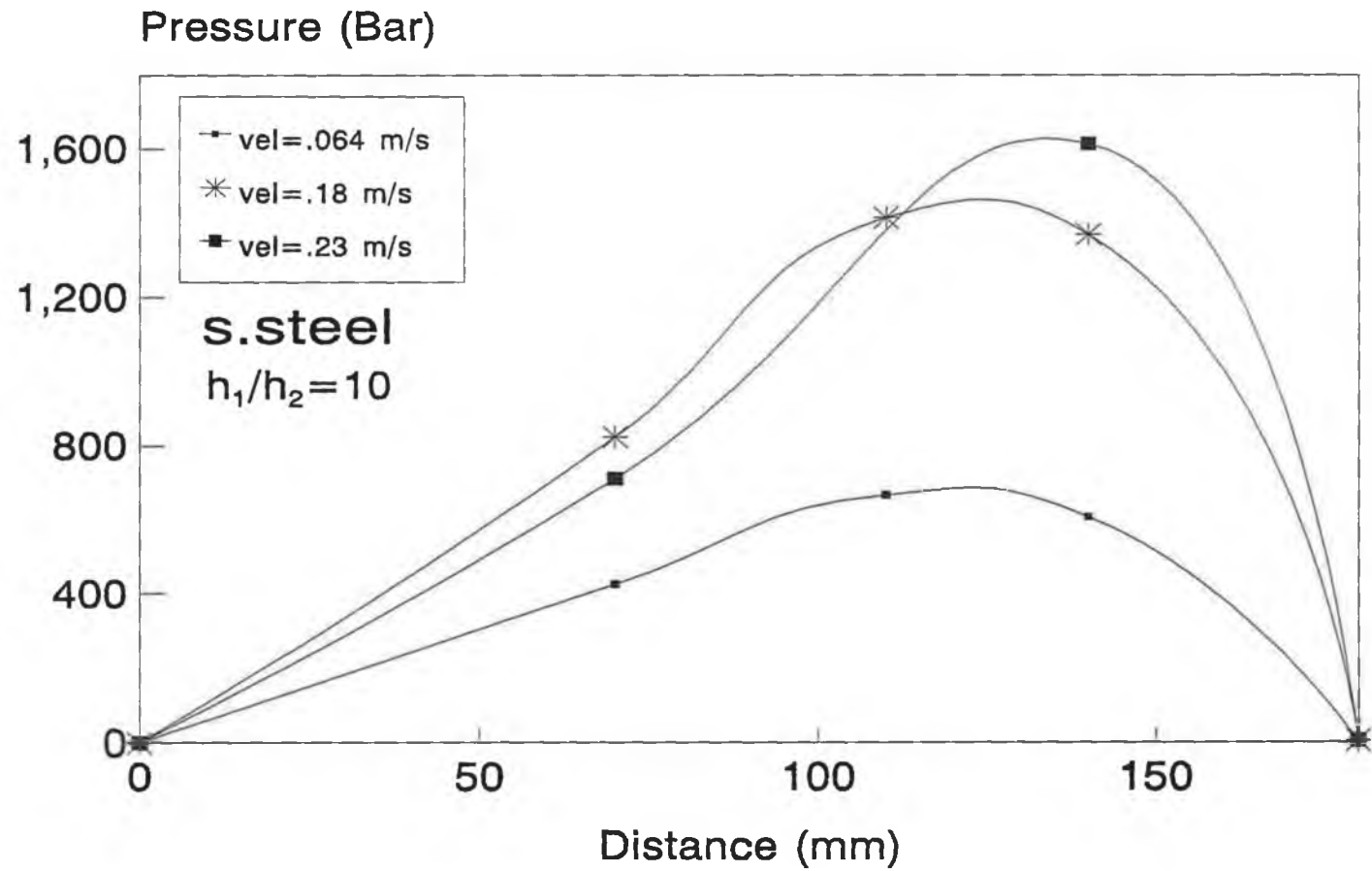


Fig. 5.12(a) Effect of drawing speed on pressure distribution

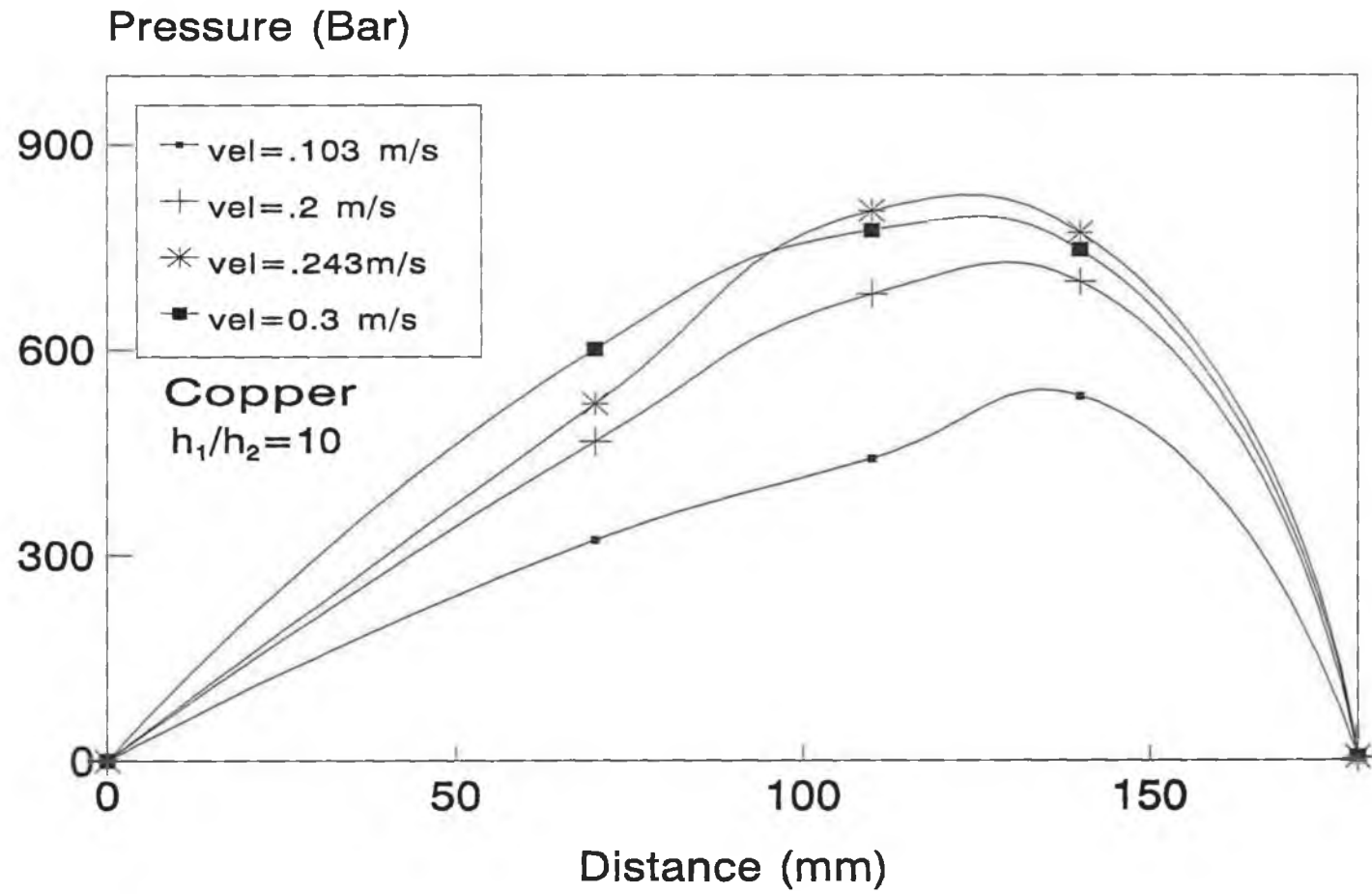


Fig. 5.12(b) Effect of drawing speed on pressure distribution

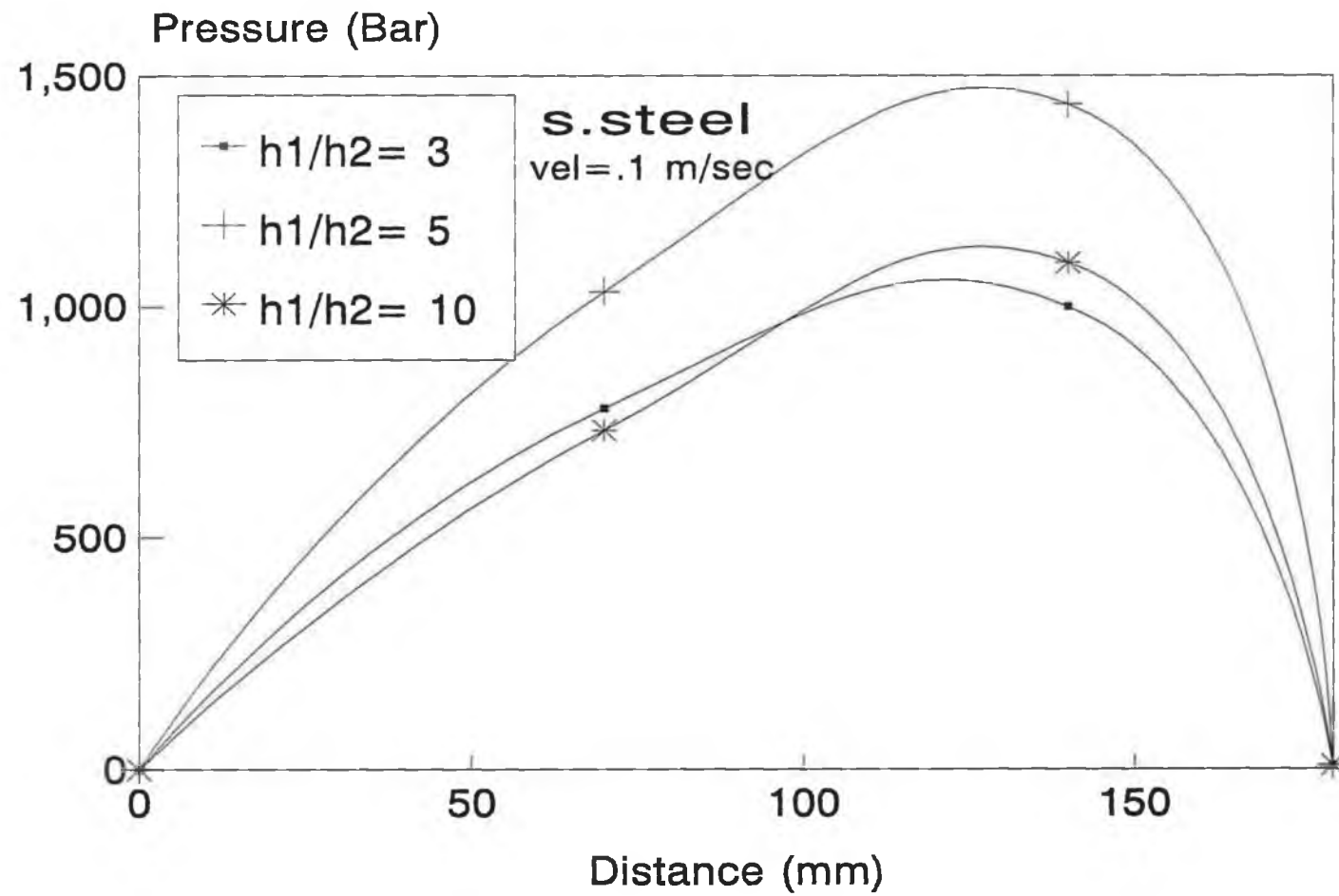


Fig. 5.13(a) Effect of gap ratio on pressure distribution

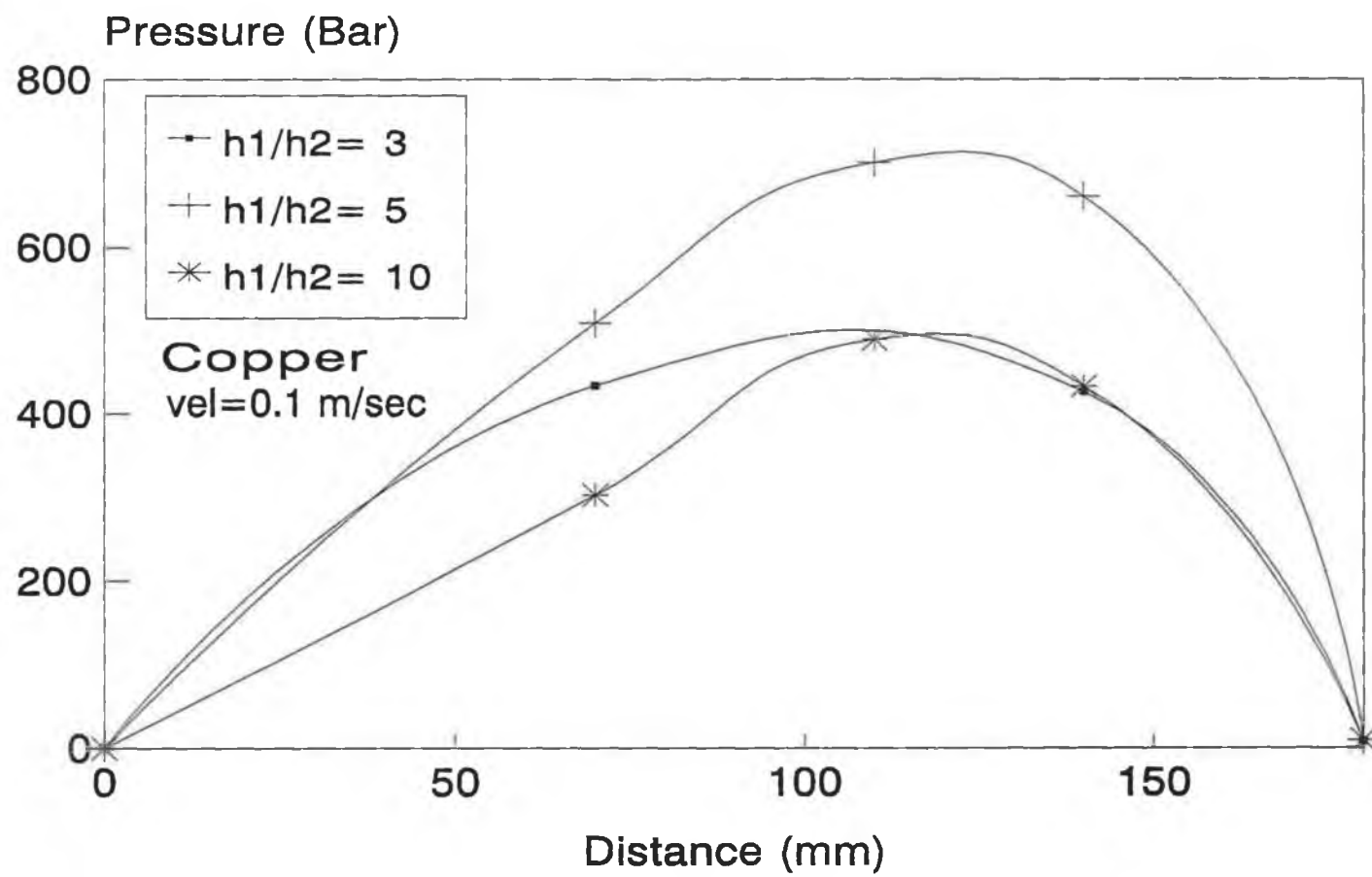


Fig. 5.13(b) Effect of gap ratio on pressure distribution

5.2.3- *Maximum Pressure*

In order to determine the optimum condition for which the magnitude of maximum pressure is predicted to be the largest, experimental data were obtained for different h_1/h_2 ratio while keeping $h_2=0.05$ mm constant.

Figures 5.14(a) and 5.14(b) demonstrates the effect of varying h_1 on the maximum pressure for a range of drawing speeds when drawing stainless steel and copper wires respectively.

Figure 5.14(a) shows that for a gap ratio of 5 the magnitude of the maximum pressure was generally greater for all drawing speeds and that as the this gap ratio is either decreased or increased, maximum pressure of reduced magnitudes was obtained. In Figure 5.12(b) the same trends as to those in Figure 5.12(a) could be observed.

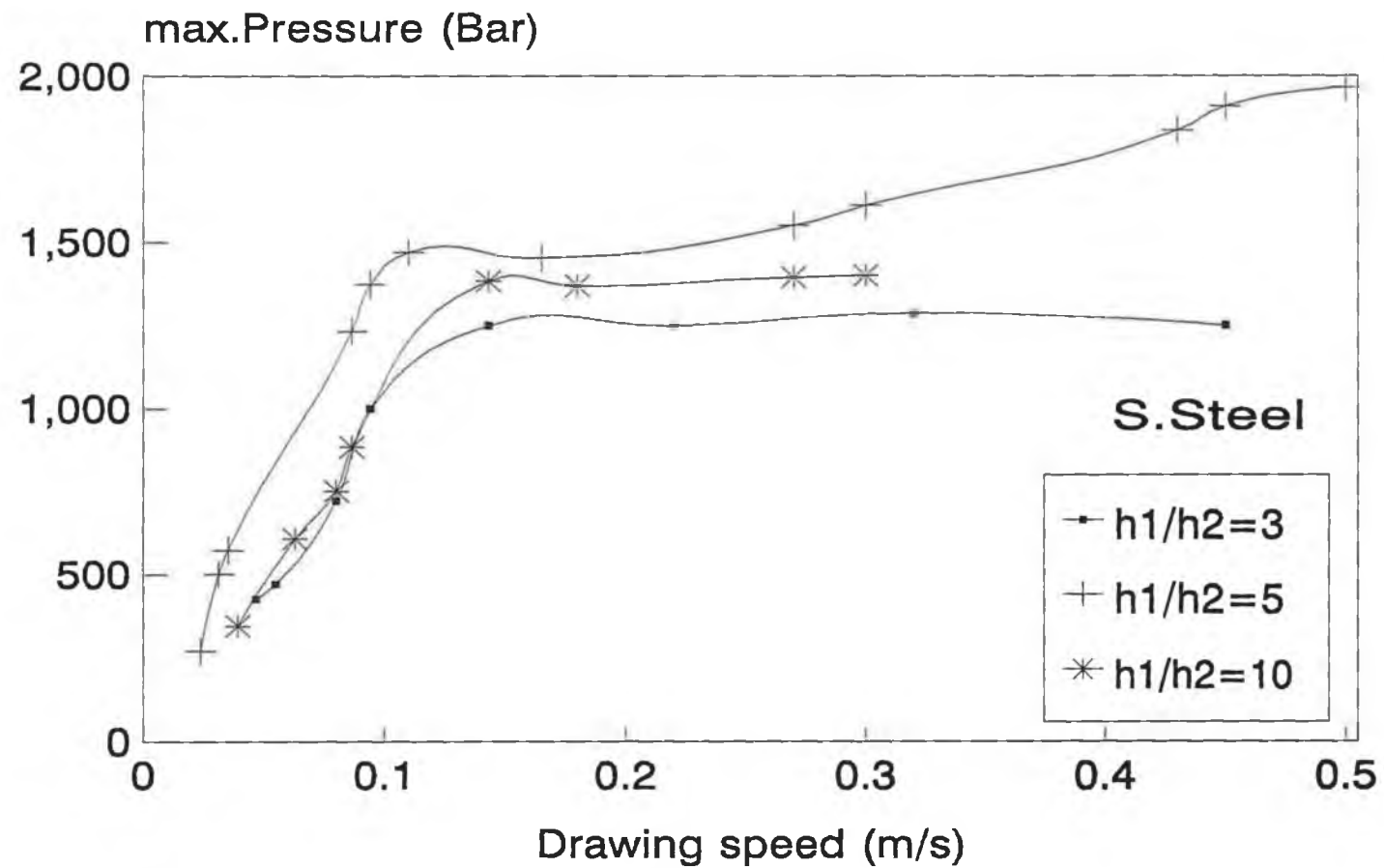


Fig. 5.14(a) Effect of gap ratio on maximum pressure for different drawing speed

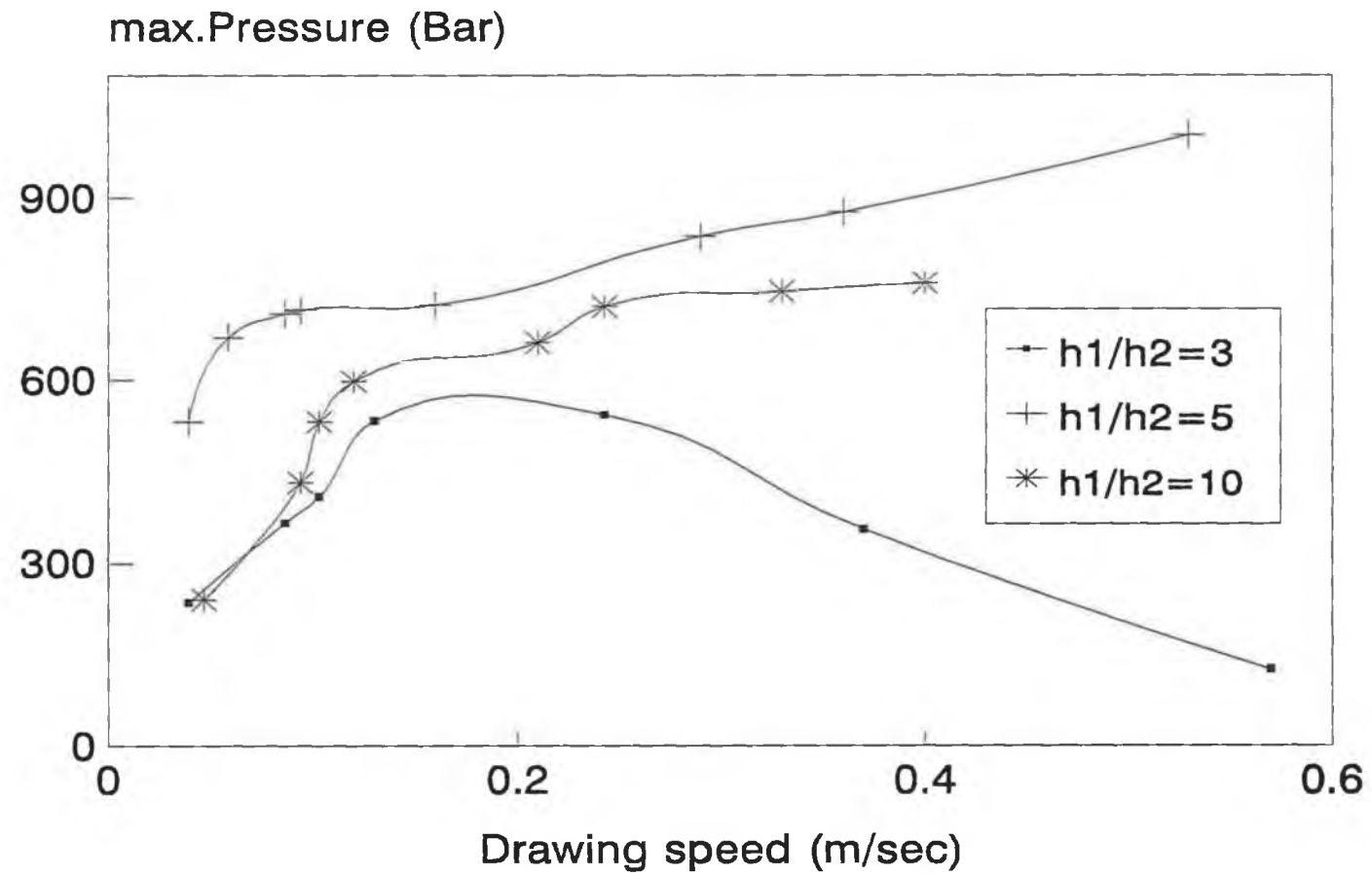


Fig. 5.14(b) Effect of gap ratio on maximum pressure for different drawing speed

5.2.4- Drawing force

Experimental results were also obtained in terms of the drawing load for different gap ratios and drawing speeds. Figures 5.15(a) to 5.15(c) demonstrate the effect of the drawing speed for both stainless steel and copper wires for gap ratios of 3, 5, 10 respectively.

Figure 5.15(a) shows the effect of drawing speed on the drawing force for a gap ratio of 3 in which a higher drawing force was obtained for drawing stainless steel wire than that using copper wire, and this may be due to the plastic deformation in the copper wire which results in higher gap between the wire and the unit which reduces the pressure generated and drawing force. Similar trends for drawing force could be seen in Figures 5.15(b) and 5.15(c) for gap ratios of 5 and 10 respectively.

To determine the gap ratios for which the magnitude of the drawing force is optimum, the combination of the gap ratio effect on drawing force for both the stainless steel and the copper wires were represented in Figures 5.16(a) and 5.16(b) respectively.

In Figure 5.16(a) drawing stainless steel wire, it is shown that for h_1/h_2 ratio of 3 the drawing force was generally greater for all drawing speeds and that as this gap ratio increased drawing force of reduced magnitudes are obtained. In Figure 5.16(b) similar trend is obtained when drawing a copper wire. Both these figures suggest that a generally higher magnitude of drawing load is obtained with lower gap ratios.

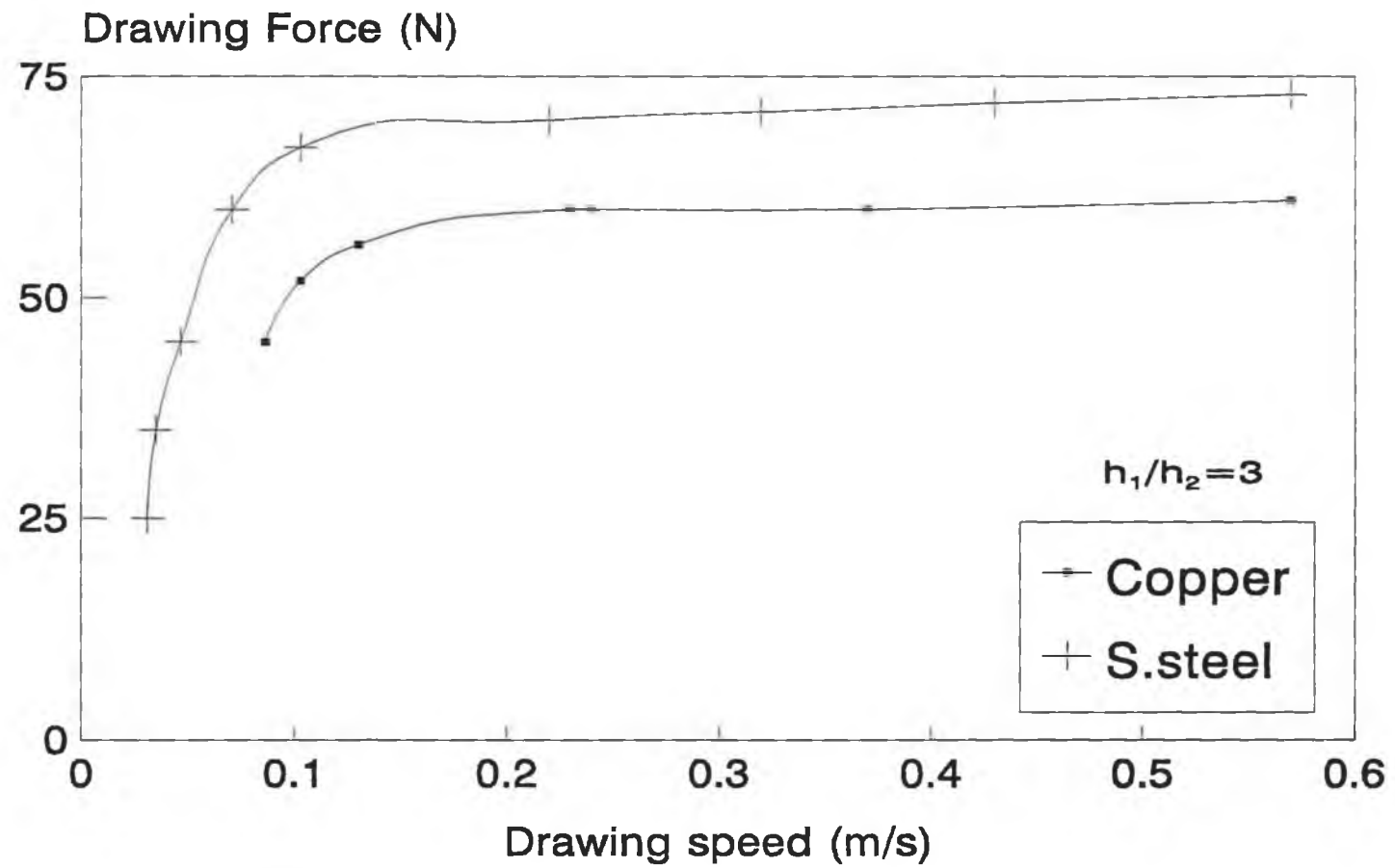


Fig. 5.15(a) Effect of drawing speed on drawing force at constant gap ratio

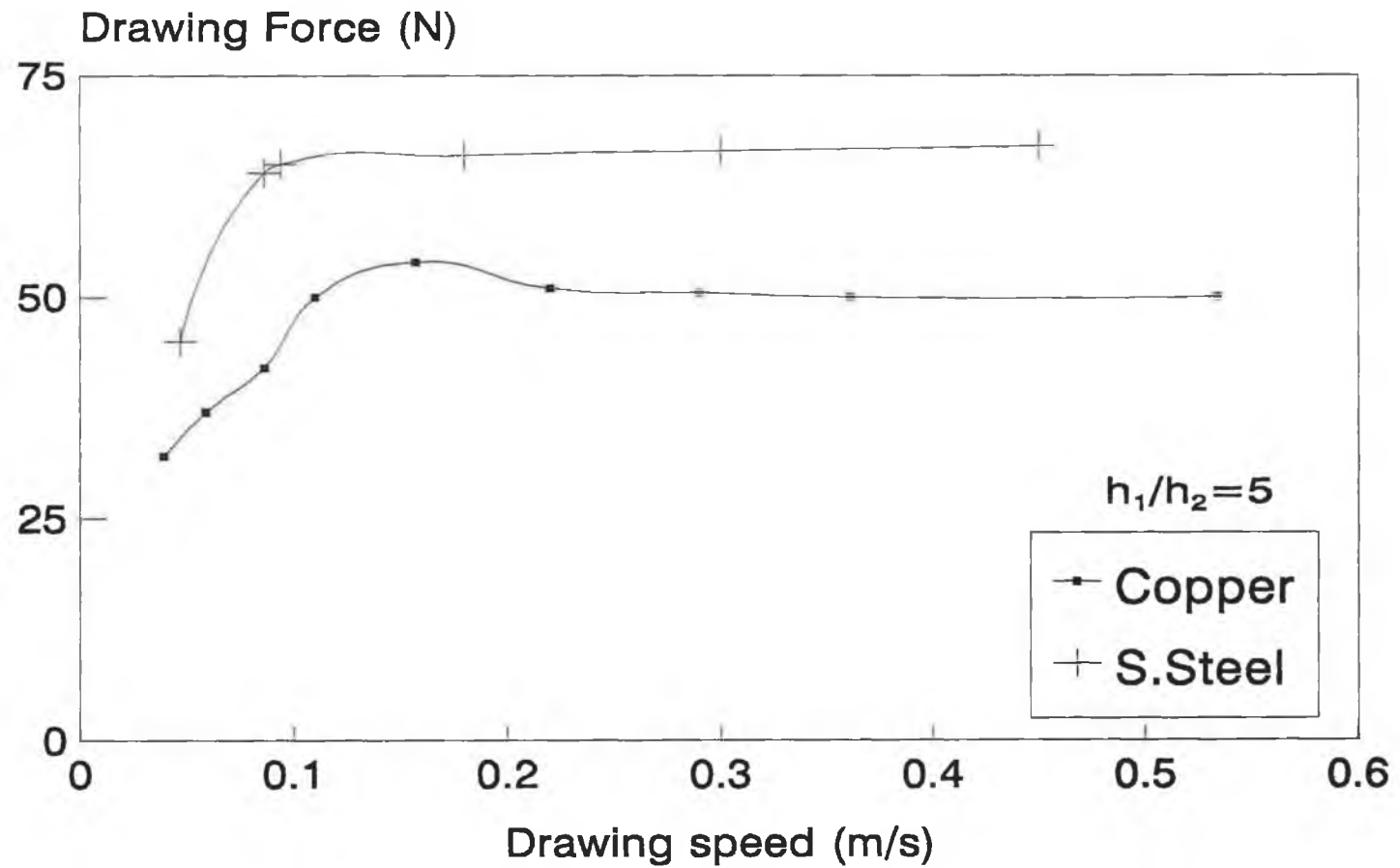


Fig. 5.15(b) Effect of drawing speed on drawing force at constant gap ratio

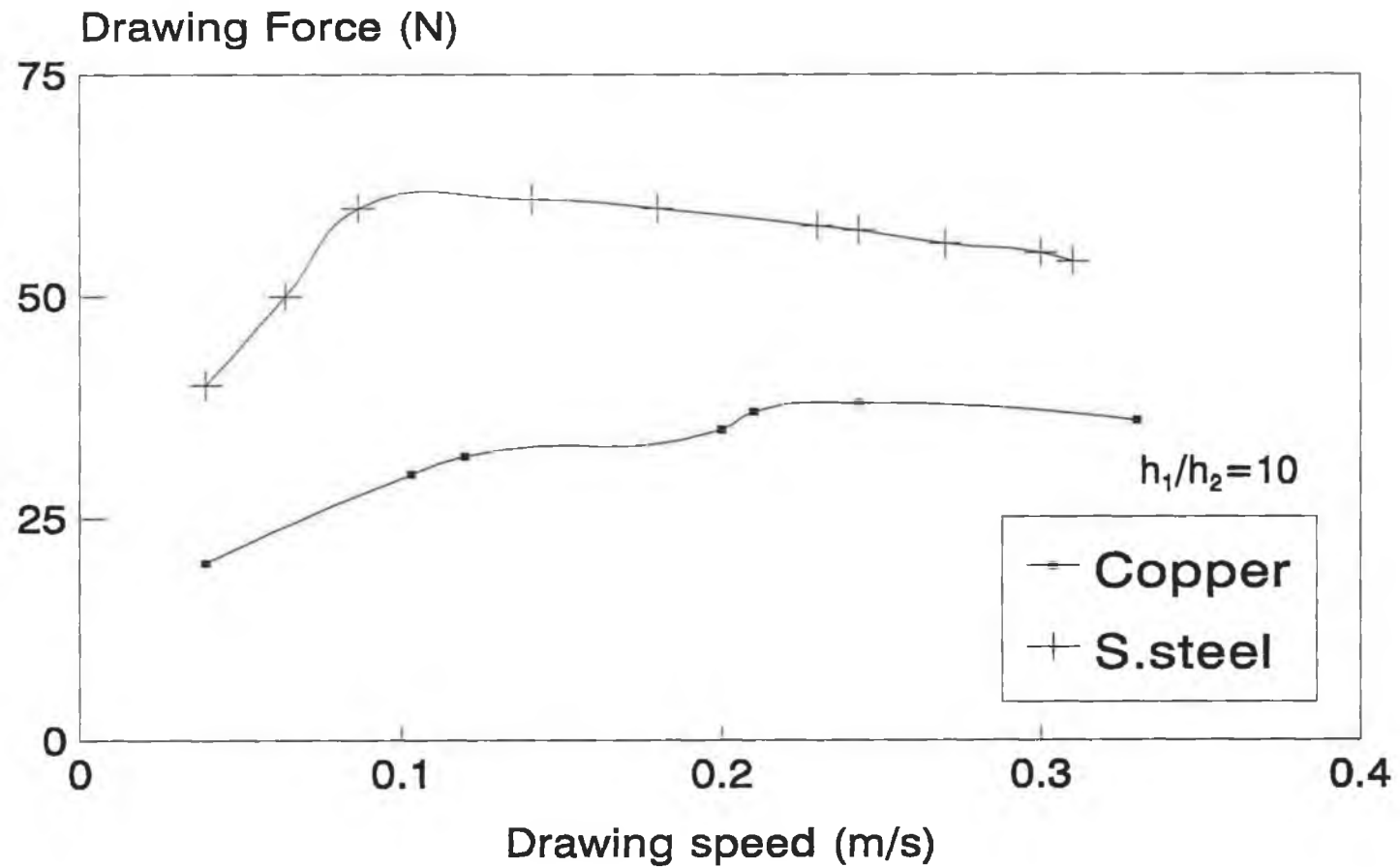


Fig. 5.15(c) Effect of drawing speed on drawing force at constant gap ratio

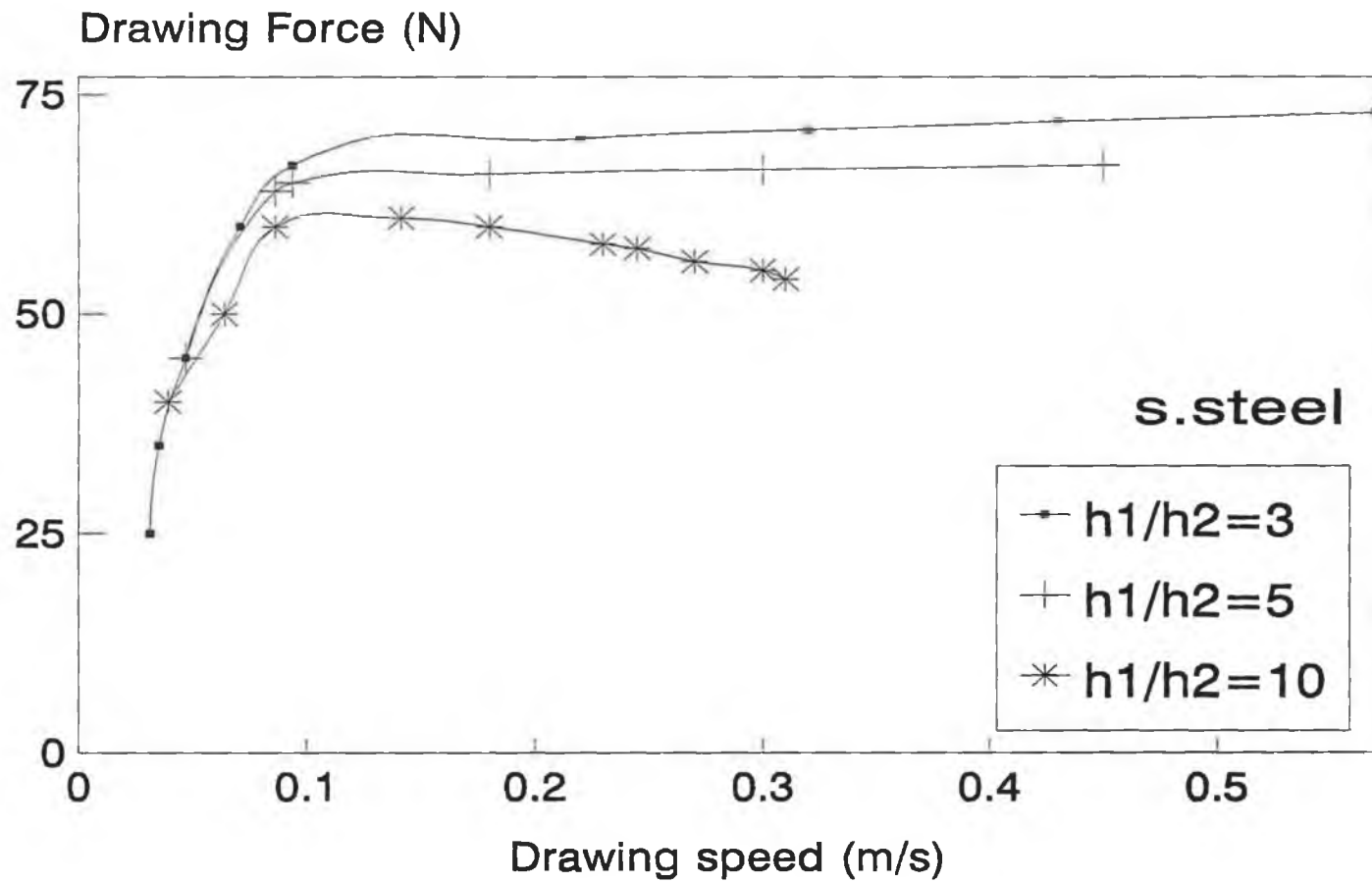


Fig. 5.16(a) Effect of drawing speed on drawing force for different gap ratios

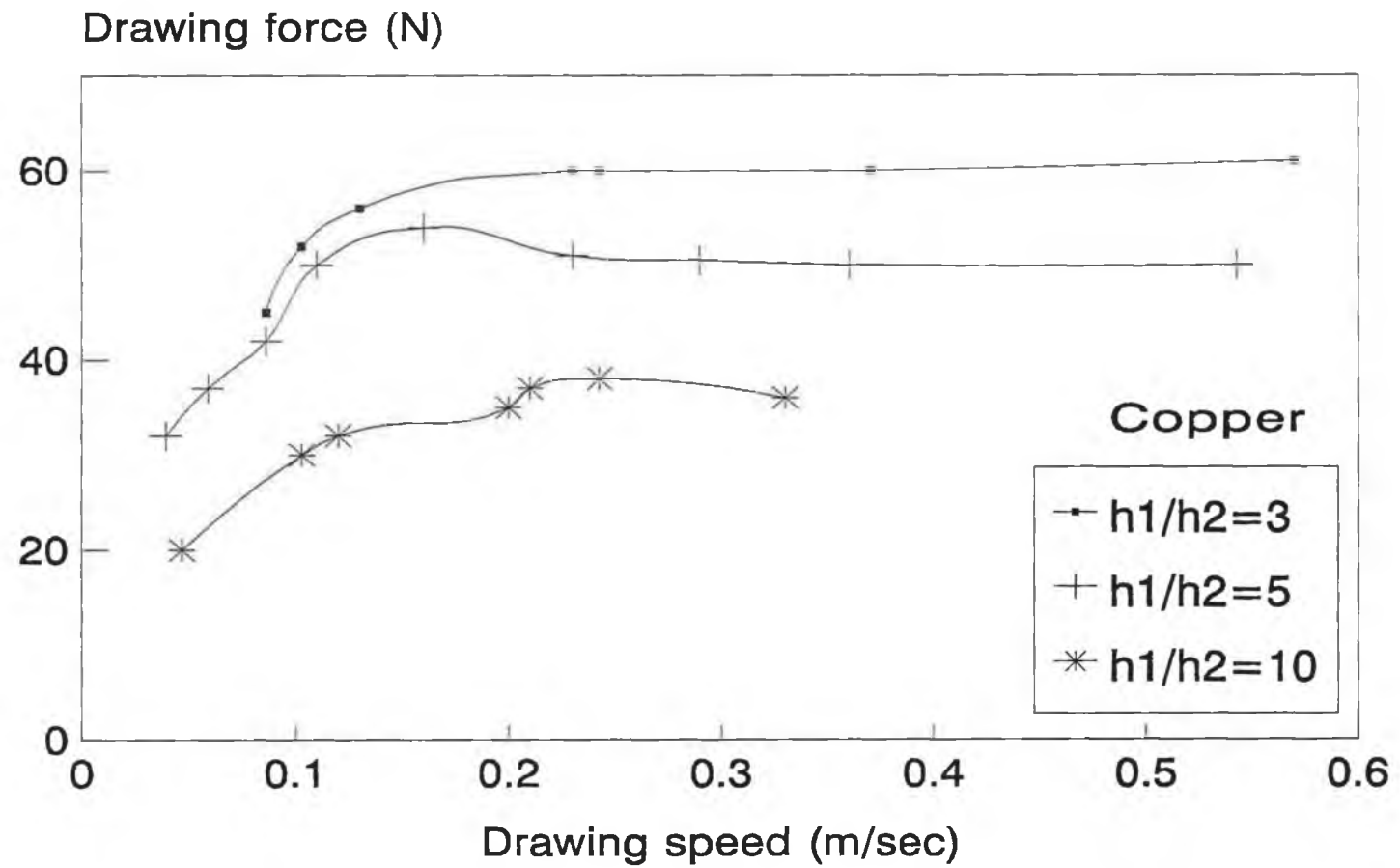


Fig. 5.16(b) Effect of drawing speed on drawing force at different gap ratios

CHAPTER- SIX

DISCUSSION

6.1- Introduction

A complex geometry (consists of combined parallel and tapered bores) and a simple tapered pressure units have been investigated in which borosiloxane melt is used in order to generate hydro-dynamic pressure within the pressure unit. To investigate the performance of the pressure units, an extensive experimental and theoretical programme was conducted during which a considerable amount of data were obtained. This chapter is aimed to highlight the important results obtained experimentally and theoretically and to carry out a comparison of typical results.

6.2- Discussion on test procedure and experimental work

A number of interesting results have been observed while carrying out the experimental tests, using both the pressure units and borosiloxane as the pressure medium. During the course of the experimental programme, parameters such as the gap ratios, drawing speed and the wire material were varied in order to investigate their effect on the performance of the pressure units. The length and the length ratio of the units were kept constant throughout the tests.

The temperature was kept constant at 110 °C with a margin of error of ± 5 °C.

Pressure transducers were located at four places on the pressure unit in order to determine the pressure distribution along the pressure unit.

6.3- Discussion on the analysis and the theoretical results

A model has been developed based on the assumption that the pressure medium

demonstrates non-Newtonian characteristics. The following assumptions were made in order to simplify the analysis.

(1) The flow of fluid medium in the pressure unit is laminar. This seems to be a reasonable assumption since the drawing speeds of the wire are low, viscosity of the pressure medium is higher and the gaps are small.

(2) The flow of the fluid pressure medium is axial. Once flow through the pressure unit has commenced, little or no back flow is expected. This assumption allowed one dimensional flow to be considered.

(3) The thickness of the fluid layer is small compared to the dimensions of the pressure unit. This assumption enabled the analysis to be conducted in cartesian rather than cylindrical coordinates.

(4) The pressure in the fluid medium is uniform in the thickness direction. This assumption simplified calculation of the pressure in the pressure unit.

(5) The process is isothermal. This assumption may introduce some error in the results since it's known that the temperature of the wire increases during the drawing process due to plastic deformation (if any) and underlayer shearing of the fluid.

(6) The shear stress was assumed to be constant for a given drawing speed. This assumption may introduce some error in the results because of the shape of the internal geometry of the pressure unit.

In addition to the above, the following assumptions was made.

(7) Viscosity and pressure coefficients were taken from reference [61], in which the polymer used is a similar one. However, there could some difference in the properties which may produce some error in the theoretical results.

(8) The length of the parallel part of the unit is almost four times the length of the tapered

part and the gap h_1 is greater than h_2 and h_3 , whereas, h_2 and h_3 were used to determine the shear rate and this may introduce some error to the theoretical results.

(9) The viscosity was determined from results reported in reference [81] which were obtained under pressures and shear rates which are different from those applicable in the present study. This could introduce some error in calculations.

6.4- Comparison between the experimental and theoretical results

In the previous two chapters theoretical and experimental results have been presented and some discrepancies were evident between the theory and experiment. In the following sections, it is aimed to point out these discrepancies and discuss the possible causes of such discrepancies.

It is clear that the predictions based on the Newtonian characteristics are considerably lower in magnitudes compared to the experimental results especially at a low drawing speed. The predicted results from the non-Newtonian analysis however is reasonably close to the experimental results both in magnitude and trend.

The reason for such considerable discrepancies between the predicted results based on Newtonian analysis is due to the fact that the pressure medium used didn't behave anything like a Newtonian fluid.

Thus, whilst these results are quite useful for understanding the mechanics of the process, they are unsatisfactory for predicting results when the fluid demonstrates non-Newtonian characteristics.

The discrepancy which is still present between the theory and the experiment even with non-Newtonian approach is possibly due to the difference in ascertaining the viscosity and shear rate relationship of the pressure medium and also due to the fact that the analysis does not take account of any variation from the assumed iso-thermal and laminar flow conditions

during the process.

The effect of other variables (non-Newtonian factor, viscosity and pressure coefficients) were also examined theoretically in order to investigate their influence on the predicted results.

It is thought that error could have arisen from the viscosity constant "a" and "b" in the viscosity equation. A large change in "a" was found necessary for a reasonable change in the theoretical results; the overall trends remaining more or less the same as before.

Increase in the pressure coefficient of viscosity "b" increased the overall results. It is believed that μ_0 and the non-Newtonian factor may contribute to the error. The shear rate effect on reducing the discrepancy between the theoretical and the experimental results was established and comparison between the experimental and the theoretical results is given.

Parameters representing the flow stress of the wire material (Y_0 , K_0 and n) were determined experimentally and it is believed that they contained very little error.

6.4.1- Combined geometry pressure unit

Figures 6.1(a) to (d) show typical experimental results of the pressure distribution and theoretical results based on Newtonian⁴ and non-Newtonian analysis under similar conditions.

Different combinations of gap ratios were used in order to compare the results. Results for both copper and stainless steel wires were plotted for comparison with the theoretical results obtained from the Newtonian and the non-Newtonian solutions. The main observation which is made from these figures is that the theoretically predicted results are considerably lower than those obtained experimentally. The trend for both the theory and experiment is very similar and the predictions according to the Newtonian and non-Newtonian solutions are

⁴ The Newtonian predictions were calculated based on the analysis developed in ref.[73]

close.

Figures 6.2(a) to (d) show a comparison between the maximum pressure obtained experimentally to those obtained theoretically. Again, the experimental maximum pressure are much higher than those predicted theoretically. One of the reasons for such discrepancy could be that the viscosity values of the polymer used to calculate the theoretical results could be significantly different from the actual ones. The values used in this study were obtained from reference [81] which were determined under different shear rate and pressure conditions.

But the principal reason for the difference between the theoretical and the experimental results could be the shear rate, which was determined using the gaps h_2 and h_3 as;

$$\dot{\gamma} = \frac{2V}{(h_2 + h_3)}$$

However, h_1 which is the gap thickness approximately 80 percent of the length of the unit will have much more effect on the shear rate. This could be observed in Figure 6.3(a) which shows better agreement between the theoretical and experimental pressure distribution (stainless steel) when the inlet gap was used to determined the shear rate (see Figure 6.1(a) for comparison).

In this Figure the shear rate was calculated using the following equation,

$$\dot{\gamma} = \frac{V}{h_1}$$

for a gap ratio of $h_1/h_2=6.6$ and $h_2/h_3=3$.

The pressure distribution curve according to non-Newtonian solution is now much closer to the experimental pressure distribution curve for stainless steel.

Figure 6.3(b) compares the maximum pressure for stainless steel to the theoretical maximum

pressure, a closer agreement could be observed again using the inlet gap thickness to determine the shear rate compared to Figure 6.2(a). It could be observed that for drawing speed of 0.15 m/sec, a maximum pressure of almost 900 bar is obtained theoretically and experimentally. However, for drawing speeds of less than about 0.14 m/sec and more than about 0.16 m/sec the agreement is not very good.

From Figures 6.1 and 6.2 it is evident that when drawing copper wire the pressures are generally much lower than those for stainless steel. This is due to elastic-plastic deformation which takes place which leads to the increase in the outlet gap thickness h_3 giving lower magnitudes of pressure.

Figure 6.4(a) compares the pressure distribution for copper wire to the theoretical pressure distribution for different outlet gaps. For the outlet gap $h_3=0.1$ mm which is twice the outlet gap without any deformation of the wire, a similar trend as that is obtained for the copper wire and much closer pressure magnitudes are predicted which suggests that elastic-plastic deformation takes place in the copper wire which contributed to the difference between the experimental and the theoretical results for copper wires. This Figure shows better agreement between the pressure distribution trends as compared to those in Figure 6.1(a).

Figure 6.4(b) compares the experimental and theoretical maximum pressures using copper wire. The theoretical maximum pressure was calculated for different outlet gap h_3 in order to verify the reduced magnitudes of the maximum pressure obtained experimentally.

Experimentally it was noticed that deformation was taking place and this would change h_3 which may be the reason for the lower magnitudes of maximum pressure obtained.

Experimental results show that at higher inlet gaps for a given outlet gap lower pressure is generated.

An increase in the inlet gap may cause back flow of the polymer melt which would reduce

pressure.

An increase in the exit gap also leads to reduced pressure, the reason for this is that as the exit gap increases, the flow of the polymer becomes less restricted, hence lower pressures are generated.

An optimum gap ratio is thus present for which a balance is struck between these effects.

The drawing speed was found to be the dominant factor to affect the performance of the pressure unit. This is due to the effect of the shear rate on the viscosity of the polymer.

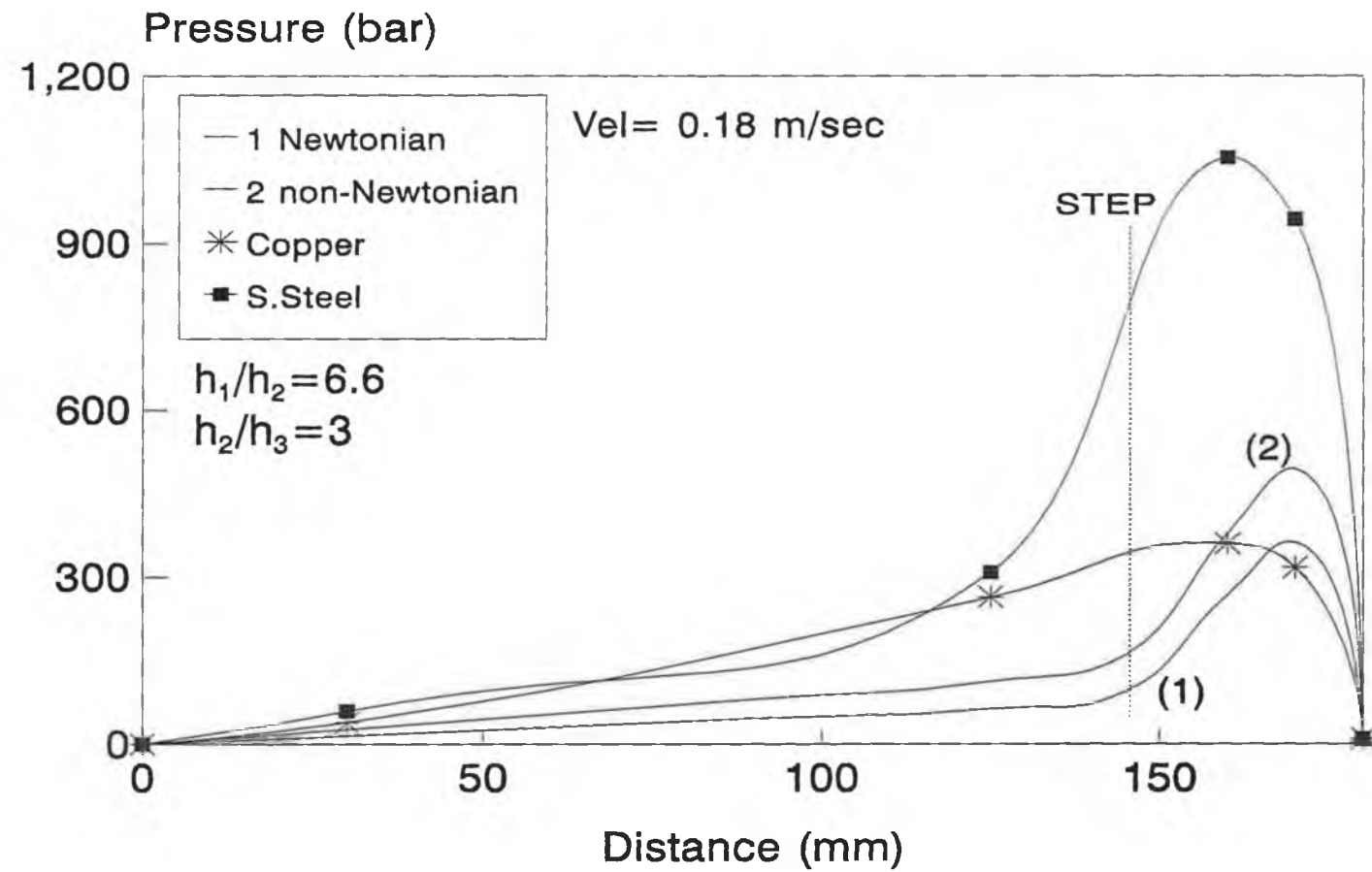


Fig. 6.1(a) Comparison between theoretical and experimental pressure distribution

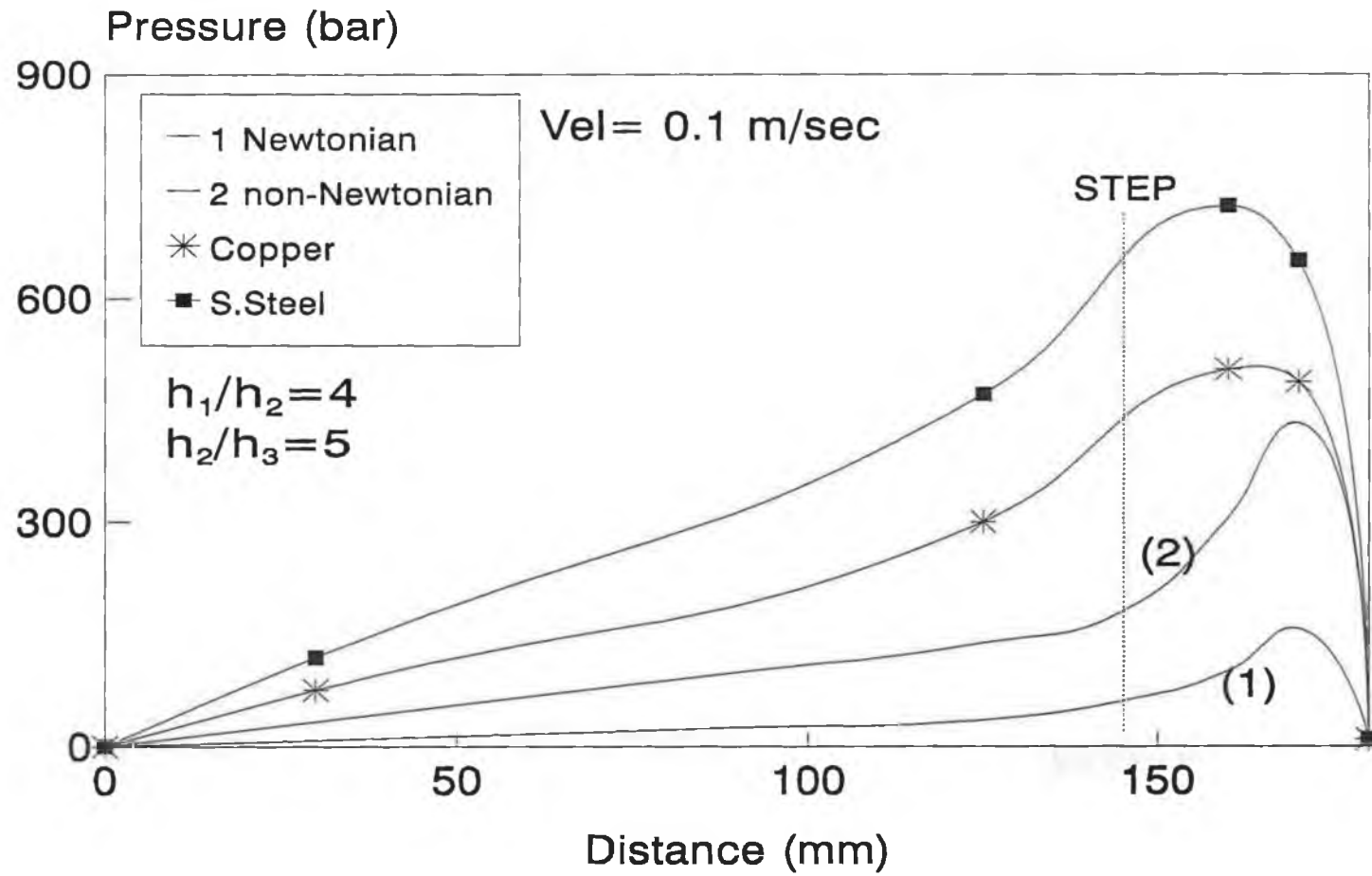


Fig. 6.1(b) Comparison between theoretical and experimental pressure distribution

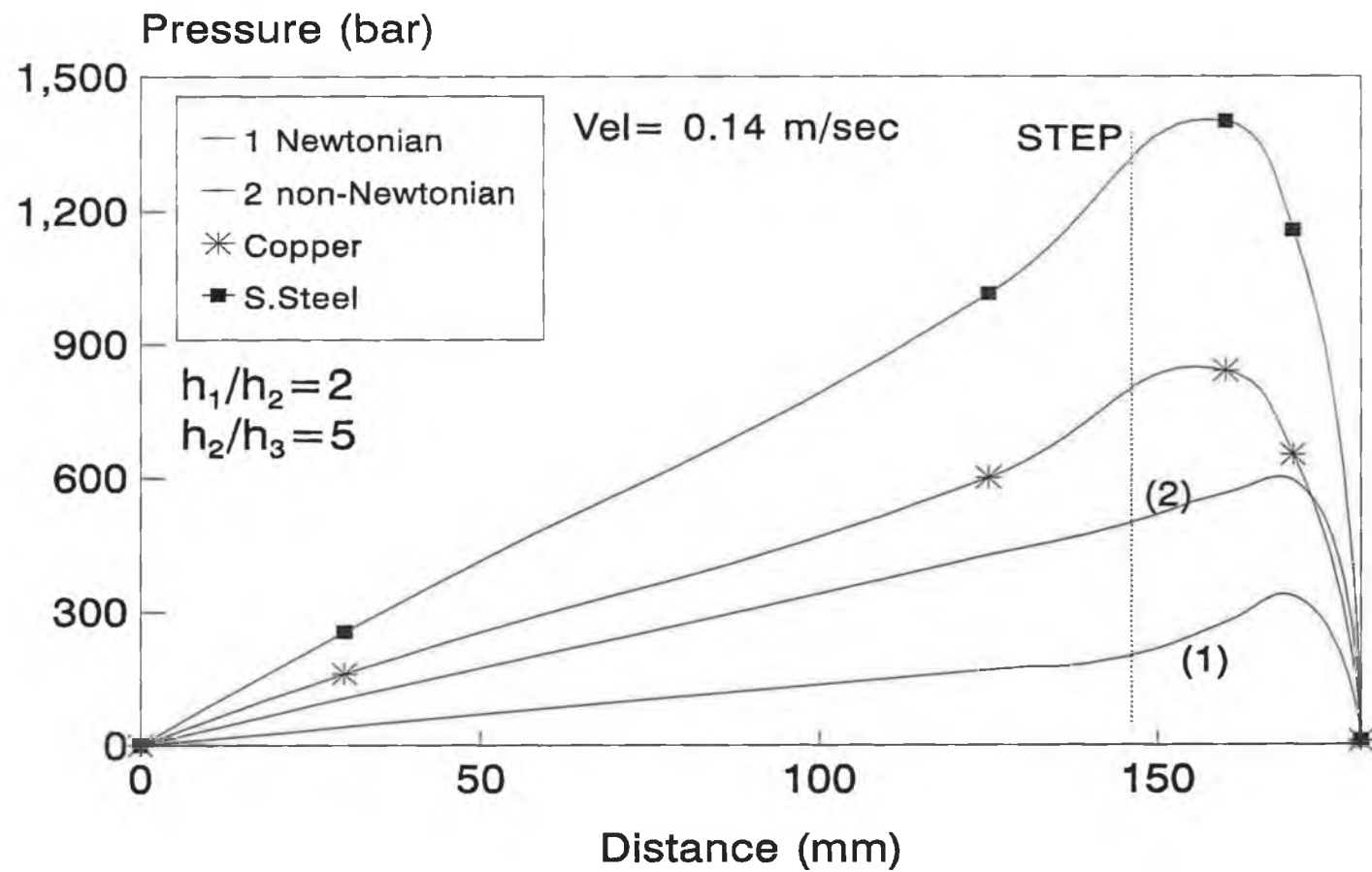


Fig. 6.1(c) Comparison between theoretical and experimental pressure results

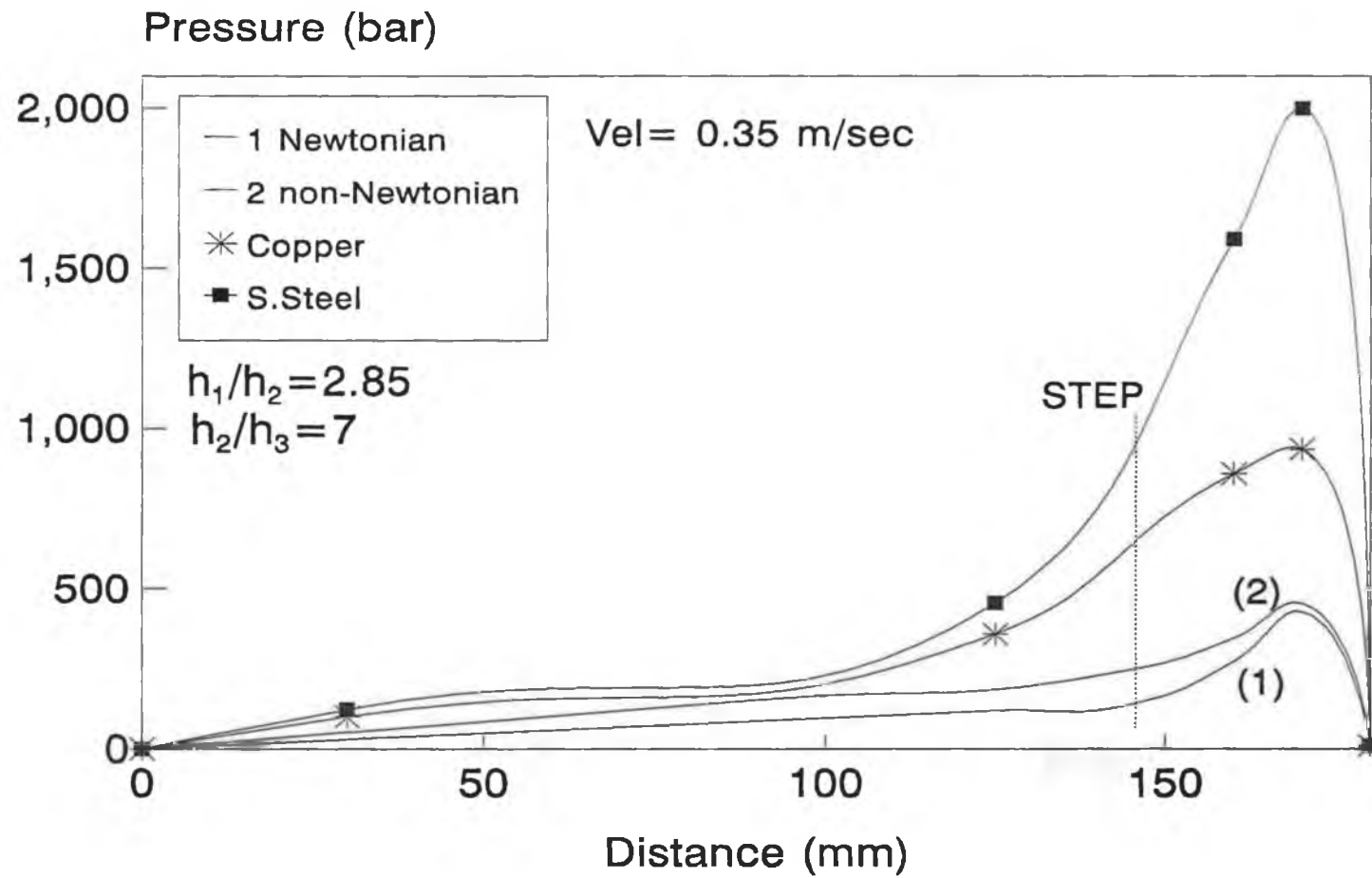


Fig. 6.1(d) Comparison between theoretical and experimental pressure distribution

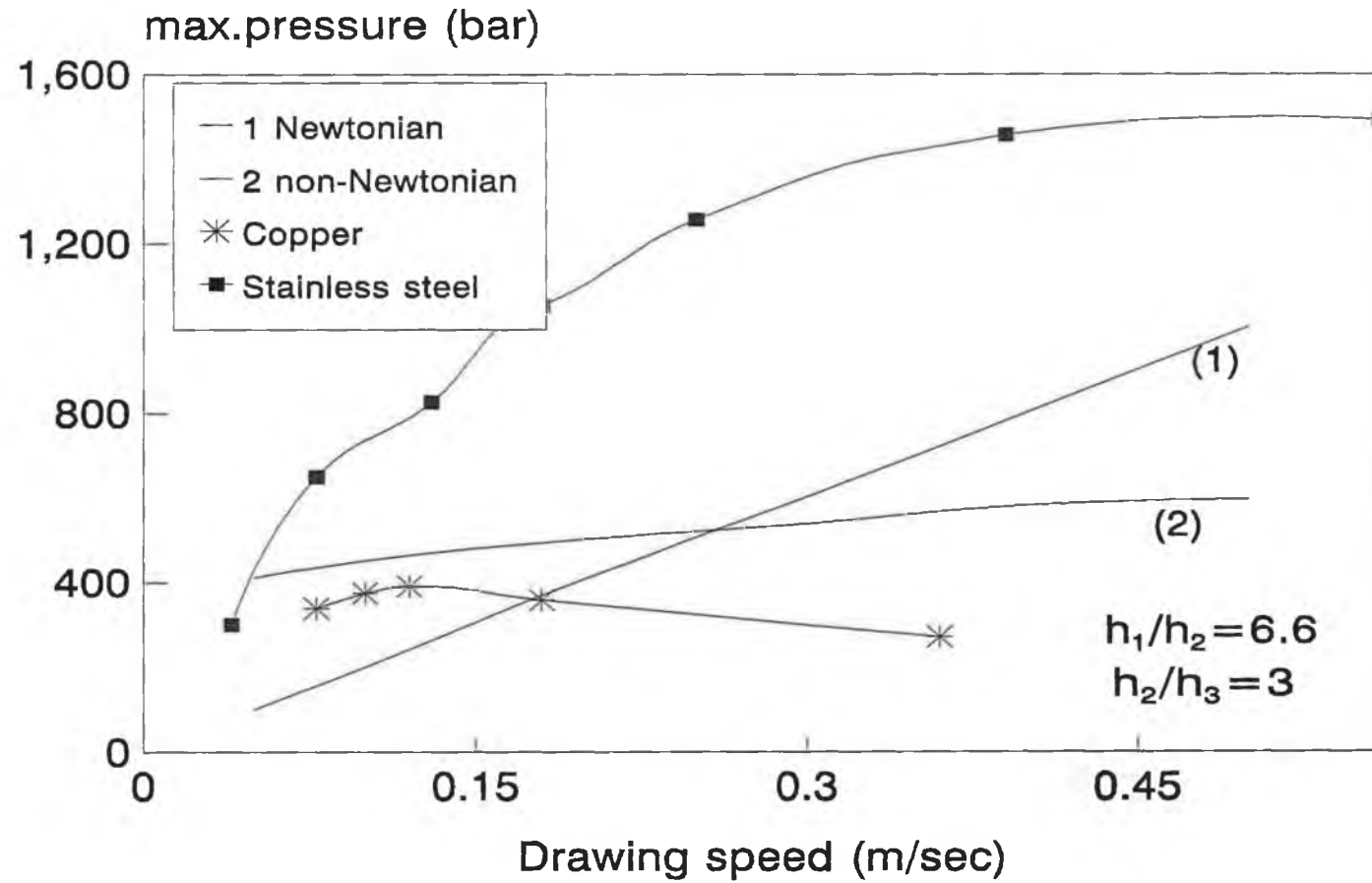


Fig. 6.2(a) Comparison between the experimental and the theoretical maximum pressure

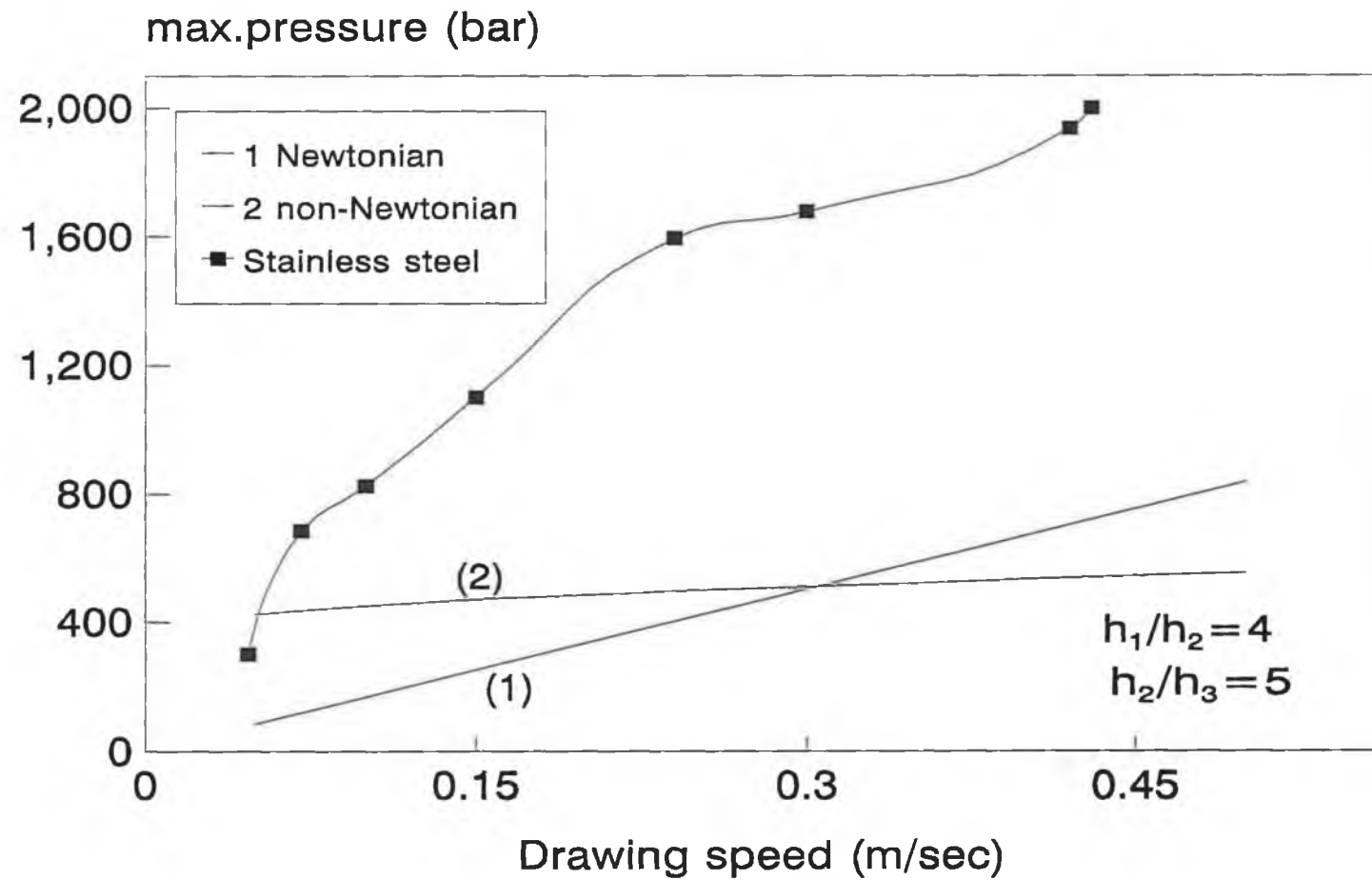


Fig. 6.2 (b) Comparison between the experimental and the theoretical maximum pressure

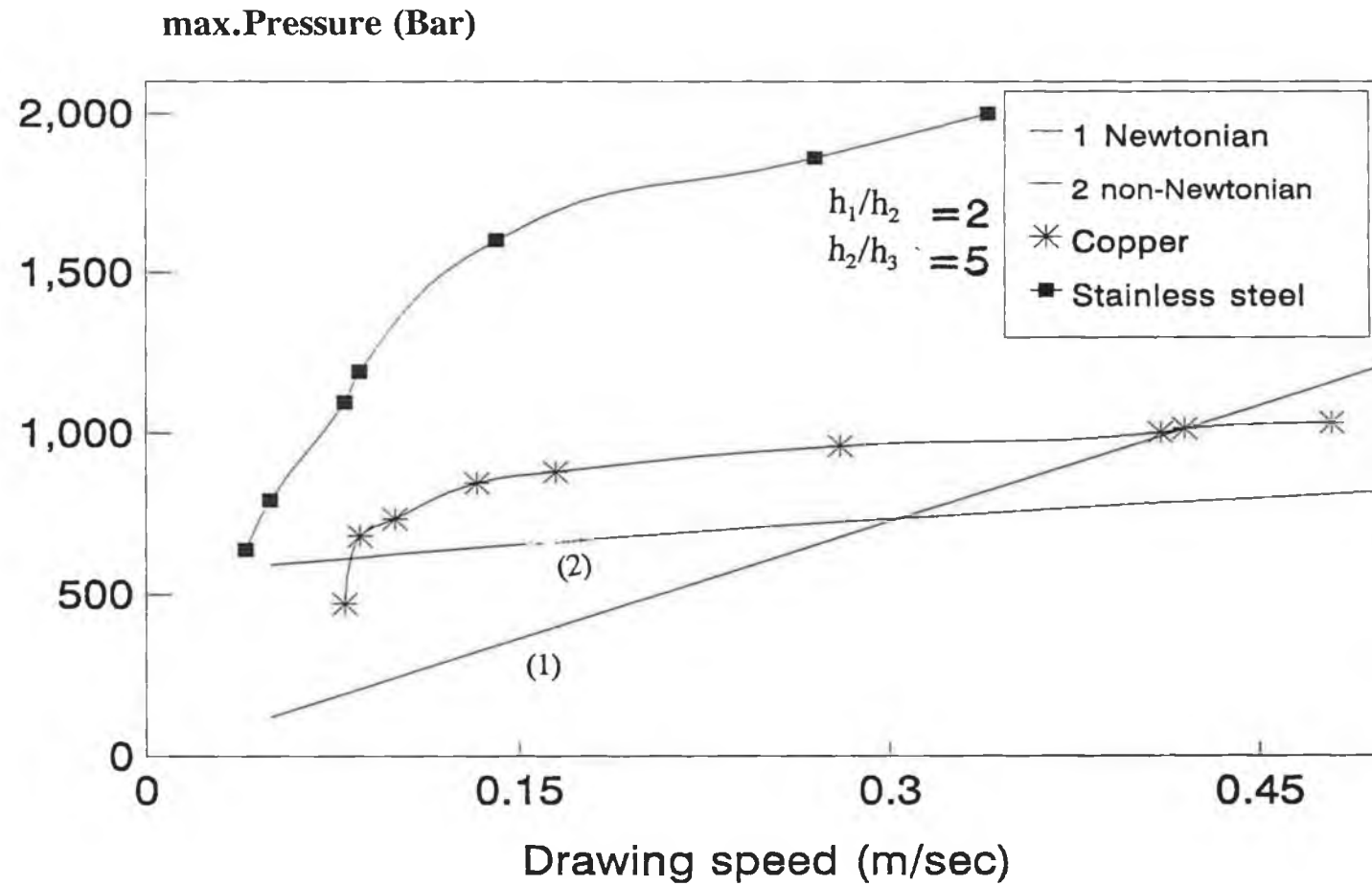


Fig. 6.2(c) Comparison between experimental and theoretical maximum pressure

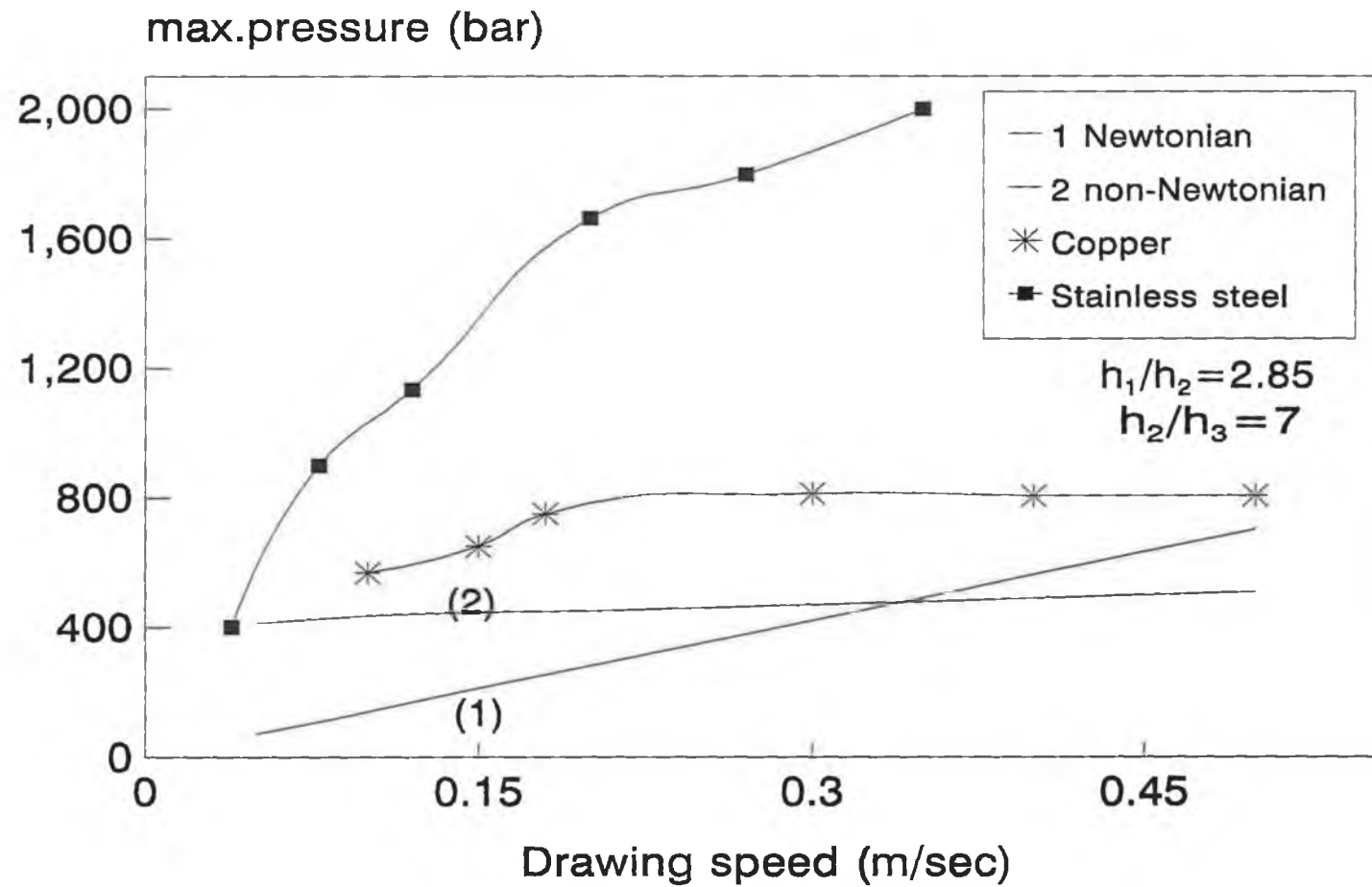


Fig. 6.2 (d) Comparison between the experimental and the theoretical maximum pressure

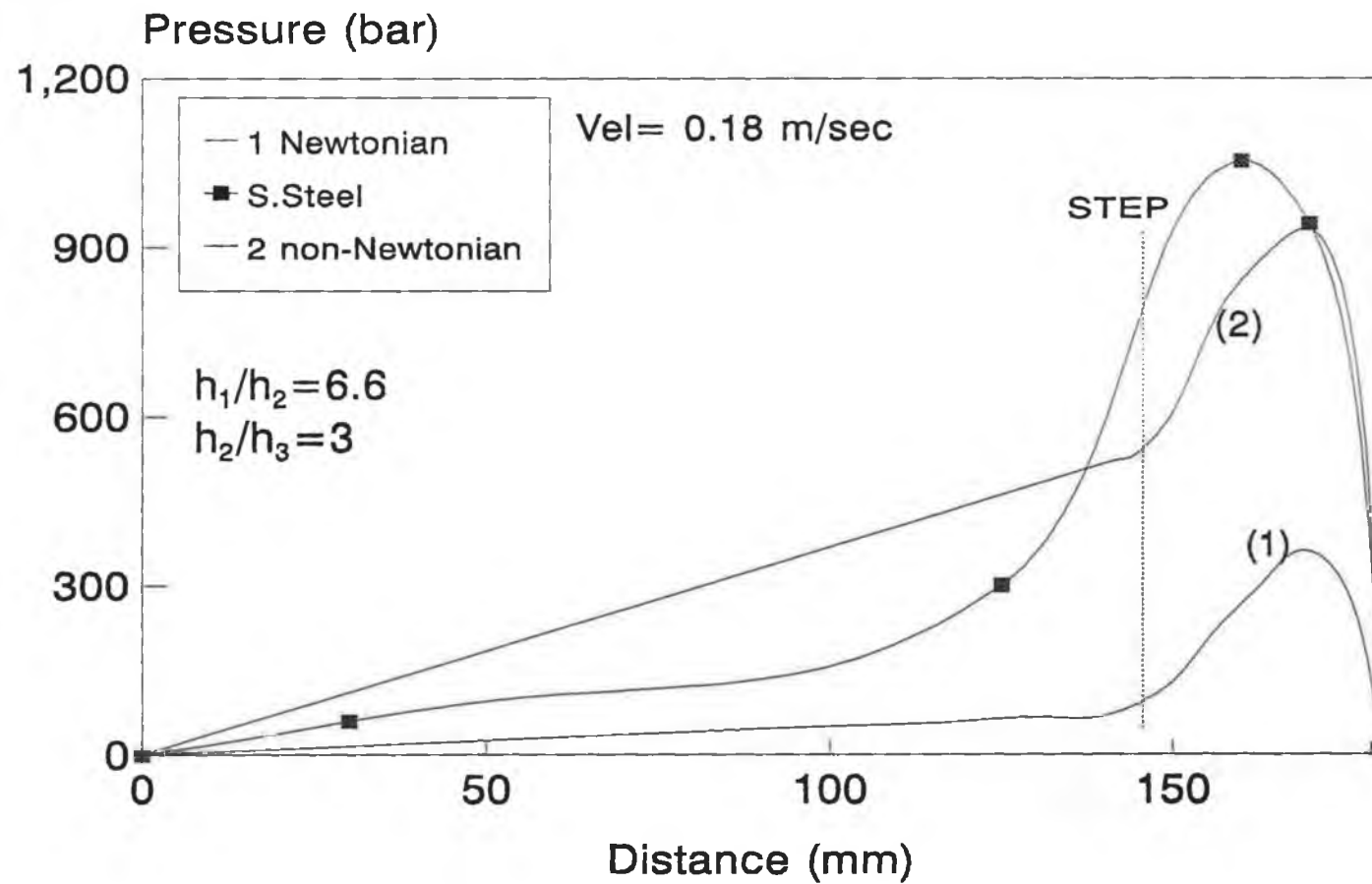


Fig. 6.3(a) Comparison between theoretical and experimental pressure distribution

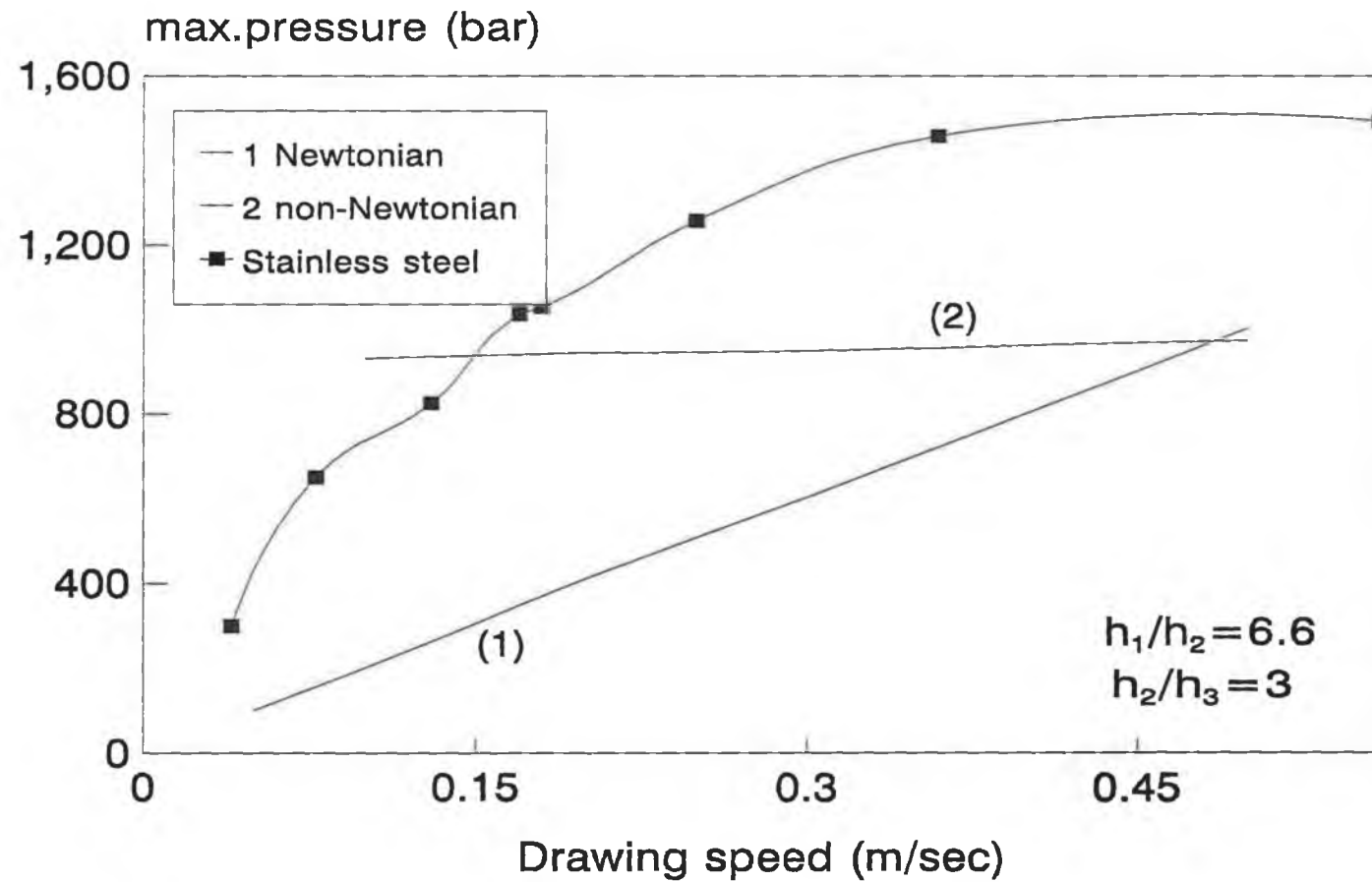


Fig. 6.3(b) Comparison between the experimental and the theoretical maximum pressure

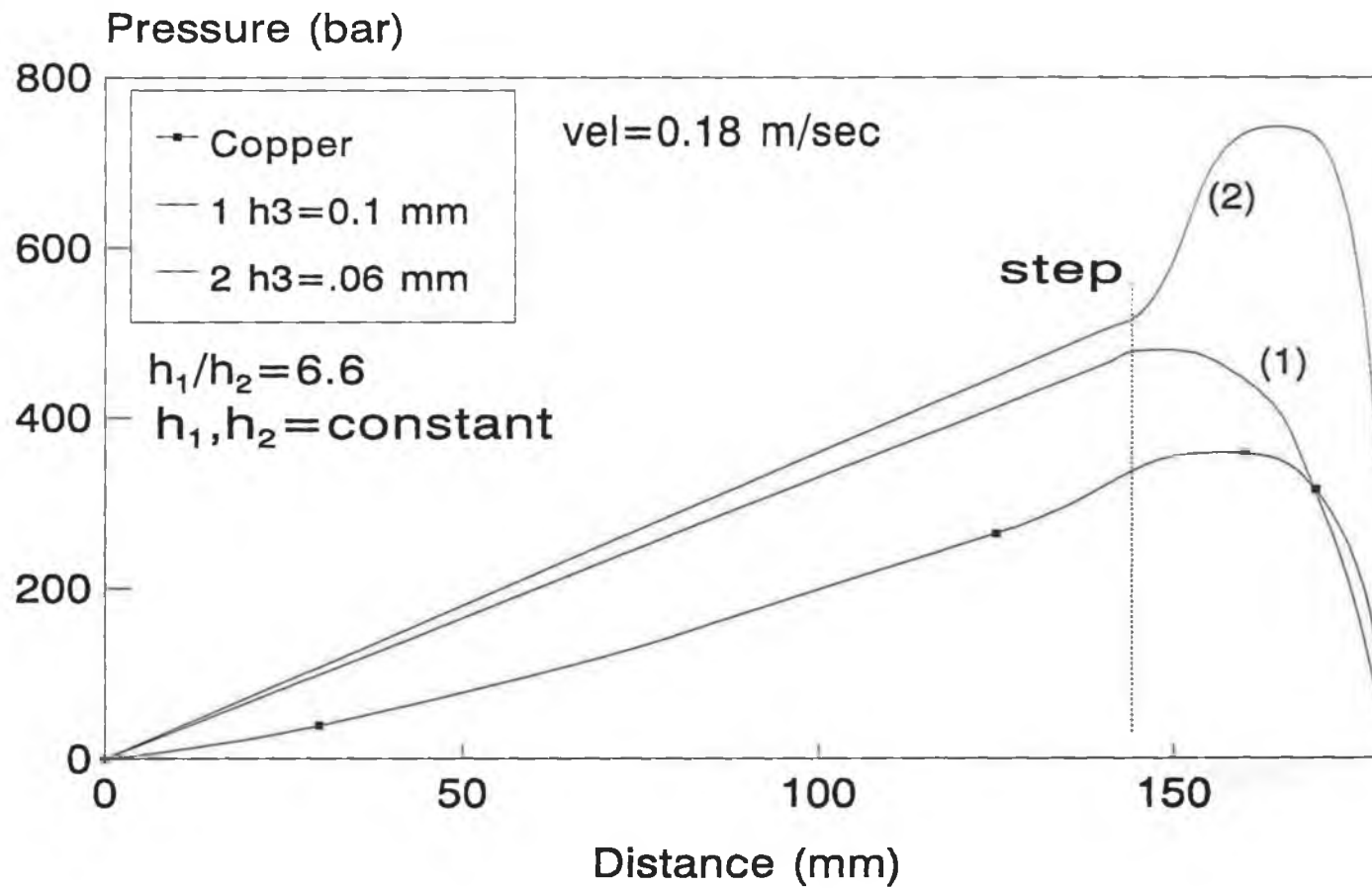


Fig. 6.4(a) Comparison between theoretical and experimental Pressure distribution

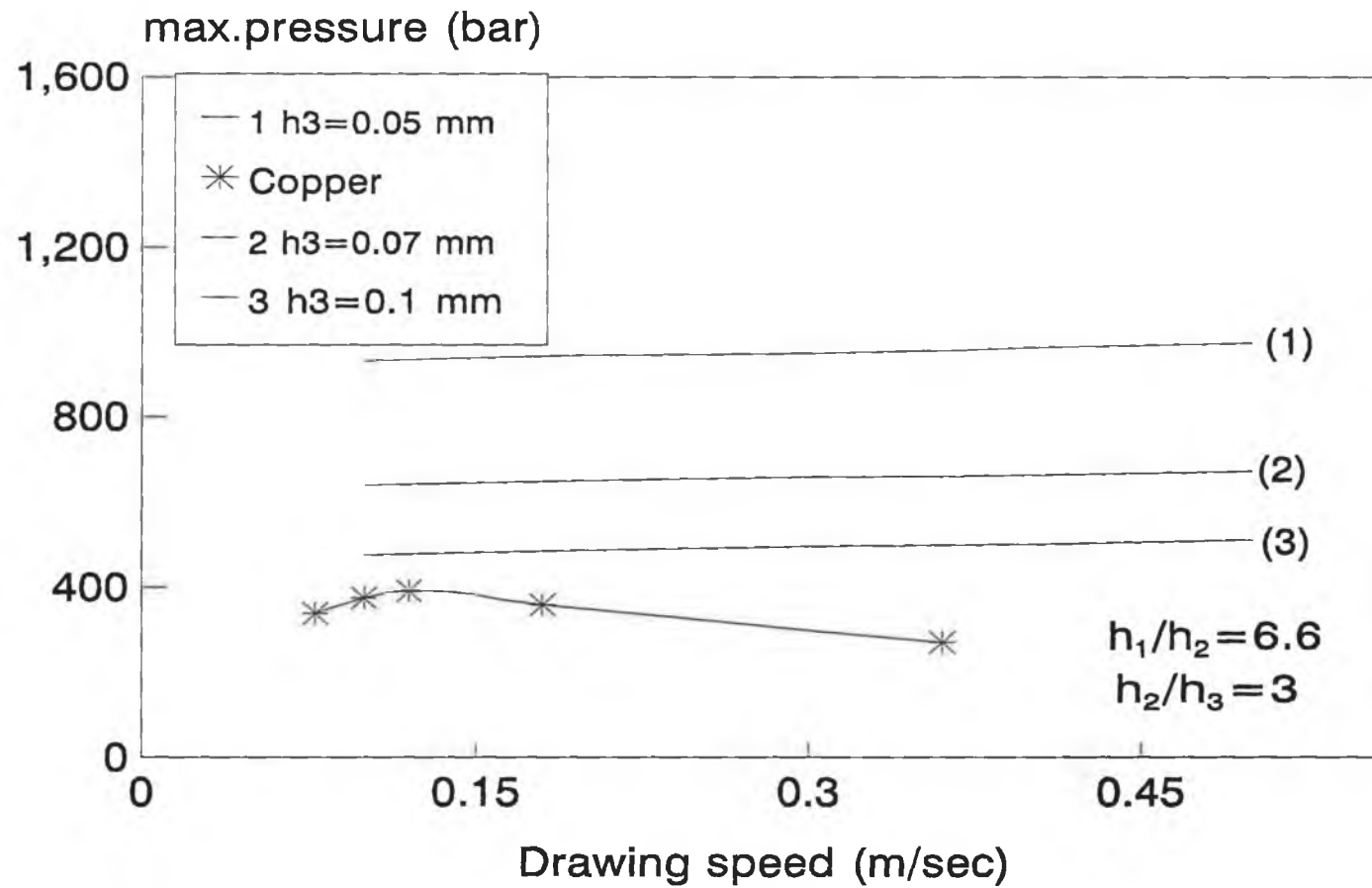


Fig. 6.4(b) Comparison between the experimental and the theoretical maximum pressure

6.4.2- Simple tapered pressure unit

The inlet gap thickness was varied in order to study its effect on the pressure generated within the unit and to compare the experimental and the theoretical results.

Figures 6.5(a) to (c) shows the experimental results of the pressure distribution (using both the copper and the stainless steel wires) and theoretical results based on Newtonian⁵ and non-Newtonian analysis for h_1/h_2 equal to 3, 5 and 10 respectively.

In Figure 6.5(a) for overall gap ratio of $h_1/h_2=3$ and drawing speed of 0.14 m/sec, a close correlation was observed between the trends of the experimental pressure results for stainless steel wires and the theoretical Newtonian and non-Newtonian solutions. A lower pressure could be observed for the copper wire which is due to elastic-plastic deformation which takes place resulting in larger outlet gap.

Figure 6.5(b), for an overall outlet gap of $h_1/h_2=5$, and drawing speed of 0.1 m/sec the non-Newtonian results seem to give better prediction as to the pressure generated compared to the Newtonian results, again lower pressure could be observed for the copper wire.

As the overall gap ratio increases to $h_1/h_2=10$, (Figure 6.5(c)) the non-Newtonian results look better when compared to experimental pressure results. Results obtained from the Newtonian solution shows much lower pressure. The lower experimental pressure for copper is due to plastic deformation in copper.

The difference between the Experimental and the theoretical pressure results becomes bigger as the inlet gap h_1 increases and that may be due to the constant shear rate assumption which seems to produce larger error as the inlet gap increases.

The experimental results of maximum pressure for the copper and stainless steel wires were compared to the theoretical maximum pressure for both the Newtonian and the non-

⁵ The Newtonian predictions were calculated based on the analysis developed in ref.[63]

Newtonian results and could be seen in Figures 6.6(a) to (c).

Figure 6.6(a) shows a close agreement between the Newtonian results and the experimental results for drawing speed up to 0.1 m/sec, while after that the non-Newtonian results gives very close magnitudes of pressure as to those obtained experimentally for stainless steel wires. Which indicates that the non-Newtonian analysis predicts closer results than the Newtonian analysis.

In Figure 6.6(b) for an overall gap ratio of 5 a reasonable agreement between the Newtonian results and the experimental results for drawing speed of about 0.2 m/sec, whereas the closer agreement could be observed for the non-Newtonian results, for speeds ranging from 0.1 to 0.5 m/sec. A much lower pressure could be observed for the copper wire which may be result of the wire deformation during the process.

For a gap ratio of $h_1/h_2=10$, a large difference could be observed in Figure 6.6(c) between the experimental and the theoretical maximum pressure and that may be due to the increase in the inlet gap h_1 and the assumption of constant shear rate which may be reasonable for smaller inlet gaps, whereas for higher h_1 , lower shear rates results in higher viscosity and predicts higher pressure.

The discrepancy between the experimental results for the copper wire and the theoretical non-Newtonian results is explained in Figures 6.7(a) and (b).

Any deformation which takes place during the process will result in larger outlet gap h_2 while there will be no change to the inlet gap h_1 . For drawing speed of 0.1 m/sec, the outlet gap was varied in order to obtain different trends of pressure distribution (Figure 6.7(a)). It shows that an outlet gap of larger than 0.07 mm and smaller than 0.1 mm exists when drawing the copper wire as a result of deformation (Figure 6.7(b)).

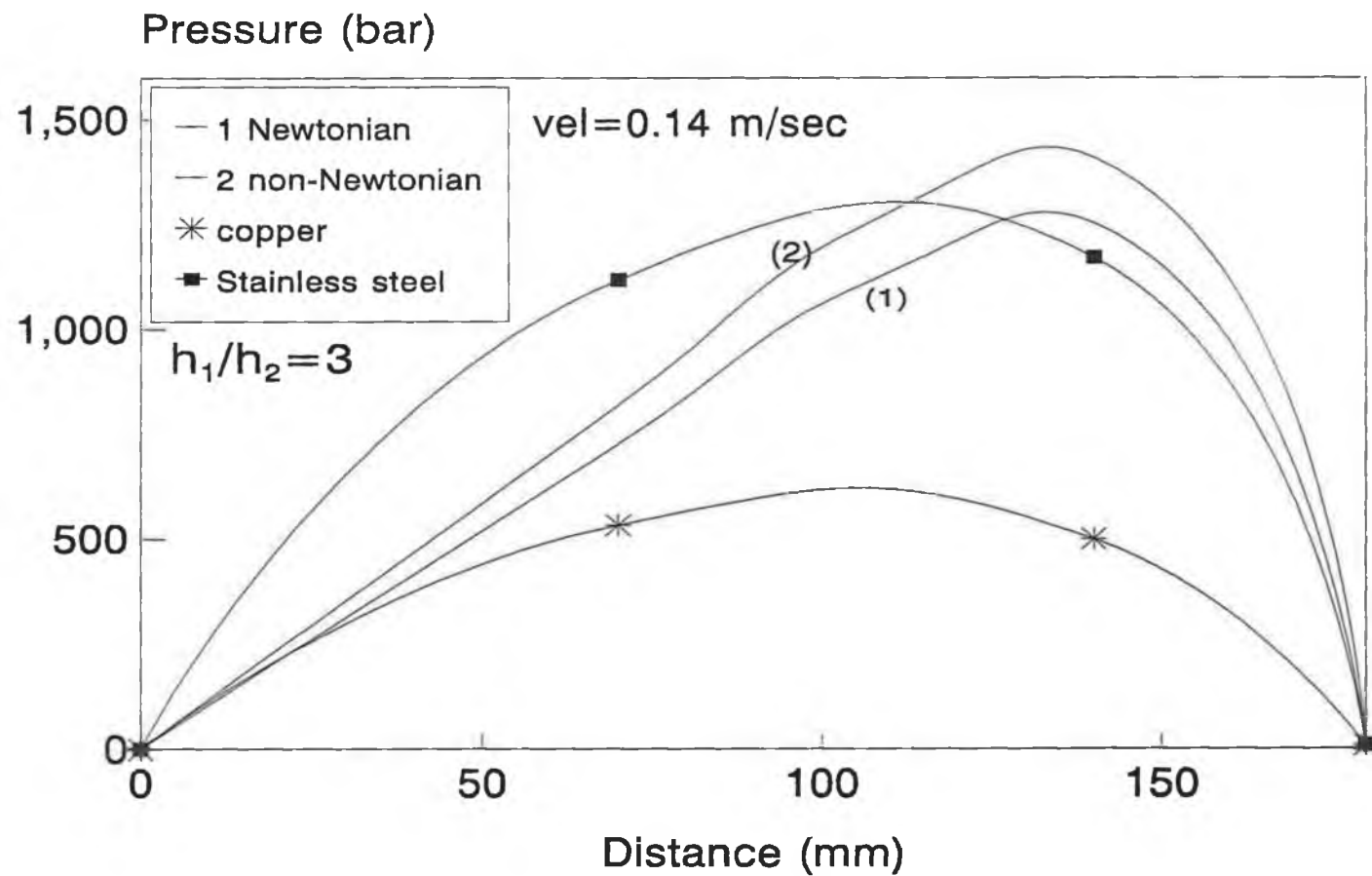


Fig. 6.5(a) Comparison between theoretical and experimental pressure distribution

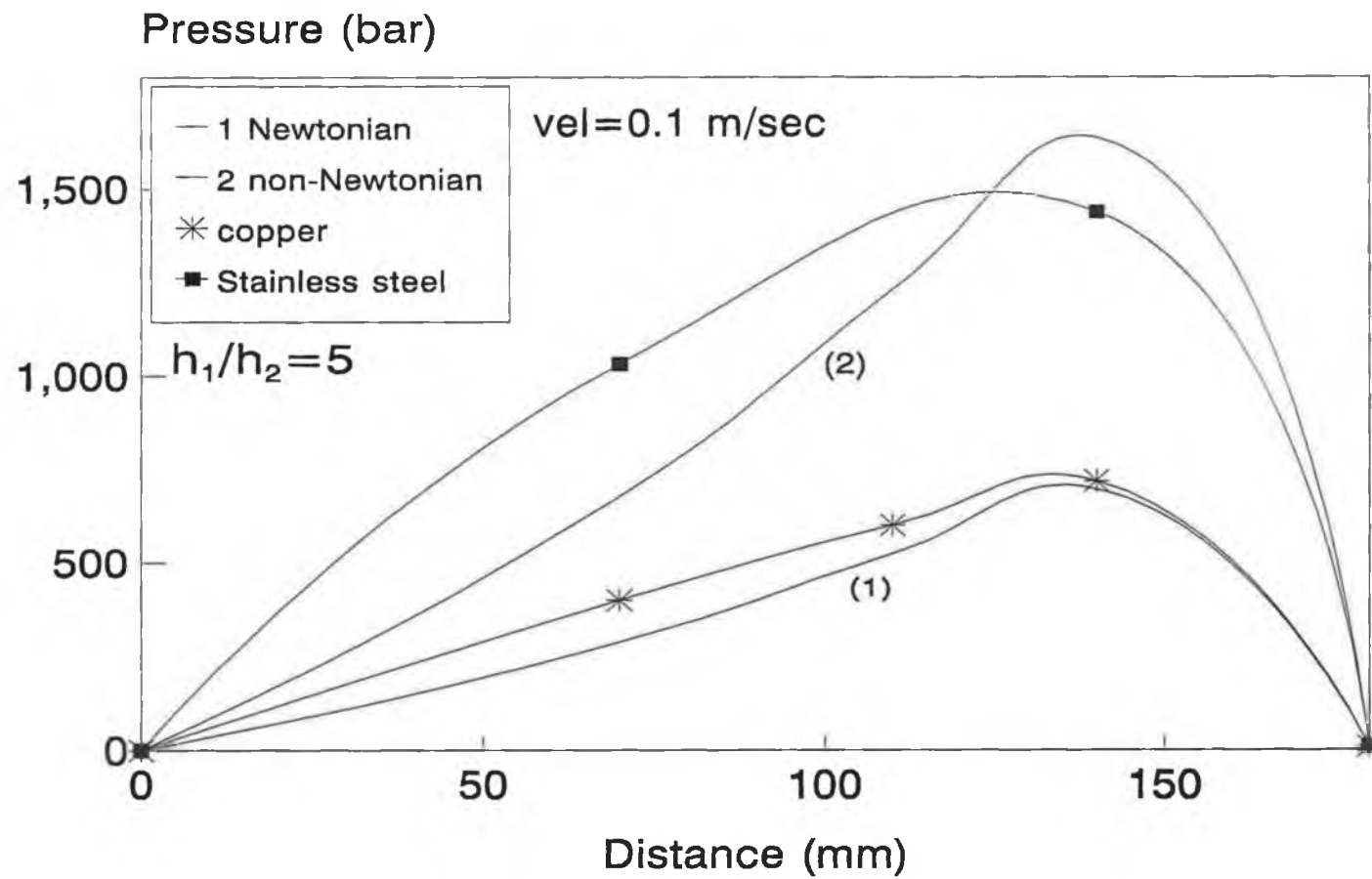


Fig. 6.5(b) Comparison between theoretical and experimental pressure distribution

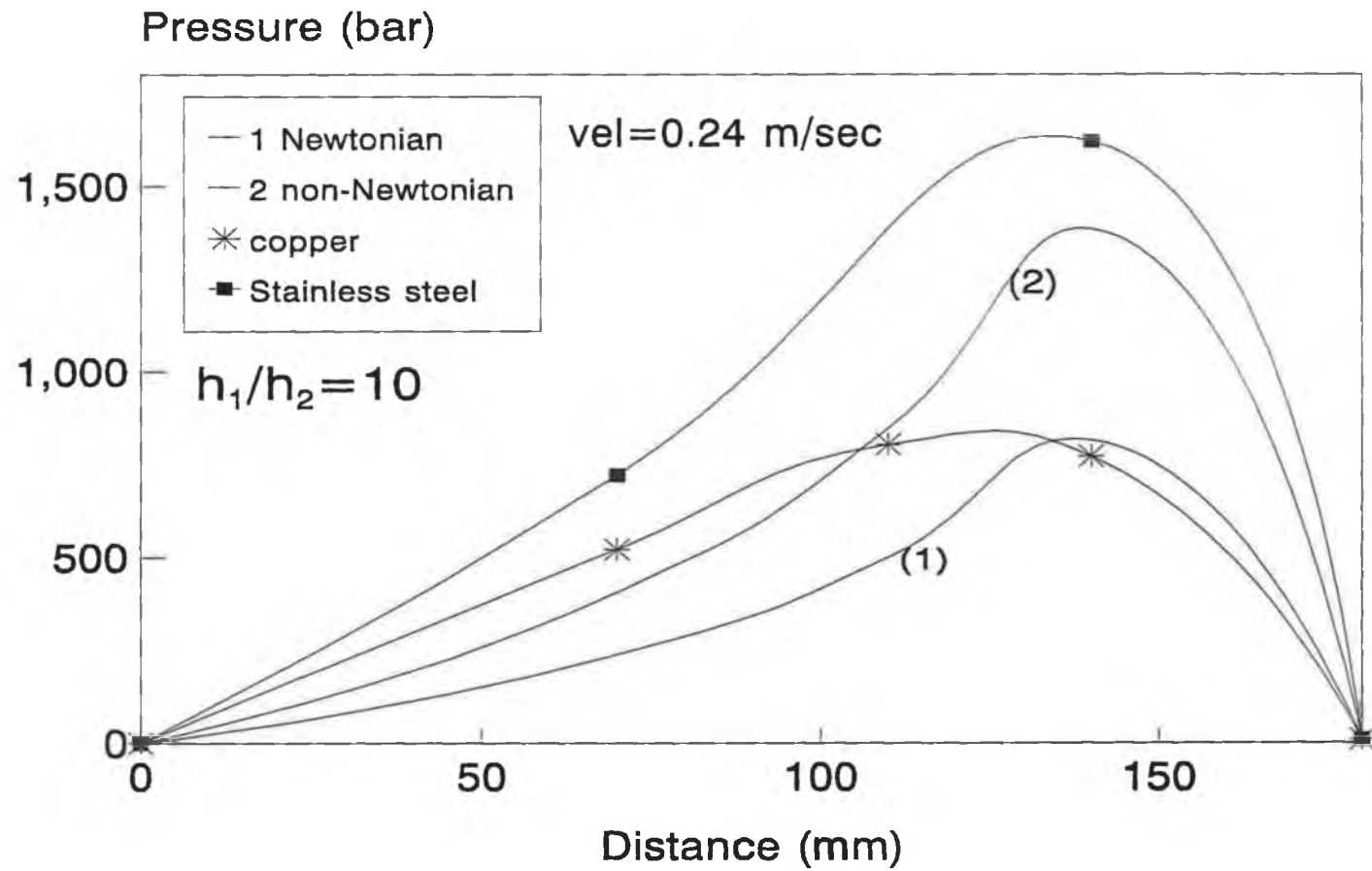


Fig. 6.5(c) Comparison between theoretical and experimental pressure distribution

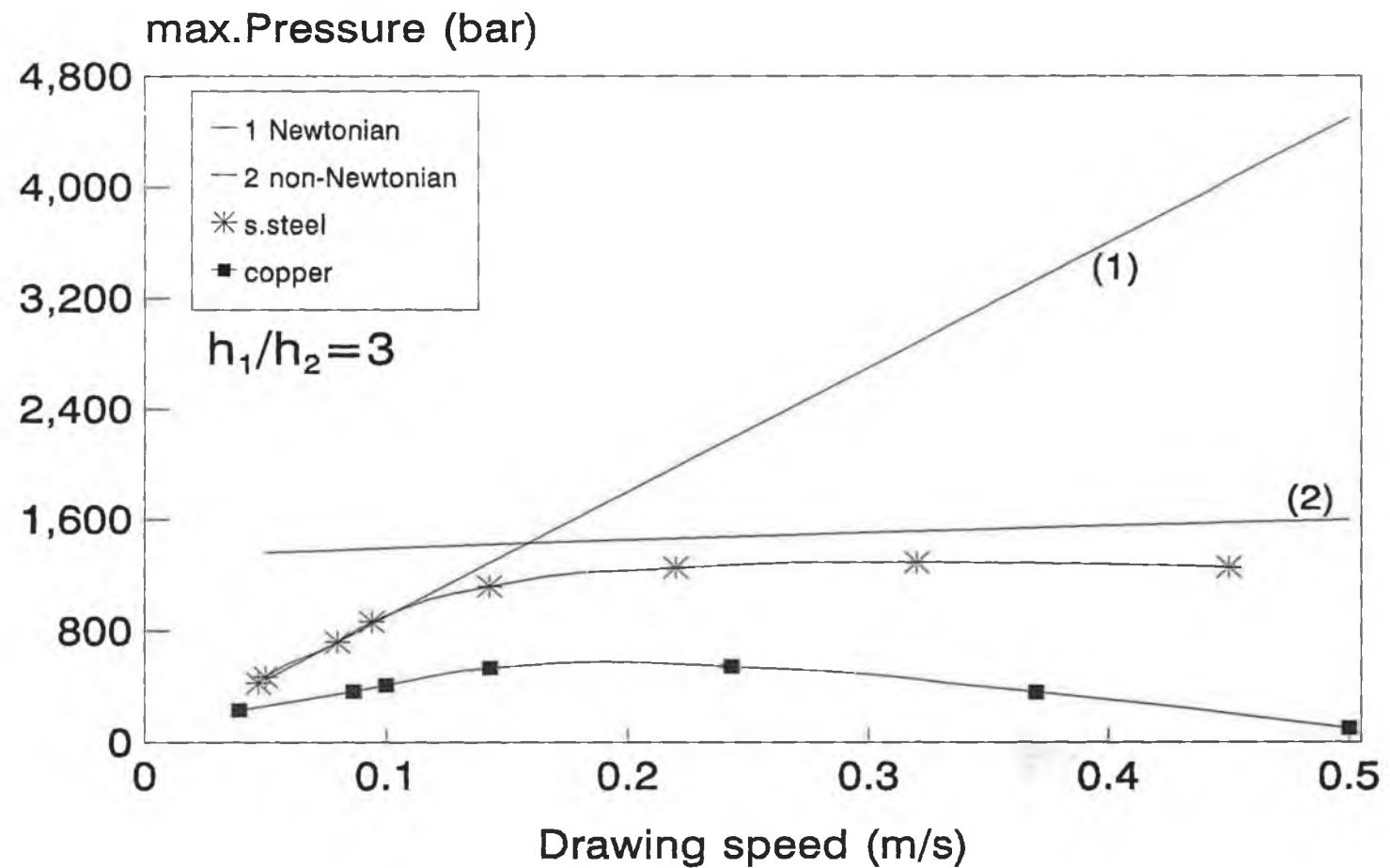


Fig. 6.6(a) Comparison between experimental and theoretical maximum pressure for simple taper

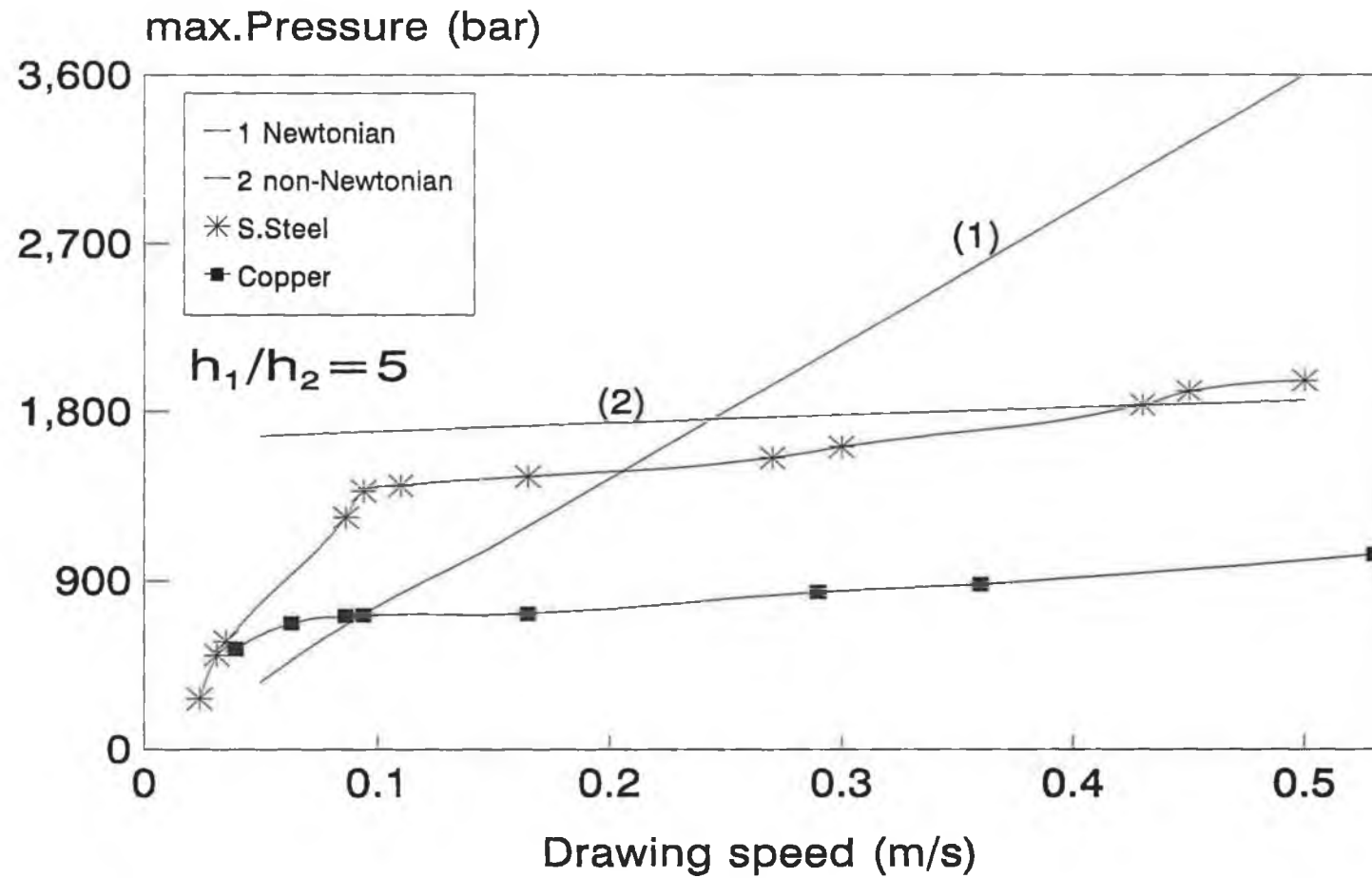


Fig. 6.6(b) Comparison between experimental and theoretical maximum pressure for simple taper

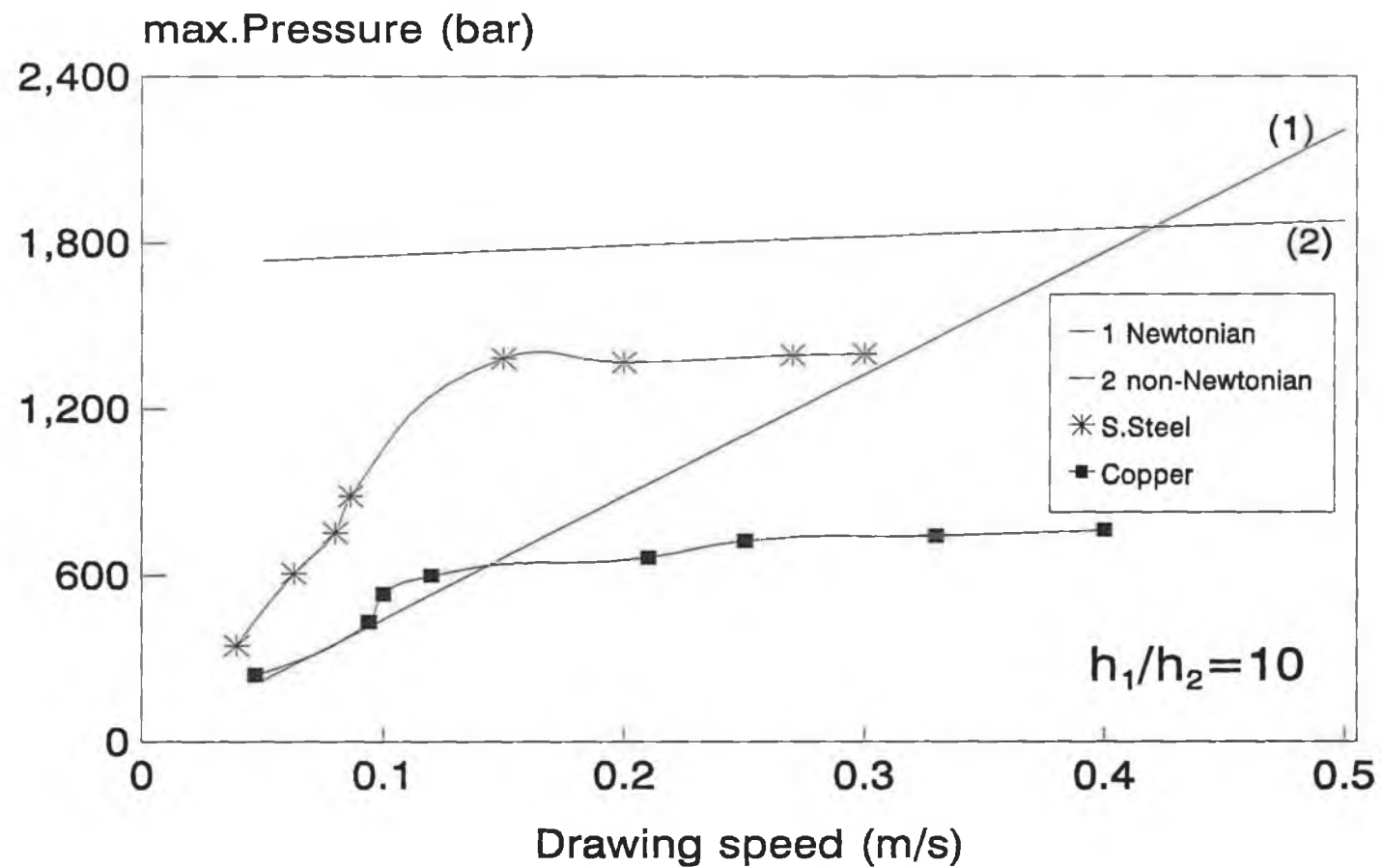


Fig. 6.6(c) Comparison between experimental and theoretical maximum pressure for simple taper

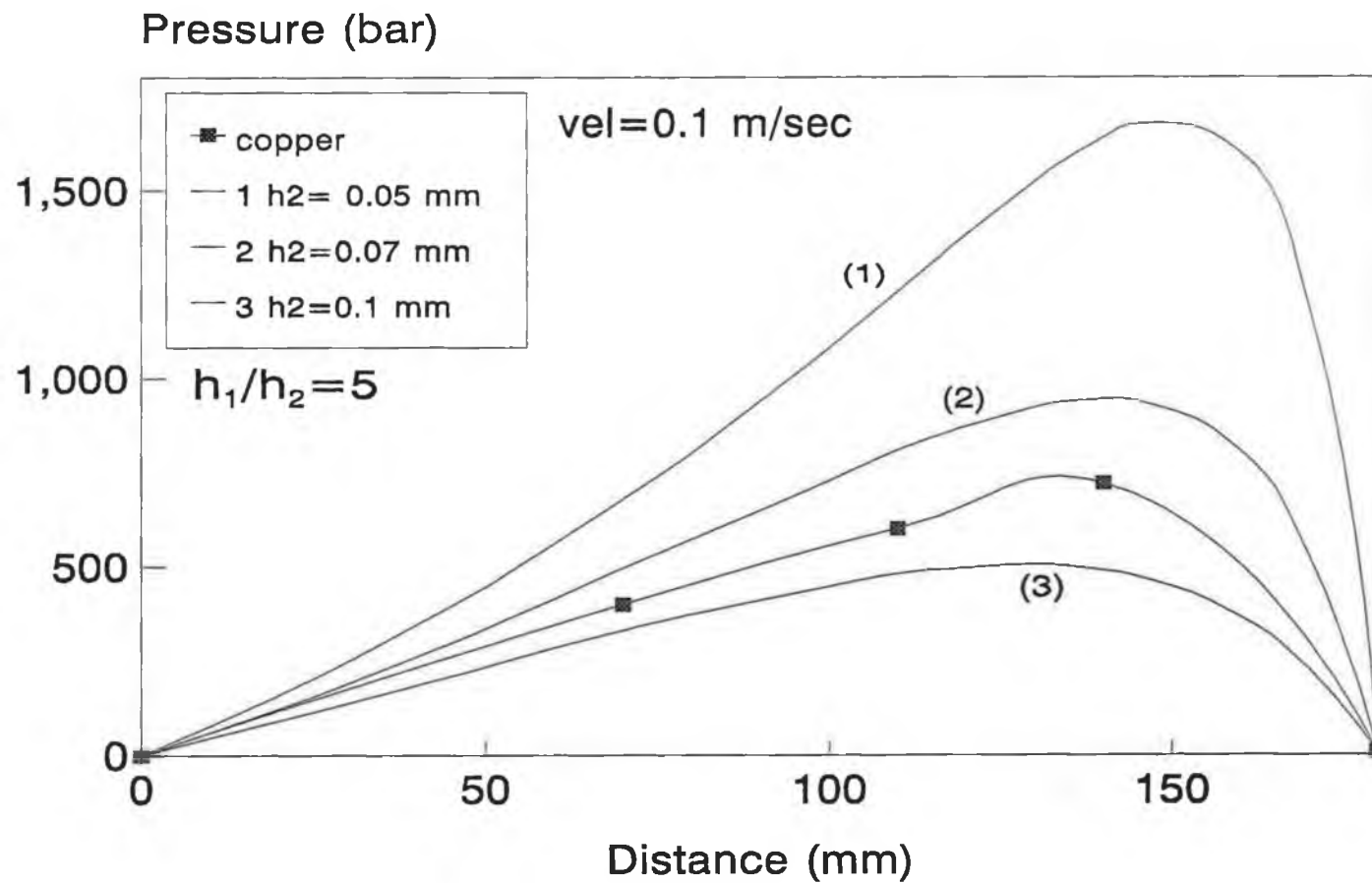


Fig. 6.7(a) Comparison between theoretical and experimental pressure distribution for different h₃

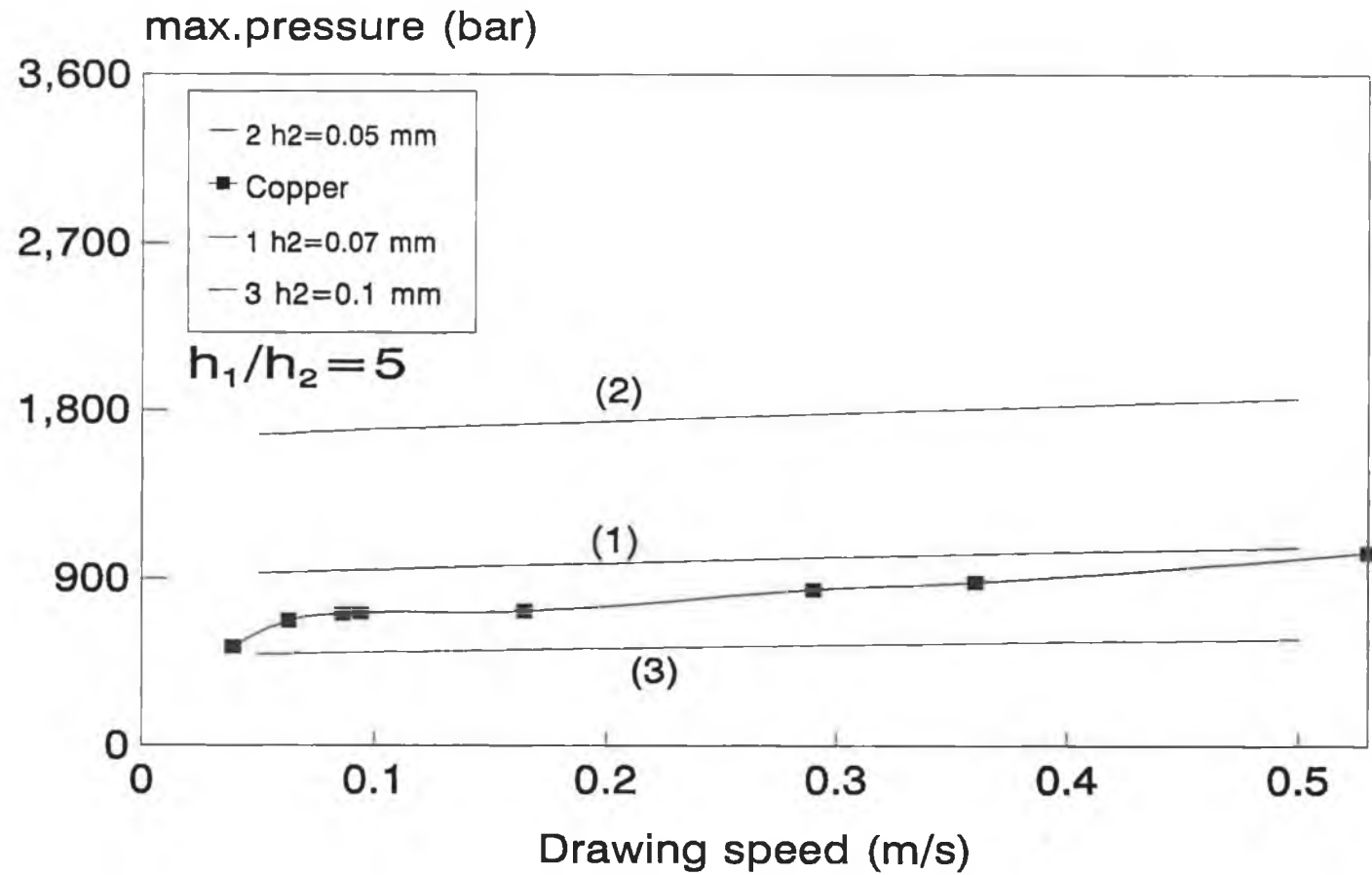


Fig. 6.7(b) Comparison between experimental and theoretical non-Newtonian maximum pressure for different h_3

CONCLUSION AND SUGGESTIONS FOR FURTHER WORK

7.1- Conclusions

Hydro-dynamic pressure units could be useful for a number of possible applications such as drawing processes, coating of wires, tubes, ropes and wire-ropes. Theoretical analysis has been developed for a complex (combined parallel and tapered bore) and simple tapered geometry pressure units assuming non-Newtonian pressure medium to study the pressure distribution within these units. For the complex geometry pressure unit the maximum pressure occurs after the step in the second part of the unit, which is different from the results showed by the parallel bore pressure unit where the maximum pressure occurs at the step.

Theoretical and experimental results on the combined geometry unit showed that there is a combination of gap ratio's h_1/h_2 and h_2/h_3 (optimum) for which the pressure is maximum. For values of the gap ratio greater or smaller than the optimum values, a decreased magnitude for the maximum pressure is obtained. The maximum pressure for that optimum gap ratio is much higher compared to the stepped bore unit of similar overall geometrical parameters and gap ratio.

Based on the theoretical and the experimental results obtained for the simple tapered pressure unit, it may also be concluded that there exists an optimum value for the gap ratio which will generate the greatest magnitude of the maximum pressure and decreasing or increasing this optimum gap ratio will result in reduced magnitudes of maximum pressure.

Experimental work has been carried out for drawing speeds of up to 0.7 m/sec and for different internal geometries to investigate the performance of the pressure units for which Borosiloxane polymer was used as pressure medium. It is evident that in general the theory underestimates the maximum pressure obtained experimentally.

This is attributed primarily to the inaccurate rheological properties used for the polymer which were obtained from the literature.

7.2- Suggestions for further work

In this study it was attempted to incorporate as many factors as possible, but further works could be usefully conducted in the following areas.

Experimentally:

The performance of the pressure units depends on the geometry of the units and on the type of the pressure fluid and its temperature. Experimental results were obtained by using several geometries of the pressure unit. Further experimental investigation using other viscous pressure medium and the geometry of the pressure unit should be carried out to verify the effectiveness of the unit. It is well known that the polymer melts are shear thinning fluids and no polymer have been found to perform otherwise. However, in reference [31] it was reported that certain polymer solutions are shear thickening (dilated). It is thought that the use of dilated pressure medium could solve the problem of shear thinning and hence improve the performance of the pressure unit at higher drawing speeds.

Theoretically:

In the present work, the theoretical analysis was developed assuming isothermal condition. The viscosity of the fluids are known to be sensitive to temperature change, hence a relationship predicting the viscosity change due to temperature variation may improve the theoretical results. The shear stress within the unit was assumed to be constant for a given

drawing speed which may affect the results. The rheology of the pressure medium should be better understood with respect to the effect of pressure and temperature on viscosity and slip characteristics. This in turn should improve the ability of the theoretical model to predict results which are in better agreement with those observed experimentally.

It was predicted theoretically that certain combination of the geometrical parameters give largest magnitude of the maximum pressure. Limited experimental results for both of the pressure units used tend to confirm that for the configurations used. A much elaborated programme of experimental work should be undertaken to establish this optimum conditions.

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APPENDIX [AA]

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APPENDIX [BB]

Listing of the computer programmes for non-Newtonian numerical solution

The combined unit computer programme

```
10 REM Non.Newtonian.aisha-ais
20 PRINT "This program calculates theoretically the average"
30 PRINT "pressure, step pressure, maximum pressure, shear "
40 PRINT "stress, drawing force, drawing stress, yield point"
50 PRINT "flow rate and the percentage reduction in area"
60 PRINT
70 DIM DIA(80),VEL(25),H(25),YI.STR(25),D.STRI(25)
80 DIM SH.STRE(25),D.STRE(25),PX1(25),PX(25),PX1A(25)
90 READ H1,H2,H3,OVIS,SH.STR,L1,L2
100 DATA .48e-3,.23e-3,.03e-3,100,4e5,.145,.035
110 DATA 99,0,0,0,0,0,0
120 IF H1=99 THEN 3120
130 GOSUB 3070
140 PRINT "    h1=";H1;"m","    h2=";H2;"m","    h3=";H3;"m"
150 PRINT "    L1=";L1;"m","    L2=";L2;"m"
160 PRINT "    Sh.str=";SH.STR;"N/m^2","    ovis=";OVIS;"N.sec/m^2"
170 GOSUB 3070
180 PRINT "    The original wire diameter    ";
190 INPUT DIA
200 PRINT "    The wire initial yield stress    ";
210 INPUT YI.STR
220 PRINT "    The strain hardening index    ";
230 INPUT N
240 PRINT "    The step size in the deformation zone ";
250 INPUT DX
260 PRINT "    The strain hardening constant    ";
270 INPUT S
280 PRINT "    The strain rate sensitivity    ";
290 INPUT U
300 PRINT "    The strain rate sensitivity index    ";
310 INPUT T
320 PRINT "    The non-Newtonian factor    ";
330 INPUT K0
340 PRINT "    The viscosity constant    ";
350 INPUT A
360 PRINT "    The pressure coefficient of viscosity ";
370 INPUT B
```



```

860 N7=1/H2
870 N8=HBAR/(2*H2^2)
880 PMAX=N3*(N4+N5-N6)
890 PSTEPC=N3*(N7-N6+N5-N8)
900 XDOT=(H2-HBAR)/K
910 AA=HBAR/(2*K*(H1-K*L2))
920 AB=(PSTEP*L1)/2
930 AC=-L2/H3
940 AD=(HBAR*L2)/(2*H3^2)
950 AE=HBAR/(2*K*H2)
960 AF=(LOG(H2))/K
970 AG=(LOG(H2-K*L2))/K
980 PA=AB+(N3*(-AG+AC+AD+AF+AE-AA))
990 PAVC=PA/(L1+L2)
1000 IF TC1>TCA THEN 3120
1010 IF PSTEP=>1.0001*PSTEPC THEN 1040
1020 IF PSTEP<1.0001*PSTEPC THEN 1030
1030 NEXT PSTEP
1040 IF PAV=>1.0001*PAVC THEN 1200
1050 IF PAV<1.0001*PAVC THEN 1060
1060 PRINT "    pav=";PAV,"    pavc=";PAVC
1070 NEXT PAV
1080 IF HBAR>H2 THEN 3120
1090 HBAR=(2*Q1)/VEL
1100 K=(H2-H3)/L2
1110 AR=(6*VIS*VEL)
1120 A1=3*K0*TC1^2
1130 A2=K*(1+A1)
1140 A3=HBAR/(2*H^2)
1150 A4=AR/A2
1160 D=1/(2*HBAR)
1170 E=1/H3
1180 F=HBAR/(2*H3^2)
1190 PMAX=A4*(D+F-E)
1200 PRINT
1210 PRINT "    TC1=";TC1,"    Pstepc=";PSTEPC,"    pstep=";PSTEP
1220 PRINT
1230 PRINT "    q1=";Q1,"    DIS.PRE=";DIS.PRE,"    xa=";XA
1240 PRINT
1250 PRINT "pavc=";PAVC,"pav=";PAV,"pmax=";PMAX
1260 PRINT
1270 FOR X1=.018 TO L1 STEP .001
1280 D.STRE=ABS((4*X1*TC1)/DIA)
1290 FD1=(3.14*D.STRE*DIA^2)/4
1300 PX1A=(PSTEP*X1)/L1
1310 IF X1<L1 THEN 1330
1320 IF X1=L1 THEN 2210
1330 GOSUB 3070

```

```

1340 PRINT
1350 PRINT "x1=";X1,"px1a=";PX1A,"d.strE=";D.STRE
1360 PRINT "fd1=";FD1
1370 PRINT
1380 B1=DIA-(.002*DX)
1390 B2=H(1)+(.0005*DX)
1400 B3=(2*DIA)-(2*B1)
1410 B4=(2*DIA)-B1
1420 B5=1-(B3/B4)
1430 B6=VEL/B5
1440 B7=LOG(DIA/B1)
1450 B8=2*B6*B7/DX
1460 B9=1+(B8/U)^(1/T)
1470 B10=(DIA/B1)^2
1480 B11=LOG(B10)
1490 B111=B11^N
1500 B12=YI.STR+S*B111
1510 B13=(DIA-B1)/B1
1520 B14=(DIS.PRE*DX)+PX1A
1530 B15=ABS(TC1*4*DX/B1)
1540 B16=(2*B12*B13)+D.STRE+B15
1550 IF B14+B16=>1*B12 THEN 1570
1560 IF B14+B16<1*B12 THEN 2190
1570 GOSUB 3070
1580 PRINT "   kg","   diai","   veli","   hi"
1590 PRINT "   d.strei","   pxli","   yi.stri"
1600 PRINT "   d.strei+pxli","   P.R.A","   fd.d1"
1610 PRINT
1620 GOSUB 3070
1630 LET I=1
1640 LET YI.STR(0)=YI.STR
1650 LET DIA(0)=DIA
1660 LET VEL(0)=VEL
1670 LET PX1(0)=PX1A
1680 LET H(0)=H1
1690 LET D.STRE(0)=D.STRE
1700 FOR KG=.001 TO .04501 STEP .001
1710 LET XP=KG+X1
1720 DIA(I)=DIA(I-1)-(2*KG*DX)
1730 H(I)=H(I-1)+(KG*DX/2)
1740 W=2*(DIA(I-1)-DIA(I))
1750 W1=2*DIA(I-1)-DIA(I)
1760 W2=1-(W/W1)
1770 VEL(I)=VEL(I-1)/W2
1780 W21=DIA(I-1)/DIA(I)
1790 W8=LOG(W21)
1800 EMI=2*VEL(I)*W8/DX
1810 ZI=1+(EMI/U)^(1/T)

```

```

1820 W3=(DIA/DIA(I))^2
1830 W35=LOG(W3)
1840 YI.STR(I)=YI.STR(0)+S*W35^N
1850 W5=(DIA(I-1)-DIA(I))/DIA(I)
1860 FOR PX.DASH=PX1A TO 9.000001E+09 STEP 400000!
1870 SD1=(PX.DASH*H(I)^3)/(6*VIS)
1880 SD2=(TC1*H(I)^2)/(2*VIS)
1890 SD3=(PX.DASH^3*H(I)^5)/20
1900 SD4=(H(I)^2*TC1^3)/2
1910 SD5=(TC1*H(I)^4*PX.DASH^2)/4
1920 SD6=(PX.DASH*H(I)^3*TC1^2)/2
1930 SD7=VEL(I)*H(I)
1940 QI=SD1+SD2+SD7+((K0/VIS)*(SD3+SD4+SD5+SD6))
1950 IF QI >= 1.00001*Q1 THEN 1980
1960 IF QI < 1.00001*Q1 THEN 1970
1970 NEXT PX.DASH
1980 PX1(I)=(PX.DASH*DX)+PX1(I-1)
1990 P.R.A=((DIA^2-DIA(I)^2)/DIA^2)*100
2000 W6=ABS(4*TC1*DX/DIA(I))
2010 D.STRE(I)=(2*W5*YI.STR(I))+D.STRE(I-1)+W6
2020 PXP=(PSTEP*XP)/L1
2030 D.STRXP=ABS((4*XP*TC1)/DIA(I))
2040 FD.D1=3.14*D.STRXP*(DIA(I)^2)/4
2050 IF PX1(I)+D.STRE(I) > YI.STR(I) THEN 2070
2060 IF PX1(I)+D.STRE(I) < YI.STR(I) THEN 2150
2070 PRINT "px.dash=";PX.DASH,"qi=";QI,"q1=";Q1
2080 PRINT
2090 PRINT KG+X1,DIA(I),VEL(I),H(I)
2100 PRINT D.STRE(I),PX1(I),YI.STR(I)
2110 PRINT D.STRE(I)+PX1(I), P.R.A,FD.D1
2120 PRINT
2130 LET I=(I+1)
2140 NEXT KG
2150 LET D.STRE=D.STRE(I):PX1=PX1(I)
2160 PRINT
2170 PRINT "xp=";XP,"yi.str(i)=";YI.STR(I)
2180 PRINT "pxp=";PXP,"d.strxp=";D.STRXP
2190 NEXT X1
2200 IF TC1 >= TCA THEN 3120
2210 FOR X2=0 TO L2 STEP .001
2220 HBAR=(2*Q1)/VEL
2230 K=(H2-H3)/L2
2240 H=H2-K*X2
2250 AR=(6*VIS*VEL)
2260 A1=3*K0*TC1^2
2270 A2=K*(1+A1)
2280 A3=HBAR/(2*H^2)
2290 A4=AR/A2

```

```

2300 C=1/H
2310 E=1/H3
2320 F=HBAR/(2*H3^2)
2330 PX2=A4*(C-A3-E+F)
2340 XDASH=(H2-HBAR)/K
2350 D.STR=ABS(4*X2*TC1/DIA)
2360 FD2=ABS(3.14*DIA*X2*TC1)+FD1
2370 GOSUB 3070
2380 PRINT
2390 PRINT "X2=";X2+L1,"PX2=";PX2,"d.str=";D.STR+D.STRE
2400 PRINT "hbar=";HBAR,"xdash=";XDASH+L1,"pmax=";PMAX
2410 PRINT "FD2=";FD2
2420 PRINT
2430 BA=DIA-(.002*DX)
2440 BB=(DIA/BA)^2
2450 BC=VEL*BB
2460 BD=(H2-.001*X2)-((K-.001)*DX)
2470 BE=(1/BD^2)-(HBAR/BD^3)
2480 BF=6*VIS*BC*DX*BE
2490 BG=PX2+(BF/(1+3*K0*TC1^2))
2500 BK=DIA/BA
2510 BN=LOG(BK)
2520 BM=2*BC*BN/DX
2530 BY=1+(BM/U)^(1/T)
2540 BP=LOG(BB)
2550 BO=BP^N
2560 BW=BY*(YI.STR+S*BO)
2570 BQ=(4*.001*DX)/BA
2580 BS=BW+TC1
2590 BZ=D.STR+D.STRE+(BQ*BS)
2600 IF BG+BZ=>1*BW THEN 2620
2610 IF BG+BZ<1*BW THEN 3050
2620 GOSUB 3070
2630 PRINT "kj","dai","veli","hi"
2640 PRINT "d.stri","pxi","yi.stri"
2650 PRINT "d.stri+pxi","P.R.A","FD.D2I=";FD.D2I
2660 GOSUB 3070
2670 LET I=1
2680 LET YI.STR(0)=YI.STR
2690 LET DIA(0)=DIA
2700 LET VEL(0)=VEL
2710 LET PX(0)=PX2
2720 LET H(0)=H2-K*X2
2730 LET D.STRI(0)=D.STR+D.STRE
2740 FOR KJ=.001 TO .4501 STEP .001
2750 LET DIA(I)=DIA(I-1)-(2*KJ*DX)
2760 RA=(DIA(I-1)/DIA(I))^2
2770 VEL(I)=VEL(I-1)*RA

```

```

2780 H(I)=H(I-1)-((K-KJ)*DX)
2790 E=(1/H(I)^2)-(HBAR/H(I)^3)
2800 EPX=6*VIS*VEL(I)*DX*E
2810 PX(I)=PX(I-1)+(EPX/(1+3*K0*TC1^2))
2820 R=(DIA/DIA(I))^2
2830 EM=DIA(I-1)/DIA(I)
2840 EMR=LOG(EM)
2850 EMI=2*VEL(I)*EMR/DX
2860 ZI=1+(EMI/U)^(1/T)
2870 R3=LOG(R)
2880 R4=R3^N
2890 YI.STR(I)=ZI*(YI.STR(0)+S*R4)
2900 R1=(4*KJ*DX)/DIA(I)
2910 R2=YI.STR(I)+(-TC1)
2920 D.STRI(I)=D.STRI(I-1)+(R2*R1)
2930 FD.D2I=(3.14*DIA(I)^2*D.STRI(I))/4
2940 P.R.A=((DIA^2-DIA(I)^2)/DIA^2)*100
2950 IF PX(I)+D.STRI(I) >= 1.05*YI.STR(I) THEN 2980
2960 GOTO 3040
2970 PRINT
2980 PRINT KJ+X2+L1,DIA(I),VEL(I),H(I)
2990 PRINT D.STRI(I),PX(I),YI.STR(I)
3000 PRINT D.STRI(I)+PX(I),P.R.A,FD.D2I
3010 PRINT
3020 LET I=(I+1)
3030 NEXT KJ
3040 D.STRI(0)=D.STRI(I):PX(0)=PX(I)
3050 NEXT X2
3060 GOTO 90
3070 FOR QWE=1 TO 11
3080 PRINT "-----";
3090 NEXT QWE
3100 PRINT
3110 RETURN
3120 END

```

```

10 REM simple non-Newtonian.AIA
20 PRINT "This programme calculates the parameters for simple taper"
30 PRINT "using non-Newtonian solution as pressure medium"
40 DIM DIA(25),VEL(25),H(25)
50 DIM PX(25),YI.STR(25),D.STR(25)
60 READ H1,H2,L,VISO
70 DATA 0.00009,.00003,0.18,100
80 DATA 99,0,0,0
90 IF H1=99 THEN 1710
100 GOSUB 1660
110 PRINT " h1=";H1;"m"," h2=";H2;"m","L=";L;"m"," viso=";VISO;"N.sec/m^2"
120 GOSUB 1660
130 PRINT " The initial wire diameter ";
140 INPUT DIA
150 PRINT " The wire initial yield stress ";
160 INPUT YI.STR
170 PRINT " The strain hardening index ";
180 INPUT N
190 PRINT " The strain hardening constant ";
200 INPUT S
210 PRINT " The strain rate sensitivity ";
220 INPUT U
230 PRINT " The strain rate sensitivity index ";
240 INPUT T
250 PRINT " The step size in the deformation zone ";
260 INPUT DX
270 PRINT
280 PRINT " dia=";DIA," yi.str=";YI.STR," n=";N
290 PRINT " s=";S," u=";U," t=";T
300 PRINT " dx=";DX
310 PRINT
320 K=5.6E-11 : AC=120000 : BC=4E-11
330 PRINT " Check your data and the unit dimensions please"
340 PRINT " _*_*_*_*_*_*_*_*_*_*_*_*_*_*_*_*"
350 PRINT
360 PRINT " The wire speed (m/sec) please";
370 INPUT VEL
380 PRINT
390 FOR PAV=1E+08 TO 5.5E+08 STEP 100000!
400 NU=2*VEL/(H1+H2)
410 VISO=(AC+(BC*PAV^2))/NU
420 VIS=VISO+VISO
430 Q=(VIS*NU)/K

```

```

440 C=1/K
450 D1=(C/3)^3
460 D2=(Q/2)^2
470 D=D1+D2
480 D4=D^.5
490 U1=(Q/2)+D4
500 U2=-(Q/2)+D4
510 TAU=U1^.333-U2^.333
520 B=(H1-H2)/L
530 HBAR=2*H2*H1/(H1+H2)
540 FLOW.RATE=(VEL*HBAR)/2
550 XDASH=(H1-HBAR)/B
560 A=B*(1+3*K*TAU^2)
570 A1=(6*VEL*VIS)/A
580 B1=LOG(H1-(B*L))
590 B2=-(B1/B)
600 B3=2*B*(H1-(B*L))
610 B4=-HBAR/B3
620 B5=-L/H1
630 B6=(L*HBAR)/(2*H1^2)
640 B7=LOG(H1)/B
650 B8=HBAR/(2*B*H1)
660 B9=(B2+B4+B5+B6+B7+B8)
670 B10=A1*B9/L
680 IF B10 <= PAV THEN 710
690 IF B10 > PAV THEN 700
700 NEXT PAV
710 PRINT " pav=";PAV," pavc=";B10
720 PRINT " tau=";TAU," vis=";VIS
730 PRINT
740 A11=1/H1
750 A12=HBAR/(2*H1^2)
760 A13=1/(2*HBAR)
770 A14=HBAR-(2*H1)
780 A15=A14/(2*H1^2)
790 FOR X=0 TO L STEP .01
800 A2=1/(H1-(B*X))
810 A3=2*(H1-(B*X))^2
820 A4=HBAR/A3
830 PX=A1*(A2-A4-A11+A12)
840 PMAX=A1*(A15+A13)
850 SIGX=(4*TAU*X)/DIA
860 F.D=3.14*SIGX*(DIA^2)/4
870 PRINT
880 GOSUB 1660
890 PRINT " px=";PX," x=";X," qx=";SIGX
900 GOSUB 1660
910 NA=DIA-(.002*DX)

```

```

920 NB=(DIA/NA)^2
930 MA=VEL*NB
940 MB=H1-((B-.001)*DX)
950 MC=(1/MB^2)-(HBAR/MB^3)
960 MC1=6*VIS*MA*DX*MC
970 MC2=1+(3*K*TAU^2)
980 MPX=PX-(MC1/MC2)
990 MD=(DIA/NA)^2
1000 ME=MD^.5
1010 MF=(2*MA/DX)*LOG(ME)
1020 MG=1+(MF/U)^(1/T)
1030 MH=LOG(MD)
1040 MN1=S*MH^N
1050 MN2=YI.STR+MN1
1060 MN=MG*MN2
1070 MV=.004*DX/NA
1080 MS=MN+TAU
1090 MX=SIGX-(MV*MS)
1100 IF MPX+MX<1.5*MN THEN 1600
1110 IF MPX+MX=>1.5*MN THEN 1120
1120 PRINT "  kj","  DIAI","  VELI","  HI"
1130 PRINT "  D.STR","  PXI","  YI.STR"
1140 PRINT "  d.stri+pxi","  P.R.A"
1150 GOSUB 1660
1160 LET I=1
1170 LET YI.STR(0)=YI.STR
1180 LET DIA(0)=DIA
1190 LET VEL(0)=VEL
1200 LET PX(0)=PX
1210 LET H(0)=H1
1220 LET D.STR(0)=SIGX
1230 FOR KJ=.001 TO .4501 STEP .001
1240 DIA(I)=DIA(I-1)-(2*KJ*DX)
1250 RA=(DIA(I-1)/DIA(I))^2
1260 VEL(I)=VEL(I-1)*RA
1270 H(I)=H(I-1)-((B-KJ)*DX)
1280 E=(1/H(I)^2)-(HBAR/H(I)^3)
1290 PX(I)=PX(I-1)+(6*VIS*VEL(I)*DX*E/(1+3*K*TAU^2))
1300 R=(DIA/DIA(I))^2
1310 R0=DIA(I-1)/DIA(I)
1320 EMI=(2*VEL(I)/DX)*LOG(R0)
1330 ZI=1+((EMI/U)^(1/T))
1340 RO=LOG(R)
1350 YI.STR(I)=ZI*(YI.STR(0)+S*((RO)^N))
1360 R1=(4*KJ*DX)/DIA(I)
1370 R2=YI.STR(I)+TAU
1380 D.STR(I)=D.STR(I-1)+(R2*R1)
1390 P.R.A=((DIA^2-DIA(I)^2)/DIA^2)*100

```

```

1400 IF PX(I)+D.STR(I) >= 1.00001*YI.STR(I) THEN 1440
1410 IF X+KJ=.062 THEN 1500
1420 IF PX(I)+D.STR(I) <= 1.00001*YI.STR(I) THEN 1590
1430 PRINT
1440 PRINT KJ+X,DIA(I),VEL(I),H(I)
1450 PRINT D.STR(I),PX(I),YI.STR(I)
1460 PRINT D.STR(I)+PX(I),P.R.A
1470 PRINT
1480 LET I=I+1
1490 NEXT KJ
1500 VELO=VEL(I)
1510 AB1=(6*VELO*VIS)/A
1520 FOR X1=KJ+X TO L STEP .001
1530 AB2 =1/(H1-(B*X1))
1540 AB3=2*(H1-(B*X1))^2
1550 AB4=HBAR/AB3
1560 PX1=AB1*(AB2-AB4-A11+A12)
1570 SIGX1=(4*TAU*X1)/DAI(I)
1580 NEXT X1
1590 D.STR(0)=D.STR(I):PX(0)=PX(I)
1600 NEXT X
1610 GOSUB 1660
1620 PRINT " Pmax=";PMAX," Pav=";B10," tau=";TAU
1630 PRINT " Xdash=";XDASH," vis=";VIS
1640 GOSUB 1660
1650 GOTO 60
1660 FOR QWE=1 TO 11
1670 PRINT " -----";
1680 NEXT QWE
1690 PRINT
1700 RETURN
1710 END

```

APPENDIX [CC]

Listing of the computer programmes for Newtonian solution

Combined unit computer programme

```

10 REM Newtonian.abubaker
20 REM "This programme calculates theoretically the maximum pressure the"
30 REM "drawing stress, the point at which the maximum pressure occur"
40 REM "the point at which deformation starts and the P.R.A using "
50 REM "Newtonian solution as pressure medium"
60 DIM DIA(50),VEL(50),H(50),YI.STR(50),D.STRI(500)
70 DIM SH.STRE(50),D.STRE(50),PXD(50),PX(500)
80 READ H1,H2,H3,L1,L2,VIS
90 DATA .9E-4,.75E-4,.03E-3,145E-3,35E-3,100
100 DATA 99,0,0,0,0,0
110 IF H1=99 THEN 2130
120 GOSUB 2070
130 PRINT "H1=";H1;"m","H2=";H2;"m","H3=";H3;"m"
140 PRINT "L1=";L1;"m","L2=";L2;"m","VIS=";VIS;"N.sec/m^2"
150 GOSUB 2070
160 DIA=.002:YI.STR=5E+07:N=.18:DX=.001
170 T=3.8:U=55000!:S=7E+08
180 PRINT "      ARE YOU SURE OF YOUR DATA AND THE UNIT DIMENSIONS"
190 PRINT "      *_**_**_**_**_**_**_**_**_**_**_**_**_"
200 PRINT
210 PRINT " If yes put the wire speed please";
220 INPUT VEL
230 K=(H2-H3)/L2
240 A1=(6*VIS*H1*VEL/(2*K))
250 A2=(1/H3^2)-(1/H2^2)
260 A3=(6*VIS*VEL/K)*((1/H2)-(1/H3))
270 A4=(1+(H1^3*A2/(2*K*L1)))
280 PSTEP =((A1*A2)+A3)/A4
290 HBAR=H1-((H1^3*PSTEP)/(6*VIS*VEL*L1))
300 XDASH=((H2-HBAR)/K)+L1
310 C1=HBAR/(2*H3^2)
320 PMAX=(6*VIS*VEL/K)*((1/(2*HBAR))-(1/H3)+C1)
330 E1=(-PSTEP*H1)
340 E2=E1/(2*L1)
350 E3=-VIS*VEL/H1
360 SH.STRE=ABS(E2+E3)
370 IF SH.STRE<=500000! THEN 390

```

```

380 IF SH.STRE > 500000! THEN 2120
390 M1=(PSTEP*H1^3)/(6*VIS*L1)
400 M2=VEL*H1
410 M3=(E2+E3)*H1^2
420 M4=M3/(2*VIS)
430 PRINT
440 Q1=M1+M2+M4
450 FA=PSTEP/L1
460 FB=(4*SH.STRE)/DIA
470 XDEF=YI.STR/(FA+FB)
480 PRINT "Pstep=";PSTEP,"Q1=";Q1,"pmax=";PMAX,"Xdef=";XDEF
490 PRINT "Hbar=";HBAR,"Xdash=";XDASH,"sh.stre=";SH.STRE
500 FOR X1=0 TO L1 STEP .001
510 PX1=(PSTEP*X1)/L1
520 D.STRE=4*(SH.STRE*X1)/DIA
530 FD.E=3.14*D.STRE*(DIA^2)/4
540 IF X1=L1 THEN 1310
550 PRINT
560 GOSUB 2070
570 PRINT
580 PRINT "X1=";X1,"PX1=";PX1,"D.STRE=";D.STRE
590 PRINT "fd.e=";FD.E
600 J1=DIA-(.002*DX)
610 J2=H1+(.0005*DX)
620 J3=2*(DIA-J1)
630 J4=2*DIA-J1
640 J5=1-(J3/J4)
650 J6=VEL/J5
660 J7=(2*J6/DX)*LOG(.002/J1)
670 J8=1+(J7/U)^(1/T)
680 J9=(DIA/J1)^2
690 J10=LOG(J9)
700 J11=YI.STR+S*(J10)^N
710 J12=((-H1^3*PSTEP)/(12*VIS*L1))+(VEL*H1/2)
720 J13=J12+(J6*J2/2)
730 J14=12*VIS*J13
740 J15=J14/((J2)^3)
750 J16=(DX*J15)+PX1
760 J17=((PSTEP*J2/(2*L1))-(VIS*J6/J2))
770 J18=(DIA-J1)/J1
780 J19=4*J17*DX/J1
790 J20=(2*J18*J11)+D.STRE+J19
800 IF J16+J20=>1.5*J11 THEN 820
810 IF J16+J20<1.5*J11 THEN 1300
820 GOSUB 2070
830 PRINT "KG","DIAi","VELi"
840 PRINT "d.strei","pxdi","hi"
850 PRINT "yi.stri","d.strei+pxdi","P.R.A"

```

```

860 GOSUB 2070
870 PRINT
880 LET I=1
890 LET YI.STR(0)=YI.STR
900 LET DIA(0)=DIA
910 LET VEL(0)=VEL
920 LET PXD(0)=PX1
930 LET H(0)=H1
940 LET SH.STRE(0)=SH.STRE
950 LET D.STRE(0)=D.STRE
960 FOR KG=.001 TO .04501 STEP .001
970 DIA(I)=DIA(I-1)-(2*KG*DX)
980 H(I)=H(I-1)+(KG*DX/2)
990 W=2*(DIA(I-1)-DIA(I))
1000 W1=2*DIA(I-1)-DIA(I)
1010 W2=1-(W/W1)
1020 VEL(I)=VEL(I-1)/W2
1030 EM=DIA(I-1)/DIA(I)
1040 EMI=(2*VEL(I)/DX)*LOG(EM)
1050 ZI=1+(EMI/U)^(1/T)
1060 W3=(DIA/DIA(I))^2
1070 W7=LOG(W3)
1080 YI.STR(I)=YI.STR+S*(W7)^N
1090 O1=((-H1^3*PSTEP)/(12*VIS*L1))+(VEL*H1/2)
1100 W4=O1+(VEL(I)*H(I)/2)
1110 Z=12*VIS*W4
1120 PDASH=Z/H(I)^3
1130 PXD(I)=(DX*PDASH)+PXD(I-1)
1140 SH.STRE(I)=ABS((-PSTEP*H(I)/2*L1)-(VIS*VEL(I)/H(I)))
1150 IF SH.STRE(I) <= 500000! THEN 1170
1160 IF SH.STRE(I) > 500000! THEN 2120
1170 W5=(DIA(I-1)-DIA(I))/DIA(I)
1180 C2=4*SH.STRE(I)*DX/DIA(I)
1190 D.STRE(I)=(2*W5*YI.STR(I))+D.STRE+C2
1200 P.R.A=((DIA^2-DIA(I)^2)/DIA^2)*100
1210 IF PXD(I)+D.STRE(I) >= YI.STR(I) THEN 1230
1220 IF PXD(I)+D.STRE(I) < YI.STR(I) THEN 1290
1230 PRINT KG+X1,DIA(I),VEL(I)
1240 PRINT D.STRE(I),PXD(I),H(I)
1250 PRINT YI.STR(I),PXD(I)+D.STRE(I),P.R.A
1260 PRINT
1270 LET I=(I+1)
1280 NEXT KG
1290 D.STRE(I)=D.STRE
1300 NEXT X1
1310 FOR X2=0 TO .035 STEP .005
1320 H0=H2-K*X2
1330 B1=1/(H2-(K*X2))

```

```

1340 B2=1/H2
1350 B3=(B1-B2)*3*HBAR
1360 B4=4*LOG((H2-K*X2)/H2)
1370 B5=(-4*VIS*VEL)/(DIA*K)
1380 B=(3*HBAR/H0^2)-(4/H0)
1390 SH.STR=ABS(VIS*VEL*B)
1400 B6=1/H0-(HBAR/(2*H0^2))
1410 B7=1/H3-(HBAR/(2*H3^2))
1420 D.STR=B5*(B3+B4)+D.STRE
1430 PX2=(B6-B7)*(6*VIS*VEL/K)
1440 FD2=(3.14*DIA^2*D.STR)/4
1450 PRINT
1460 GOSUB 2070
1470 PRINT
1480 PRINT "X2=";L1+X2,"Fd2=";FD2
1490 PRINT "Px2=";PX2,"SH.STR=";SH.STR,"D.STR=";D.STR
1500 PRINT
1510 E1=DIA-.002*DX
1520 E2=(DIA/E1)^2
1530 E3=VEL*E2
1540 E4=H1-(K-.001)*DX
1550 E5=6*VIS*E3*DX
1560 E6=PX2+(E5*(1/E4^2-HBAR/E4^3))
1570 E7=(DIA/E1)^2
1580 E8=(2*E3/DX)*LOG(DIA/E1)
1590 E9=1+(E8/U)^(1/T)
1600 E10=YI.STR+S*(LOG(E7))^N
1610 E11=3*VEL*HBAR/E4
1620 E12=(VIS/(.001*E4))*(4*E3-E11)+E10
1630 E13=.004*DX/E1
1640 E14=D.STRE+(E12*E13)
1650 IF E6+E14=>1.5*E10 THEN 1670
1660 IF E6+E14<1.5*E10 THEN 2050
1670 GOSUB 2070
1680 PRINT"ki","DIAi","VELi"
1690 PRINT "d.stri","pxi","hi"
1700 PRINT "yi.stri","d.stri+pxi","p.r.a"
1710 GOSUB 2070
1720 PRINT
1730 LET I=1
1740 LET YI.STR(0)=YI.STR
1750 LET DIA(0)=DIA
1760 LET VEL(0)=VEL
1770 LET PX(0)=PX2
1780 LET H(0)=H2-K*X2
1790 LET D.STRI(0)=D.STRE
1800 FOR KJ=.001 TO .4501 STEP .001
1810 DIA(I)=DIA(I-1)-2*KJ*DX

```

```

1820 RA=(DIA(I-1)/DIA(I))^2
1830 VEL(I)=VEL(I-1)*RA
1840 H(I)=H(I-1)-(K-KJ)*DX
1850 C3=6*VIS*VEL(I)*DX
1860 PX(I)=PX(I-1)+(C3*(1/H(I)^2-HBAR/H(I)^3))
1870 R=(DIA(I-1)/DIA(I))^2
1880 EMI=(2*VEL(I)/DX)*LOG(DIA(I-1)/DIA(I))
1890 ZI=1+(EMI/U)^(1/T)
1900 YI.STR(I)=YI.STR(0)+S*(LOG(R))^N
1910 P.R.A=((DIA^2-DIA(I)^2)/DIA^2)^2
1920 C4=3*VEL*HBAR/H(I)
1930 R1=(VIS/(KJ*H(I)))*(4*VEL(I)-C4)+YI.STR(I)
1940 R2=(4*KJ*DX)/DIA(I)
1950 D.STRI(I)=D.STRI(I-1)+(R2*R1)
1960 IF PX(I)+D.STRI(I) >= 1*YI.STR(I) THEN 1980
1970 GOTO 2040
1980 PRINT KJ+X2+L1,DIA(I),VEL(I)
1990 PRINT D.STRI(I),PX(I),H(I)
2000 PRINT YI.STR(I),D.STRI(I)+PX(I),P.R.A
2010 PRINT
2020 LET I=(I+1)
2030 NEXT KJ
2040 D.STRI(0)=D.STRI(I):PX(0)=PX(I)
2050 NEXT X2
2060 GOTO 80
2070 FOR QWE=1 TO 11
2080 PRINT "-----";
2090 NEXT QWE
2100 PRINT
2110 RETURN
2120 PRINT "there is a slip with such a speed"
2130 END

```

The simple taper computer programme

```
10 REM "This programme for simple taper parameters calculations"
20 REM "Using Newtonian solution as the unit pressure medium"
30 DIM DIA(25),VEL(25),H(25),YI.ST(25)
40 DIM D.ST(25),PX(25)
50 READ H1,H2,VIS,L
60 DATA .075e-3,.05e-3,50,.180
70 DATA 99,0,0,0
80 IF H1=99 THEN 780
90 GOSUB 730
100 PRINT "h1=";H1;"m", "h2=";H2;"m", "vis=";VIS;"N.sec/m^2", "l=";L;"m"
110 GOSUB 730
120 DIA=.002:DX=.001
130 PRINT "The wire speed";
140 INPUT VEL
150 YI.ST=5E+07:N=.18:K0=7E+08
160 B=(H1-H2)/L
170 HBAR=2*H1*H2/(H1+H2)
180 FOR X=0 TO L STEP .01
190 H=H1-(B*X)
200 A1=(6*VIS*VEL)/B
210 A2=1/(H1-B*X)
220 A3=2*(H1-B*X)^2
230 A4=HBAR/A3
240 A5=1/H1
250 A6=HBAR/(2*H1^2)
260 PX=A1*(A2-A4-A5+A6)
270 AF=1/(2*HBAR)
280 PMAX=A1*(AF-A5+A6)
290 A7=3*HBAR/(H1-B*X)^2
300 A8=4/(H1-B*X)
310 TAU=VEL*VIS*(A7-A8)
320 S=(3.14*DIA*VIS*VEL)/B
330 S1=3*HBAR/(H1-B*X)
340 S2=3*HBAR/H1
350 S4=4*LOG((H1-B*X)/H1)
360 FD=S*(S1-S2+S3)
370 SIGMA=4*FD/(3.14*DIA^2)
380 GOSUB 730
390 PRINT "vel=";VEL,"Px=";PX,"x=";X,"tau=";TAU
400 PRINT "Qx=";SIGMA,"pmax=";PMAX
410 GOSUB 730
420 PRINT "ki","dai","veli","hi"
430 PRINT "d.sti","Pxi","yi.sti"
440 PRINT "d.sti+pxi","P.R.A"
```

```

450 GOSUB 730
460 LET I=1
470 LET DIA(0)=DIA
480 LET VEL(0)=VEL
490 LET PX(0)=PX
500 LET H(0)=H1-(B*X)
510 LET D.ST(0)=SIGMA
520 FOR KI=.001 TO .04501 STEP .001
530 DIA(I)=DIA(I-1)-(2*KI*DX)
540 RA=(DIA(I-1)/DIA(I))^2
550 VEL(I)=VEL(I-1)*RA
560 H(I)=H(I-1)-((B-KI)*DX)
570 PX(I)=PX(I-1)+(6*VIS*VEL(I)*DX)*((1/H(I)^2)-(HBAR/H(I)^3))
580 R=2*LOG(DIA/DIA(I))
590 YI.ST(I)=YI.ST+K0*(R)^N
600 AIA=VIS*(4*VEL(I)-(3*VEL*HBAR/H(I)))/KI*H(I)
610 D.ST(I)=D.ST(I-1)+(4*KI*DX/DIA(I))*(YI.ST(I)+AIA)
620 P.R.A=((DIA^2-DIA(I)^2)/DIA^2)*100
630 IF PX(I)+D.ST(I)<6.0001*YI.ST(I) THEN 710
640 IF PX(I)+D.ST(I)=6.016133*YI.ST(I) THEN 650
650 PRINT
660 PRINT KI+X,DIA(I),VEL(I),H(I)
670 PRINT D.ST(I),PX(I),YI.ST(I)
680 PRINT D.ST(I)+PX(I),P.R.A
690 LET I=(I+1)
700 NEXT KI
710 NEXT X
720 GOTO 50
730 FOR QWE=1 TO 11
740 PRINT "-----";
750 NEXT QWE
760 PRINT
770 RETURN
780 END

```

Appendix [DD]

Determination of the yield characteristics of the wires

Wire materials selected for the experiment tests were copper and stainless steel of 2 mm nominal diameter. The yield characteristics of the wires were determined using a . Small samples of the wires with $L/D=1$ were subjected to uniaxial compression. The contact surfaces between the specimen and the plates were lubricated in order to minimise the frictional effects .

Readings of loads and compression were taken at close intervals throughout the test,. Knowing the initial length and the diameter of the specimen, true stress and natural strain values were calculated assuming constant volume and ignoring the "Barrelling" effect. At least three compression tests were carried out for each wire material and the results were shown in Figures DD.1 and DD.2 which are assumed to take the form;

$$Y = Y_0 + S\epsilon^n$$

where

Y_0 = initial yield stress N/m^2 .

S = Strain hardening constant N/m^2 .

n = Strain hardening index.

ϵ = Natural strain.

Using the experimental results, the above parameters were evaluated, by curve fitting for each wire, these are;

for copper wire $Y = 130 + 340 \epsilon^{.29} \quad N/m^2$

for stainless steel wire $Y = 180 + 1050 \epsilon^{.58} \quad N/m^2$

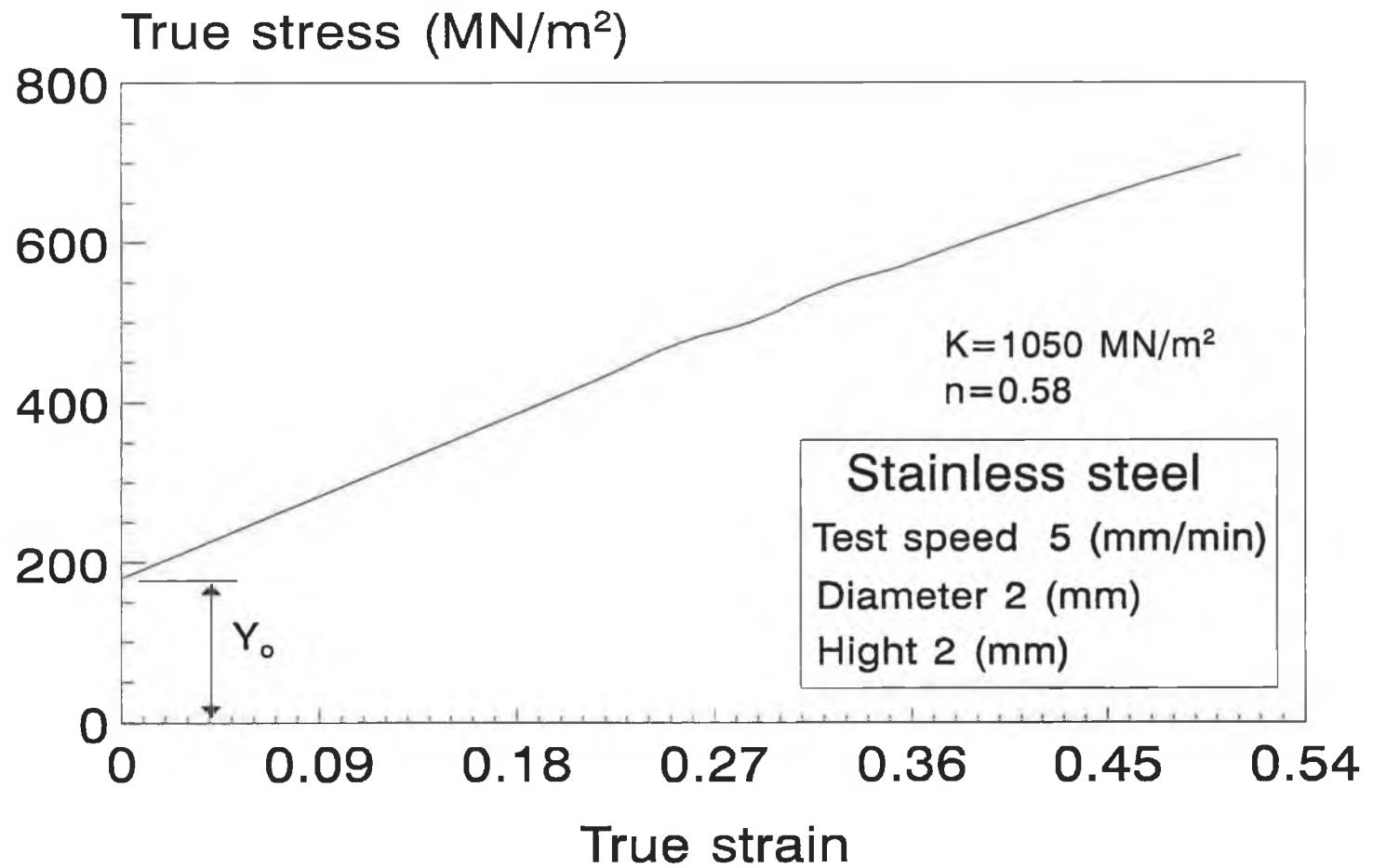


Fig. DD.1 True stress strain curve for stainless steel wire

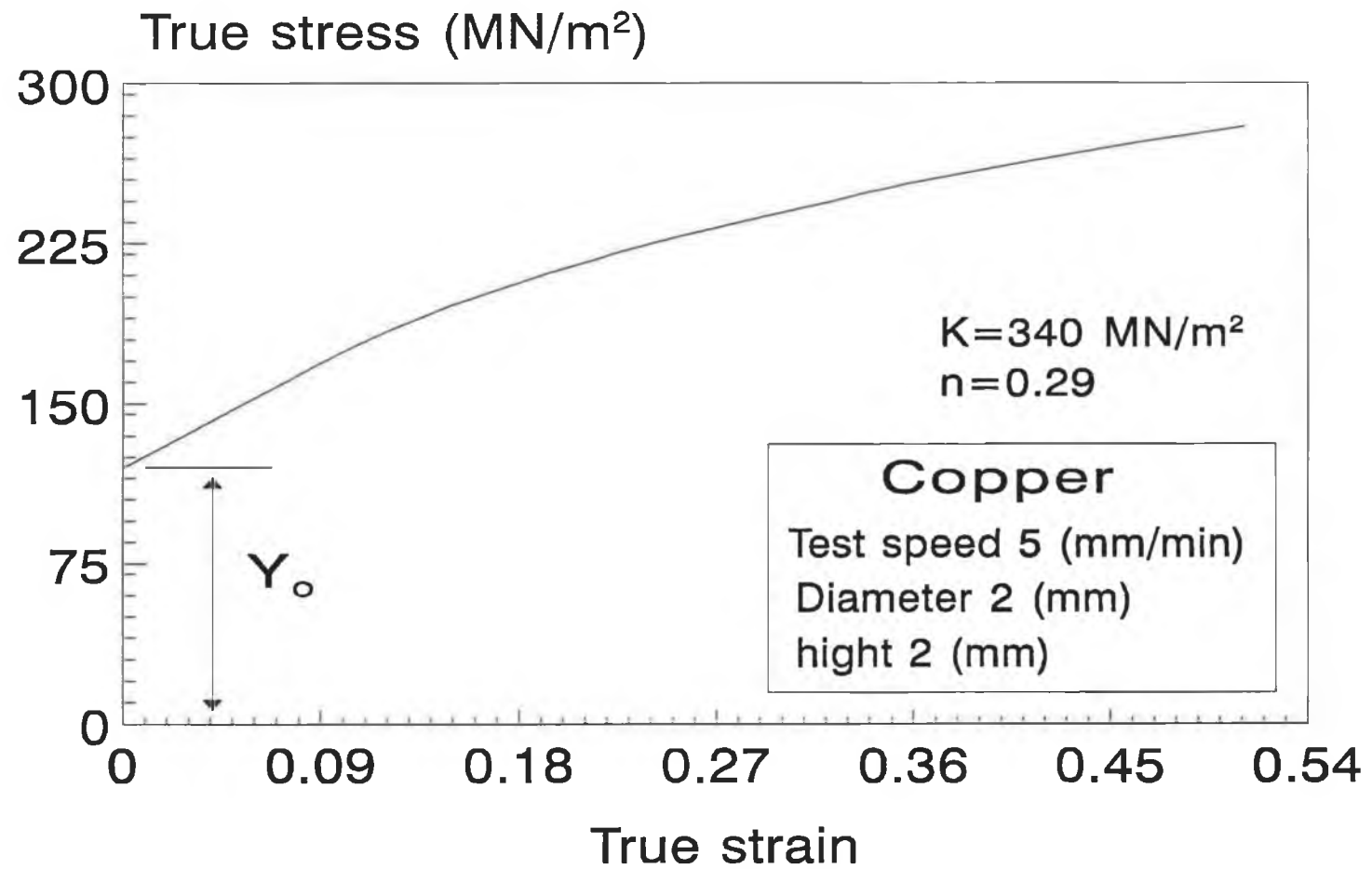


Fig. DD.2 True stress strain curve for copper wire