# TUBE DRAWING IN DIE-LESS CONICAL PRESSURE UNIT

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## Abstract

A theoretical study of the die-less tube sinking was carried out in which the conventional die is replaced by a die-less conical orifice reduction unit. The process involves pulling the wire through the conical die-less unit which is filled with a polymer melt, the pulling action causes yielding of the continuum and a reduction in area is then obtained.

A Newtonian behavior of the polymer melt and a rigid non-linear strain-hardening continuum were considered in which non-linear equations are formulated for the pressure and the stress increment in the die unit. A finite difference numerical technique was applied to solve these equations for the plasto-hydrodynamic pressure and the stress, which enabled prediction of the non-linear deformation profile of the continuum, the pressure distribution, and the percentage reduction in area for various drawing speeds.

The maximum reduction in area for tube sinking is (15%). The maximum pressure lies in the rear half of the die unit for various drawing speeds and it was found to be larger than that obtained by previous experimental work, however the drawing stress attained in this technique was less than that obtained using conventional dies.



## Introduction

Tube sinking operation involves pulling metal through a die by means of a tensile force applied to the exit side of the die. The material within the die is rendered plastic by the combined action of the applied longitudinal pull and the pressure developed between the wire and the die [1].

The reduction in diameter of a solid bar or rod by successive drawing is known as bar, rod, or wire drawing, depending on the diameter of the final product. In addition to direct application such as electrical wiring, wire is the starting material for many products including wire frame structures (ranging from coat hangers to shopping carts), nails, screws, bolts, rivets, wire fencing, etc.

In this technique, the wire is pulled through a tubular orifice of conical or stepped bore shape, which is filled with viscous fluid as shown in figure (1). Experiments [2] have shown that products having comparable dimensional and surface qualities can be achieved using this method. The only limitation observed during this process was the decrease in the reduction of the wire diameter at higher drawing speeds [3].

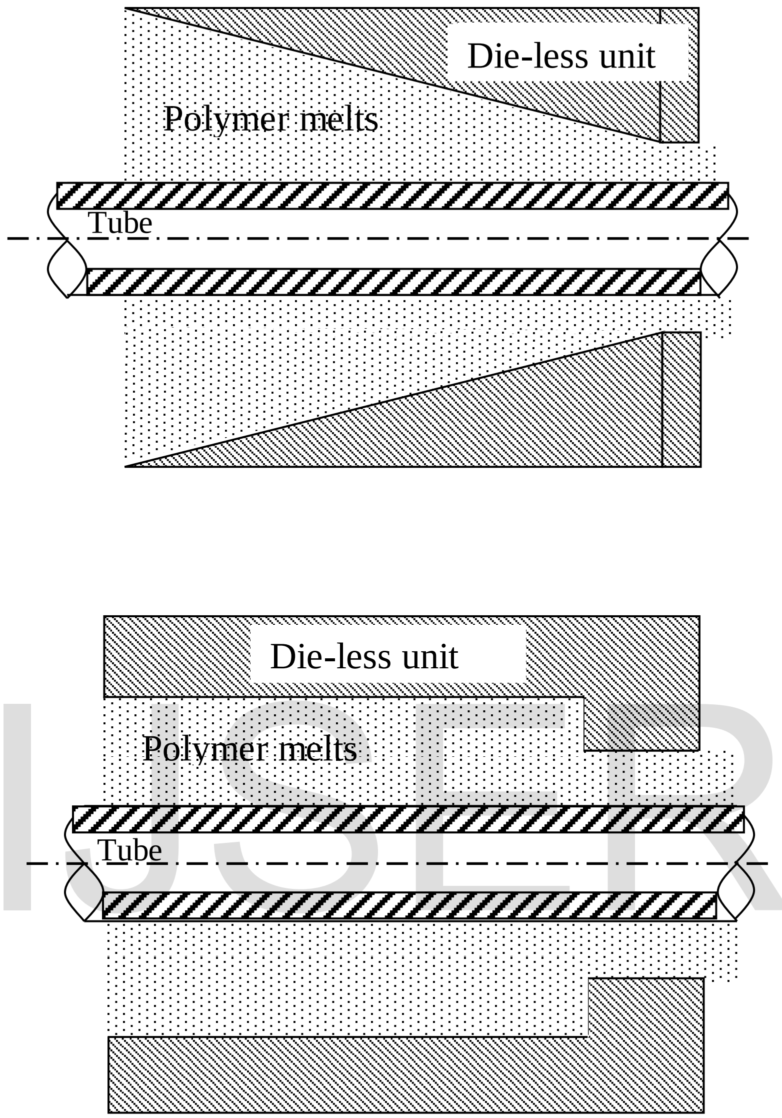


**Figure (1)** Schematic diagram showing (a) the tapered bore (b) the stepped bore die-less reduction unit.

## Theoretical Analysis

This study is focused on die-less tube sinking of constant thickness, the pressure medium is considered Newtonian. Non-linear equations are formulated for the pressure and axial stress increment in a conical tubular orifice with viscous fluid through which a circular cross-section continuum is being pulled. A finite difference numerical technique was applied to solve these equations for the plasto-hydrodynamic pressure and the resulting axial stress, which in turn enabled prediction of the non-linear deformation profile of the continuum, the pressure distribution and the percentage reduction in area for various drawing speeds.

## Analysis Prior to the Deformation of Die-Less Tube Sinking Process

The pressure at any point (x) within the orifice may be expressed by:

$$P=\frac{6\mu v}{k}[\{\frac{1}{(h_1-kx)}-\frac{h_0}{2(h_1-kx)^2}\}-\{\frac{1}{h_1}-\frac{h_0}{2h_1^2}\}] \quad (1)$$

Where, (P) is the hydrodynamic pressure exerted on the continuum. However ($h_0$) is still not determined. Using the boundary condition that P = 0 at x = B where ($h_1$-kx) = $h_2$ in equation (1) and rearranging:

$$h_0=\frac{2h_1h_2}{(h_1+h_2)} \quad (2)$$

Referring to figure (2), which represents an element in the continuum of the tube. In using a tube in the sinking process, the maximum and minimum stresses are the axial pulling stress and the hoop stress respectively. Resolving forces in a pressure direction is made to show the stress order, thus



$$P(r_s+t)d\theta*1=2\sigma_2 t\sin\frac{d\theta}{2}*1$$

For small angles sin($d\theta/2$) = ($d\theta/2$) in radian. Canceling and rearranging the above equation, we obtain the following relationship is obtained:

$$P=(\frac{t}{r_s+t})\sigma_2 \quad (3)$$

where, ($\sigma_2$) is the internal hoop stress, (t) is the thickness of the tube, ($r_s$) is the internal radius of the tube, and ($d\theta$) is the radial angle defining the element.

Since ($t/(r_s+t)$) is less than one, thus

$$P<\sigma_2$$

Since the pressure and the hoop stress are compressive stresses, then the hoop stress is used in Tresca yield criterion to define where yield commences. The pressure can be represented upon substitution into equation (3), and rearranging yields:

$$\sigma_2=\frac{(r_s+t)6\mu v}{kt}[\{\frac{1}{(h_1-kx)}-\frac{h_0}{2(h_1-kx)^2}\}-\{\frac{1}{h_1}-\frac{h_0}{2h_1^2}\}] \quad (4)$$

ISSN 2229-5518

The analysis of the stress and the drag force in the tube sinking process is the same as in the wire drawing process, after replacing ($D_1$) by ($D_b$) and ($D_s$), thus the axial pulling stress is given by:

$$\sigma_1 = \frac{4F_d}{\pi(D_b^2 - D_s^2)} = \frac{4D_b \mu v}{k(D_b^2 - D_s^2)}[\frac{3h_0}{(h_1 - kx)} - \frac{3h_0}{h_1} + 4\ln\{\frac{(h_1 - kx)}{h_1}\}]$$

(5)

where, ($\sigma_1$) is the axial pulling stress in the tube, ($D_b$) is the outer diameter of the tube, and ($D_s$) is the inner diameter of the tube.

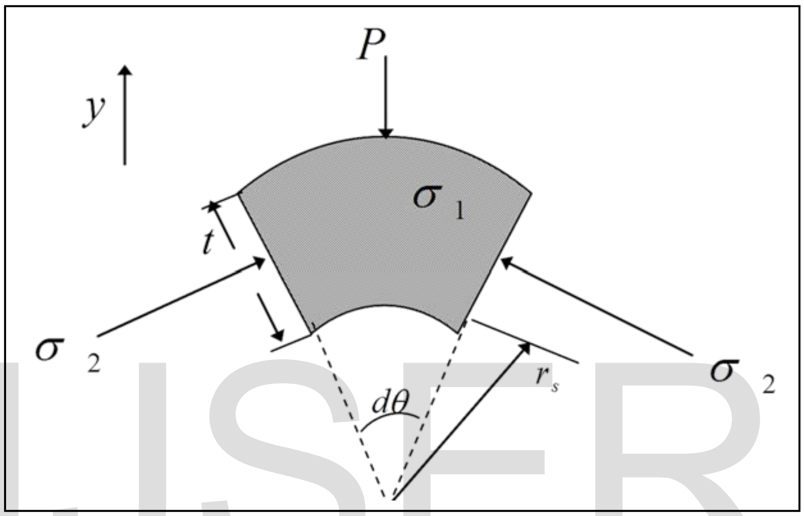


**Figure (2)** An element before the deformation commences in the tube shows the stresses acting on it.



## Analysis of deformation zone of die-less tube sinking process

## Plastic deformation

The combined effects of the axial stress and the internal hoop stress will cause plastic yielding of the continuum at any point (x), within the orifice as soon as the plastic yield criterion becomes satisfied. In the wire drawing process the flow stress is expressed by:

$$Y = Y_e + A\varepsilon^n \quad (6)$$

Also Tresca yield criterion

$$\sigma_1 + \sigma_2 = Y_e \quad (7)$$

Thus for a known value of ($Y_e$), equation (7) can be solved for ($x_p$) after substituting for ($\sigma_1$) and ($\sigma_2$) from equations (4) and (5) respectively. Once plastic yielding is predicted to commence for given values of ($\mu$), (v) and the geometrical parameters of the orifice, further permanent deformation of the continuum should continue to take place as long as:

$$\sigma_1 + \sigma_2 \geq Y = Y_e + A\varepsilon^n \qquad (8)$$

is satisfied at any distance from ($x_p$).

**2.4.2.2 Pressure and the hoop stress in the deformation zone**

The pressure gradient equation which is represented, and the finite difference of wire drawing can be used in tube sinking analysis after replacing ($D_i$) by ($D_{oui}$), and ($D_{i-1}$) by ($D_{oui-1}$).

Substituting into equation (3) gives the hoop stress, thus it can be written in a finite difference form as:

$$\sigma_{2i} = \frac{(r_{ini} + t)}{t}[P_{i-1} + 6\mu\Delta x(\frac{v_i}{h_i^2} - \frac{v_0 h_0}{h_i^3})] \qquad (9)$$

where,

$$r_{ini} = r_{ini-1} - b_i dx$$

**2.4.4.3 Axial stress in the deformation zone**

Referring to figure (3) which shows an element of the continuum within the deformed profile of the tube, the increment in axial stress may be expressed as:

$$\frac{d\sigma_1}{dx} = -\frac{\tau_x}{tr_{in}}(\frac{t + r_{in}}{\cos\alpha}) - \frac{Y\tan\alpha}{r_{in}} \qquad (10)$$

But cos ($\alpha$) $\cong 1$ (for small angles) and since ($\tau_x$) is given by:

$$\tau_x = -\frac{\mu}{h}(4v - \frac{3v_0 h_0}{h})$$

then by substituting for ($\tau_x$) and cos ($\alpha$) in equation (10), it becomes:

$$\frac{d\sigma_1}{dx} = \frac{\mu(t + r_{in})}{htr_{in}}(4v - \frac{3v_0 h_0}{h}) - \frac{Y\tan\alpha}{r_{in}} \qquad (11)$$

This can be written in finite difference form as:

$$\sigma_{1i} = \sigma_{1i-1} + \frac{\mu(t + r_{ini})\Delta x}{h_i tr_{ini}}(4v_i - \frac{3v_0 h_0}{h_i}) - \frac{Y_i b_i \Delta x}{r_{ini}} \qquad (12)$$

where,

$$Y_i = Y_e + A\{\ln(\frac{D_1}{D_{oui}})^2\}^n$$

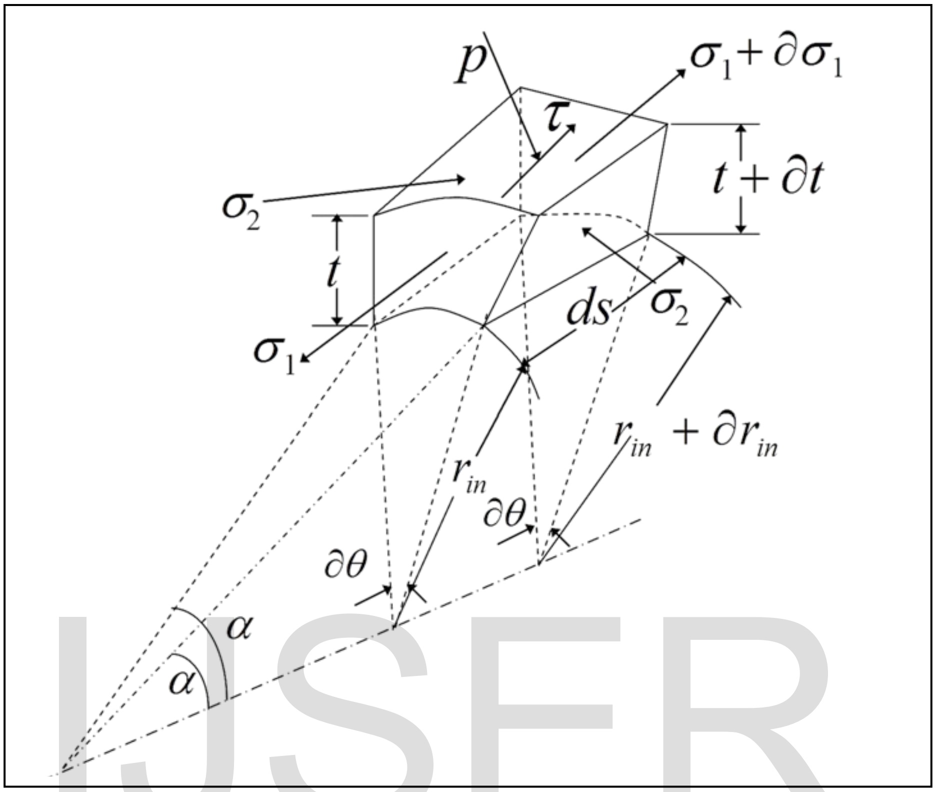


**Figure (3)** Isometric element in the deformation zone of the tube showing the stresses acting on it.

### 2.4.3 Analysis after the deformation has ceased

The deformation of the tube ceases completely at some distance before the exit of the die-less reduction unit, taking a final shape (diameter) to the tube. In order to determine the pressure in this region, the analysis of this region is similar to that before the deformation begins, thus:

$$P = \frac{6\mu v}{k}[\{\frac{1}{(h_1 - kx)} - \frac{h_0}{2(h_1 - kx)^2}\} - \{\frac{1}{h_1} - \frac{h_0}{2h_1^2}\}] \quad (13)$$

The final value for (v) is used in equation (13), and (x) is any distance after the deformation has ceased.

In summary, the procedure for predicting the theoretical results, involves the determination of ($x_p$), the distance from the die entry of the reduction unit to where plastic deformation commences, by iterative computation of equation (7) in conjunction with equations (5), and (6).

From this point until the deformation is stopped, the extent of plastic deformation is calculated on the basis of equation (8) when combined with equations (9), and (12) for small increment ( $\Delta x$ ) from ($x_p$). The current slope of the deformation profile ($b_i$) is determined by iterative computation of equation (8).

After the deformation has ceased the pressure can be determined from equation (13).

## Discussion of Results

A rigid non-linear strain hardening continuum and a Newtonian plasto-hydrodynamic analysis of the die-less unit is carried out.

A finite difference numerical technique is used to determine the pressure distribution, the coat thickness, and the resulting non-linear deformation profile of the drawn continuum.

## Pressure Distribution

The pressure is a very important parameter in the process of die-less tube sinking, because the pulling action of the wire through the viscous fluid generates hydrodynamic pressure and gives rise to drag force. Depending on the type of the fluid and the unit, the combined effect of the pressure and the drag force can be sufficient to cause plastic yielding and subsequently to deform the wire permanently [4].



## Deformation Profile

The non-linear deformation profile of the wire is shown in figure (4) for various drawing speed (0.5-4 m/s). From the figure it can be seen that as the drawing speed increases the deformation in the wire increases. Figure (5) shows the commencement of yield in the wire which is identical to that obtained by Hashmi [3]. Referring to the figure, the yield starts at a distance of (31.825 mm) from the entry at a drawing speed of (0.5 m/s) and at a distance of (12.317 mm) from the entry at a drawing speed of (2 m/s), while Hashmi [3] located the start of yield at a distance of (31.5 mm) from the entry at a drawing speed of (0.5 m/s) and at a distance of (12.1 mm) from the entry at a drawing speed of (2 m/s). The non-linear deformation profile of the wire obtained is identical to that obtained by Hashmi [3]. Hashmi however obtained a greater reduction in area than that obtained from figure (4). Hashmi found that about (24) percent reduction in area was produced at a drawing speed of (1 m/s) and which increased to about (36) percent reduction in area at a drawing speed of (4 m/s), while from figure (5) about (0.86) percentage reduction in area is obtained at a drawing speed of (1 m/s) and which increases to about (5.5) percent reduction in area at a drawing speed of (4m/s). Experimental results [2] show that about (23) percentage reduction in area was obtained at a drawing speed of about (0.21 m/s) and thereafter rapidly decreases down to about (6) percent reduction in area and remains unchanged for drawing speeds in excess of (2 m/s). This discrepancy can be attributed mainly to the fact that some constants in the deformation zone and the exact position of maximum pressure at various drawing speeds were not clearly given.

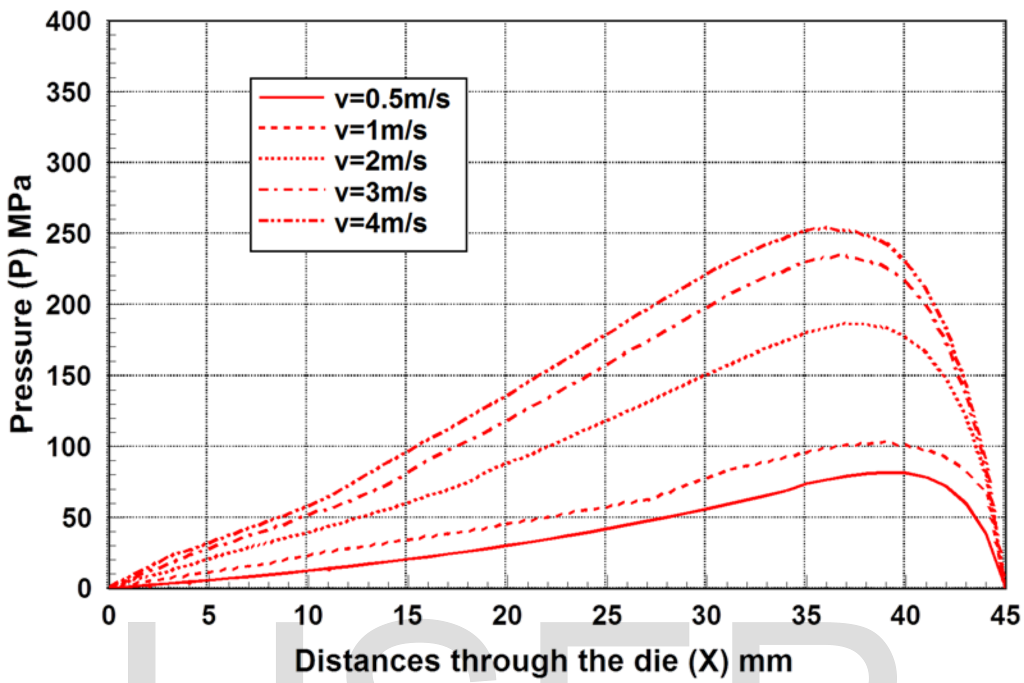


**Figure (4) Pressure distribution for tube sinking through a conical die with polymer melt (μ=120 N.s/m$^2$) at different drawing speeds.**

## Influence of the Drawing Speed

The drawing speed of the wire material has a great effect on all of the parameters, and it may be considered the most important parameter in the die-less wire drawing process. It can be seen from figure (5), that as the drawing speed is increased the reduction ratio and the coat thickness of the polymer melt on the wire also increase. It was found [3] that further reduction in area would not occur in the wire when the drawing speed was in excess of (2 m/s). A certain range of the drawing speed could be used in order to assure the optimum performance of the die-less drawing process.

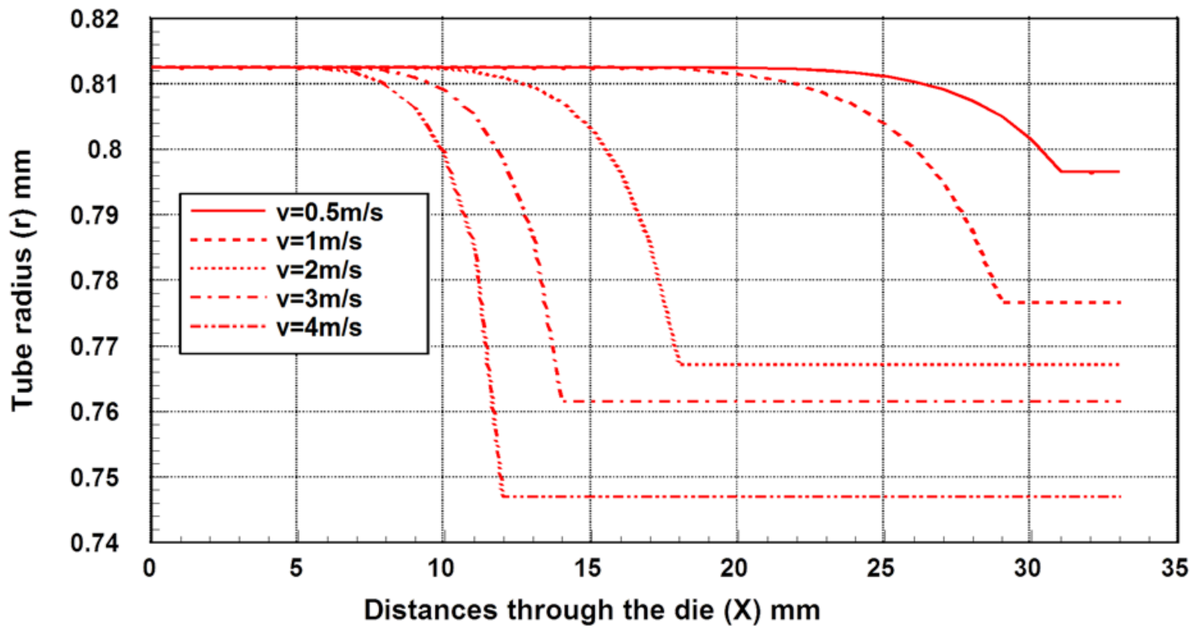


**Figure (5) Non-linear deformation profile for tube sinking through a conical die with polymer melt (μ=  N.s/m$^2$) at various drawing speeds.**



## Conclusions

A theoretical analysis for drawing wire and tube using a novel technique in which a die-less reduction unit in conjunction with a polymer melt is presented.

The main conclusions can be summarized as follows:

1. The plastic deformation starts and ends in the wire and tube before the pressure reaches its maximum value.
2. The deformation profile of the wire (or tube) inside the die-less reduction unit is non-linear and the deformation starts at a distance from the die entry and ends at a distance before the die exit. As the drawing speed increases the deformation range decreases.
3. The drawing stress attained in this technique is less than that obtained using conventional dies. A drawing stress of about (48 MPa) at a drawing speed of (0.5 m/s) for wire is needed by the die-less reduction technique, while a drawing stress [5] of about (190 MPa) is needed for the same conditions in a conventional reduction unit.

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