THE EFFECT OF WEB RHEOLOGY AND PEELING ON WEB TRANSFER IN OPEN DRAW

by

M. Kurki[1], J. Vestola[1], P. Martikainen[2], and P. Pakarinen[1]
[1]Valmet Corporation
[2]Technical Research Center of Finland
Finland

ABSTRACT

To achieve higher productivity in papermaking, the increasing of web speed is the most efficient way. However, velocity increase will also immediately cause greater demands according to the web strength.

In normal papermaking process, the form of the web changes gradually through the forming and press sections from suspension to solid form. After the press section, the basic fiber structure of the paper has already been created, but its rheological properties are in the beginning state of their development. Due to the water removal method by pressing the wet fiber network against a press roll surface, an adhesion force is generated between the web and the surface.

At the end of the press section, the strength of the web is still very low due to the web's great moisture content. At this point, the mechanical properties of the paper can be affected or even deteriorated by wrong web peeling methods. For this reason, the understanding and controlling of the adhesional behaviour of the web is essential especially in the cases of high velocity levels.

This paper studies the adhesional behaviour of the open draw, which is usually the first time during the papermaking process when the wet web is stressed mechanically in the longitudinal direction. This behaviour is studied by a quasi-dynamic mathematical model, which includes force balance and continuity models and also a rheological model for the open draw and material properties of the web respectively.

The model consists of steady-state and nonsteady-state portions. Time-dependency is applied through mass flow and rheological equations, force balance equation is in static form. The

solving method for this coupled equation system is to first solve the ideal steady-state situation and, after this nonsteady-state equations which can be solved by using the steady-state situation as an initial condition.

The qualitative behaviour of this model is correct, for example the increase in peeling angle between the surface and the web can be observed in cases of both velocity increase and adhesion energy increase even if the relative speed difference of the open draw has remained constant. Limitations appear mainly in the correctness of web material, adhesion and external pressure parameters. However, by using this model, also the effects of such external disturbances as adhesion and pressure disturbances can be studied efficiently.

One of the main results is also an exponential increase in the peeling angle as a function of velocity. In this paper, it is caused by the centripetal force affecting the web.

As a conclusion, the peeling behaviour of the wet web in an open draw is a very sensitive system. The main advantage of this system is its capability to self-adjustment through changes of the mass flow rate and peeling angle. However, also the rheological properties of the web and the adhesion force itself play a significant role in the optimization and stabilization of the web transfer in an open draw.

NOMENCLATURE

b	Strain coefficient	
C	Aerodynamic constant	
c	Ratio of two steady-state tensions	
d	Distance	m
E	Specific modulus of elasticity	m^2/s^2
g	Gravitational constant	m/s^2
h	Thickness of the web	m
k	Strain rate constant	1/m
l	Length	m
m	Basis weight	kg/m^2
p	Pressure	N/m^2
r	Radius of the roll	m
R	Local radius of the web	m
t	Time	s
T	Tension	N/m
u	Axial displacement	m
v	Velocity	m/s
w	Vertical displacement	m
x	Axial coordinate	m
Y	Young's modulus	N/m^2
Δ	Difference	
δ	Difference	
ε	Strain	

γ	Top angle	radian
φ	Take-off angle	radian
ρ	Density	kg/m^3
Θ	Local angle of the web	radian
ν	Kinematic viscocity	m^2/s

SUBSCRIPTS

a	Air
d	Drag
f	Friction
T	Total
0	Undeformed or sum
1	Beginning
2	Ending

1. INTRODUCTION

In papermaking, the material behaviour of the web can be very different. Paper web is formed from suspension whose consistency can be appr. 0.7 % and, after the forming section and press section, the web can be considered solid 'web' which already has some kind of elastic behaviour. After the press section, the dry solids content of the web is typically 45 - 50%, and the strengh of the web is mainly the result of some hydrogen bonds between the fibers and also finer fiber particles (fines) and also the frictional behaviour of the above mentioned particles contacting each other.

The strength and elastic moduli of this kind of structure are low and the elastic behaviour is also time-dependent, e.g. viscoelasticity plays a major role in the material behaviour of the web. At this point of the papermaking process, the paper web is usually peeled off from the press roll and, also in this point, the major part of the stretch against the web is executed.

The amount of the stretch can be adjusted with relative speed difference between the press roll and paper guide roll (≈strain), and this adjustment is very sensitive according to the overall runnability of the press and drying section and also the quality of the paper. Therefore, the peeling of the web from the press roll is one of the bottlenecks in increasing the productivity of the paper machine by speed increase, and therefore, the handling of this process is essential.

2. THE MODEL

2.1 Time-dependent model of the open draw

Once again, we describe the time-dependent tension behaviour of a moving web in the open draw with the following non-linear time-dependent equations [1], [2]:

$$T = \Delta p R + m g R\cos\Theta + \frac{Y h^3}{12}\frac{\partial^4 w}{\partial x^4}R + m R\left(\frac{d^2 w}{d t^2}\cos\Theta - \frac{d^2 u}{d t^2}\sin\Theta\right) + \frac{1}{2}C_d \rho_{ai} R\left(\left(\frac{d w}{d t}\right)^2 \cos^2\Theta - \left(\frac{d u}{d t}\right)^2 \sin^2\Theta\right) \tag{1}$$

and

$$dT = \frac{1}{2}C_f \rho_a v^2 R d\Theta + m R\left(\frac{d^2 u}{d t^2}\cos\Theta + \frac{d^2 w}{d t^2}\sin\Theta\right)d\Theta + \frac{1}{2}C_d \rho_a R\sin\Theta\cos\Theta\left(\left(\frac{d u}{d t}\right)^2 + \left(\frac{d w}{d t}\right)^2\right)d\Theta \tag{2}$$

where

$$\frac{d u}{d t} = v\cos\Theta - \frac{\partial w}{\partial t}\sin\Theta\,\cos\Theta \tag{3}$$

$$\frac{d w}{d t} = \frac{\partial w}{\partial t} + \frac{d u}{d t}\frac{\partial w}{\partial x} \tag{4}$$

$$\frac{d^2 w}{d t^2}\cos\Theta - \frac{d^2 u}{d t^2}\sin\Theta = \frac{\partial^2 w}{\partial t^2} + \frac{d u}{d t}\frac{\partial^2 w}{\partial x \partial t} + \left(\frac{d u}{d t}\right)^2 \frac{\partial^2 w}{\partial x^2} \tag{5}$$

If we assume that the shape of the web deflection $w(x,t)$ is an arc which has a time-dependent radius, we assume the following:

$$w(x,t) = \sqrt{R^2(t) - \frac{\ell_0^2}{4}} - \sqrt{R^2(t) - x^2} \tag{6}$$

where ℓ_0 is the span length of the arc.

If we omit time-dependent partial time derivatives from Eqns. (1) - (5) and calculate only place-dependent derivatives from Eq. (6) and substitute them back in Eqns. (1) - (5), we obtain the following tension statement at the middle point of the arc $(\Theta = 0, x = 0)$:

$$T = \Delta p R + m g R + \frac{Y h^3}{4 R^2} + m v^2 + \frac{1}{2}C_f \rho_a v^2 R d\Theta \tag{7}$$

However, in the case of Fig.1, total web tension T also includes tension component T_{ad}, which decribes the effect of the adhesion force between the web and peeling surface. If we also integrate the last term over the length of the open draw, we obtain the friction force for both sides of the web caused by air drag. Now, the total tension T_{tot} can be written as follows:

$$T_{tot} = \Delta p R + m g R + \frac{Y h^3}{4R^2} + m v^2 + C_f \rho_a v^2 \ell + \frac{W}{1-\cos\varphi} \tag{8}$$

2.2 Runnability geometry

The realistic runnability geometry can also be seen in Fig. 1. If we are observing web behaviour between the length d, we can write the following geometry equations:

$$\gamma = \varphi + \arcsin\left(\frac{r_1 \cos\varphi + r_2}{d}\right) \tag{9}$$

$$\ell_0 = \sqrt{d^2 + r_1^2 - r_2^2 - 2 r_1 d \sin\gamma} \tag{10}$$

One of the most important feature of a continuous moving web is its ability to self-adjust the mass of the open draw according to the force balance of the web. The basis of this phenomenon is in the behaviour of continuity equation. The mass in unit length can be written as follows:

$$M = m r_1 \gamma + \frac{m\ell}{1 + b\varepsilon_T} + \frac{m r_2 (\gamma - \varphi)}{1 + \varepsilon_T} \tag{11}$$

Constant b defines the strain distribution in open draw length l. In the case of high strain rate $b \approx 1$ respectively, in the case of low strain rate (high viscosity values or very high web speed) $b \approx 0.5$. The difference of incoming and outgoing mass flow can be defined in the following manner:

$$\frac{dM}{dt} = m v_1 - \frac{m v_2}{1 + \varepsilon_T} \tag{12}$$

If we differentiate Eq. (11) and set it equal to Eq. (12) we obtain, after simplification, the following continuity equation:

$$\begin{aligned} v_1(1+\varepsilon_T) - v_2 = {} & \frac{dm}{m\,dt} r_1 \gamma (1+\varepsilon_T) + \frac{d\gamma}{dt} r_1 (1+\varepsilon_T) + \\ & \frac{dm}{dt}\frac{\ell}{m}\frac{1+\varepsilon_T}{1+b\varepsilon_T} + \frac{d\ell}{dt}\frac{1+\varepsilon_T}{1+b\varepsilon_T} - \frac{d\varepsilon_T}{dt}\frac{b\ell(1+\varepsilon_T)}{(1+b\varepsilon_T)^2} + \frac{dm}{dt}\frac{\gamma r_2}{m} + \frac{d\gamma}{dt} r_2 - \\ & \frac{d\varepsilon_T}{dt}\frac{\gamma r_2}{(1+\varepsilon_T)} - \frac{dm}{dt}\frac{\varphi r_2}{m} - \frac{d\varphi}{dt} r_2 + \frac{d\varepsilon_T}{dt}\frac{\varphi r_2}{(1+\varepsilon_T)} \end{aligned} \tag{13}$$

In a steady state situation, the above will reduce to form:

$$\varepsilon_T = \frac{v_2 - v_1}{v_1} \tag{14}$$

Thus, the solving of this peeling model consists basically of the solution of Eqns. (8) and (13). The solution of this open draw model is discussed more in Chapter 4.

3. MATERIAL BEHAVIOUR OF THE WEB

3.1 Strain behaviour

The strain behaviour of the moving web can be derived using equations of axial wave mechanics of viscoelastic bar. The strain behaviour of the open draw can be found using for example the famous Kelvin-Voigt viscoelastic model. According to Newton's Second Law, we can write the following for axial displacement:

$$m\frac{d^2 u}{d t^2} = \frac{\partial T}{\partial x} \tag{15}$$

In the case of the Kelvin-Voigt model, the web tension can also be written as follows:

$$T = m\left(E\varepsilon + v\frac{d\varepsilon}{dt}\right) \tag{16}$$

If we differentiate Eq. (16) according to the place and remembering that $\varepsilon = \partial u/\partial x$, we obtain equation the following for a stationary web:

$$m\frac{d^2 u}{d t^2} = mE\frac{d^2 u}{d x^2} + mv\frac{d^3 u}{d x^2 d t} \tag{17}$$

When the web is moving, the displacement u depends both on place and time $u = u(x,t)$. Now the differentials in Eq. (17) can be defined in the following form:

$$\frac{d^2 u}{d t^2} = \frac{\partial^2 u}{\partial t^2} + 2v\frac{\partial^2 u}{\partial x \partial t} + v^2\frac{\partial^2 u}{\partial x^2} \tag{18}$$

$$\frac{d^3 u}{d x^2 d t} = \frac{\partial^3 u}{\partial x^2 \partial t} + v^2\frac{\partial^3 u}{\partial x^3} \tag{19}$$

Thus, the full linear viscoelastic (Kelvin-Voigt) equation of an axial moving web is:

$$\frac{\partial^2 u}{\partial t^2} + 2v\frac{\partial^2 u}{\partial x \partial t} + v^2\frac{\partial^2 u}{\partial x^2} = E\frac{\partial^2 u}{\partial x^2} + v\left(\frac{\partial^3 u}{\partial x^2 \partial t} + v^2\frac{\partial^3 u}{\partial x^3}\right) \tag{20}$$

Remembering the definition of strain mentioned earlier, the steady-state equation of the moving web can be written as follows:

$$\frac{\partial^2 \varepsilon}{\partial x^2} + k\frac{\partial \varepsilon}{\partial x} = 0\ \text{, where} \tag{21}$$

$$k = \frac{E - v^2}{\nu v} \tag{22}$$

If we assume that at the beginning of the open draw, the strain $\varepsilon = 0$ and $\varepsilon = \varepsilon_T$ at the end of the open draw, the solution of Eq. (21) is:

$$\varepsilon(x) = \varepsilon_T \frac{1 - e^{-kx}}{1 - e^{-k\ell}}\ \text{, where}\ \ \varepsilon_T \approx \frac{v_2 - v_1}{v_1} \tag{23}$$

A schematic plot of the solution of Eq. (23) with different viscoelasticity parameter values can be found in Fig. 2. Above kind of strain behaviour has also been found in experimental results [4].

3.2 Viscoelastic model of the paper web

It is a well-known fact that paper web is a material which exhibits both relaxational and creeping behaviour. These rheological properties affect the earlier expressed strain behaviour and thus the overall tension behaviour of the web. Rheological models have been widely used in the area of plastic industry but, due to similarities in the behaviour between plastic and paper, these models have also been used in the paper industry and paper science.

Rheological models can easily be developed by combining both springs and dampers. In some cases, these can also have nonlinear behaviour. Usually, the policy is to use a such number of these components which can imitate the rheological behaviour of the paper accurately enough. However, the number of undefined material parameters increases with every new component. Therefore, the usual way is to make a reasonable choice between these two cases.

In this paper, we have used a rheological model which contains two springs and one damper. By arranging these components so that one spring is attached parallel with the combination of another spring and damper which are both connected in series we get a model which is known as Linear Standard Model (Fig. 3). Linear Standard Model can be expressed as follows:

$$\frac{dT(t)}{dt} = \frac{mE_1E_2}{\nu}\varepsilon(t) + mE_0\frac{d\varepsilon(t)}{dt} - \frac{E_1}{\nu}T(t)\ , \quad \text{where } E_0 = E_1 + E_2 \tag{24}$$

The relaxation behaviour of the above equation can be found in Fig. 4. In the case of a very slow strain rate, the tension level is relaxation tension level, which is equal to $mE_2\varepsilon$. In the case of a very fast strain rate the highest tension level ("peak" tension) is $m E_0 \varepsilon$ [5]. The benefit of using this kind of model is the relative easiness in parameter determination. Examples of real relaxational behaviour of fine office paper can be found in Fig. 5.

4. SIMULATION

4.1 Simulation method

Two types of cases are analyzed: steady state and transient phenomena, as well as their dependence on design parameters and material rheology. In steady state, the evolution of state variables occurs along the open draw. In transient analysis, the steady state is the basis and starting point for transient calculations.

In a steady state, the outer loads on the web consisting of pressure, peeling energy, inertial and frictional forces are in equilibrium with the tension produced by "draw difference " i.e. the relative velocity difference between successive rolls. The tensional state of a web reflects this force balance. In our case, steady state is governed by the equations (8)-(10), (14) and

$$\mathrm{Sin}\left(\frac{l}{2R}\right)=\frac{l_0}{2R} \tag{25}$$

$$T_0=\frac{m E_2 \varepsilon_T}{1-e^{-\frac{E_1 E_2 l}{(E_1+E_2) v_1 v}}} \tag{26}$$

where T_0 is the steady state tension in the paper web. The values of variables T_0, l, l_0, φ and γ are searched using Newton's method. The search space seems to be quite convex and good first values for iteration are not needed.

Dynamic analysis of web bevaviour is based on the equations (8), (9), (10), (13) and

$$\frac{dT}{dt}=\frac{m E_1 E_2 c\, \varepsilon_T(t)}{v}+m(E_1+E_2)\frac{d\varepsilon_T(t)}{dt}-\frac{E_1}{v}T(t) \tag{27}$$

which is used to describe the relation between the tension and strain ε_T at the end of the draw. In not far from elastic cases, factor c is 1 or close to 1. In the case of more viscous materials, factor c gets greater values than 1. This trick is used to simplify the model at the cost of slight inaccuracy in process dynamics. The limitation disappears with less viscous materials.

The equation system describing web dynamics can be reduced to two coupled first-order differential equations for φ and ε. Peeling energy W(t) and pressure difference $\Delta p(t)$ over the web can be used as disturbing inputs. The classical fourth-order Runge-Kutta formula is used to solve the set differential equations with the steady state solutions as initial condition. For this integration scheme, step error approaches zero like δt^5 where δt is the integration step size. If high-order derivatives are not continuous, which is usual, superiority in accuracy is lost. But essentially, potential defects of the results lie in governing equations not in the numerical method used.

5. RESULTS

5.1 Steady-state situation

The basic geometric data for analysis was as follows. The axes of two successive rolls were at the same level and their radii were $r_1 = 700$ mm (upstream roll) and $r_2 = 350$ mm (downstream roll). The shortest distance between roll surfaces was 50 mm. Web velocity at the beginning of the draw was v_1=18.00 m/s and at the end v_2=18.54 m/s.

Paper web was considered rather elastic. The spring constants of linear standard material were selected in the basic case to be E_1 = 10 000 m^2/s^2, E_2 = 25 000 m^2/s^2 and kinematic viscosity ν = 5 m^2/s. Weight of paper per surface area was 140 g/m^2. Adhesion energy level was selected to be 2.5 J/m^2 and pressure difference over the web 20 Pa.

Three important aspects, take-off angle, tension and strain evolution in open draw were considered. For viscous material modelled e.g. by Maxwell model, a linear evolution into the final strain occurs. The behaviour of Kelvin-Voigt material can vary from nearly Maxwell to elastic one. The same is true for linear standard material discussed here. The steady state strain distributions in an open draw for three kinematic material viscosities ν = 5, 15 and 30 m^2/s are shown in Fig. 2. For materials with dominating elasticity strain evolution occurs mainly at the beginning of the open draw.

Peeling energy and viscosity of the web material are important factors in open draw dynamics. Figure 6 illustrates the dependence of the take-off angle on peeling energy and material kinematic viscosity at a constant machine velocity. Increasing machine velocity tends to increase take-off angle in an open draw (Fig 7.). This can lead to unstable web transfer and break in production.

5.2 Nonsteady-state situation

Paper web with characterictics chosen above was exposed to peeling energy disturbances in open draw. Two types of inputs were used. In the first case, the pulse of constant shape and peak height of 6.0 J/m^2 but varying duration were added to the basis load of 2.5 J/m^2 (Fig. 8). The length of the disturbance was 2, 20, 100, 200 or 400 ms. The responses in tension, strain and take-off angle were studied. The shorter the pulse duration, the bigger the peak tension and strain in response.

When increasing the length of disturbance pulse, undershoot in tension and strain below the steady state level increased. But after a certain pulse length, it began to diminish. Already a disturbance signal with a length of 400 ms was seen by the process more as trend input resulting in a rather smooth response. Also, the lowest tension value noticed in response was slightly bigger for 400 ms pulse duration than for that of 200 ms . The longest pulse led to the largest range in take-off angle.

In the second case, the system was exposed to peeling energy step changes with time constants of 2, 20 or 100 ms (Fig. 9). Also, in this case, the largest change rate in input caused top values in tension and strain. Take-off angles drifted slowly to new steady states. Strain and tension returned essentially to the same level where they started. That was because of the elastic part of the material was dominating. In a highly viscous case, that would not have happened.

Resinous sticky spots can sometimes cause problems in paper web handling. Figure 10 gives an approximation what happens in an open draw when a resinous spot comes up on the side of the upstream roll. In the analysis, spring constants were the same as in our basic case. Materials of three kinematic viscosities 5, 15 and 30 m^2/s were considered. The most viscous material developed the greatest range and values in tension but the smallest ones in strain.

6. CONCLUSIONS

In this paper, open draw behaviour in the case of adhesion force has been studied.

In general, the external forces in the presence of peeling force in the first open draw form a very sensitive runnability system due to the low strength of the wet web. One essential feature of this system is its capability to self-adjust the tension level even if the level of external forces changes. The adjustment is possible through the changing of the take-off angle. However, the levels of external disturbances (adhesion force etc.) can temporarily give rise to tension changes which eventually can break the web. This phenomenon is greatly affected by viscosity parameters of the web. The greater the viscosity parameter, the greater the tension disturbance. Due to this feature, the smoothness of adhesion force behaviour is very important. Also, knowledge of the web parameters is important to achieve good runnability in the press section and at the beginning of the drying section.

INDEX

1. Pakarinen ,P., Ryymin, R., Kurki, M., Taskinen, P., "On the Dynamics of Web Transfer in an Open Draw", Proceedings of the Second International Conference on Web Handling. Oklahoma State University,1993, 18 p.

2. Kurki, M., Juppi, K., Ryymin, R., Taskinen, P., Pakarinen, P., "On the Web Tension Dynamics in an Open Draw", Proceedings of the Third International Conference on Web Handling. Oklahoma State University,1995, 16 p.

3. Findley, W.,N., Lai, J., S., Onaran, K., Creep and Relaxation of Nonlinear Viscoelastic Materials, Dover Publications, Inc., New York, 1976, 371 p.

4. Hauptmann, E., G., Cutshall, K., A., "Dynamic Mechanical Properties of Wet Paper Webs", Tappi Journal, Vol. 60, No. 10, Oct. 1977, pp. 106-108.

5. Tekniikan käsikirja 5, 3 rd ed., K. J. Gummerus Oy, Jyväskylä, 1975, pp. 202-206.

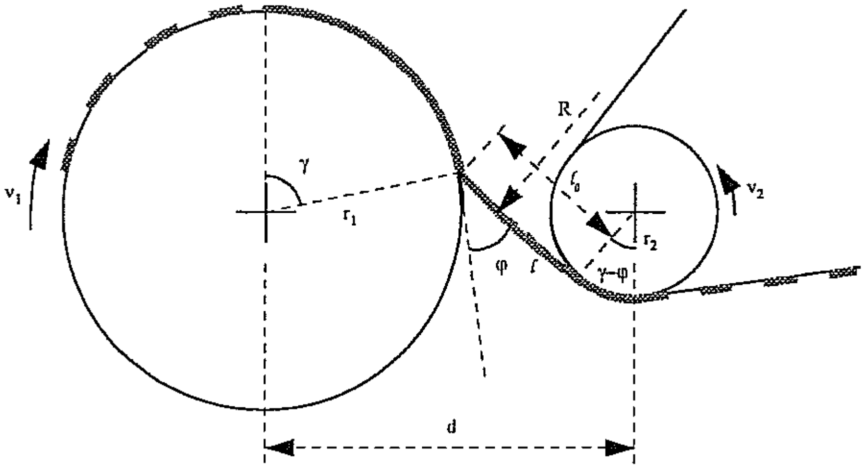

Fig. 1. Adhesional open draw in press section.

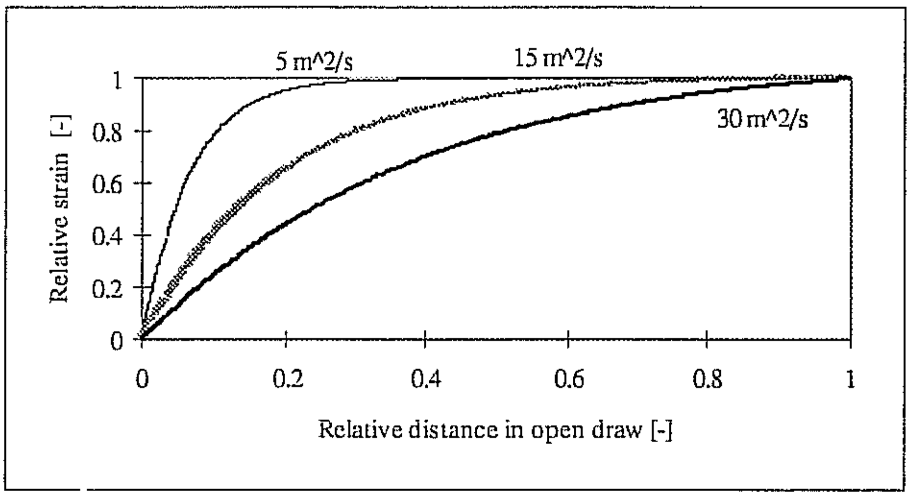

Fig. 2. Relative strain in an open draw with different material kinematic viscosities.

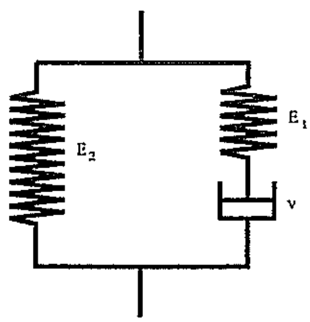

Fig. 3. Linear Standard Model for viscoelastic behaviour of paper.

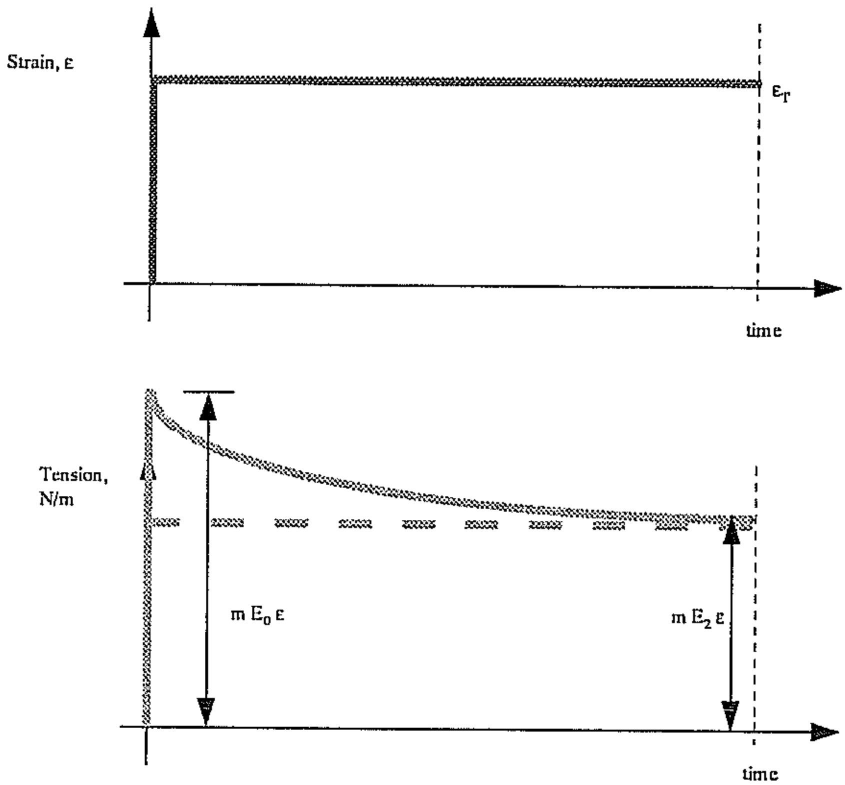

Fig. 4. Relaxational behaviour of Linear Standard Model.

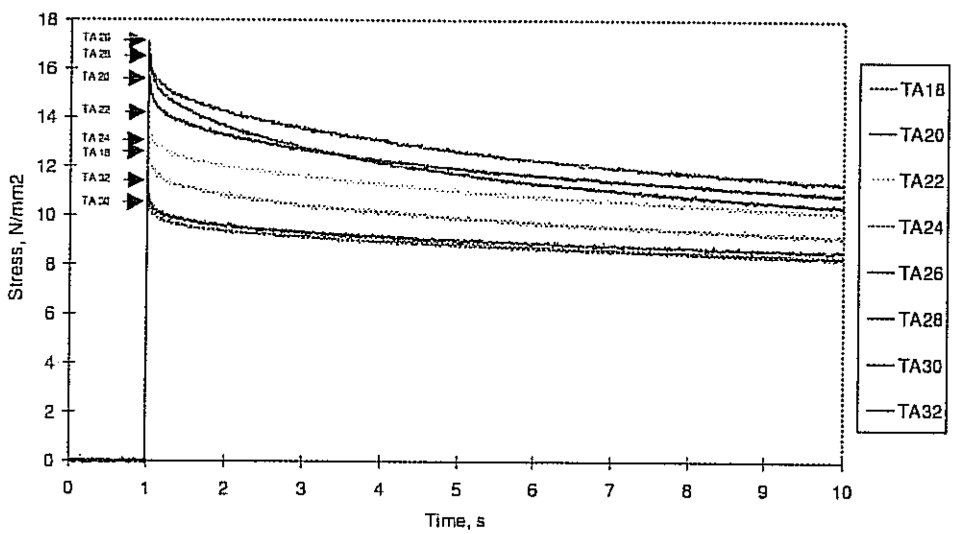

Fig. 5. Real relaxation behaviour of dry fine paper.

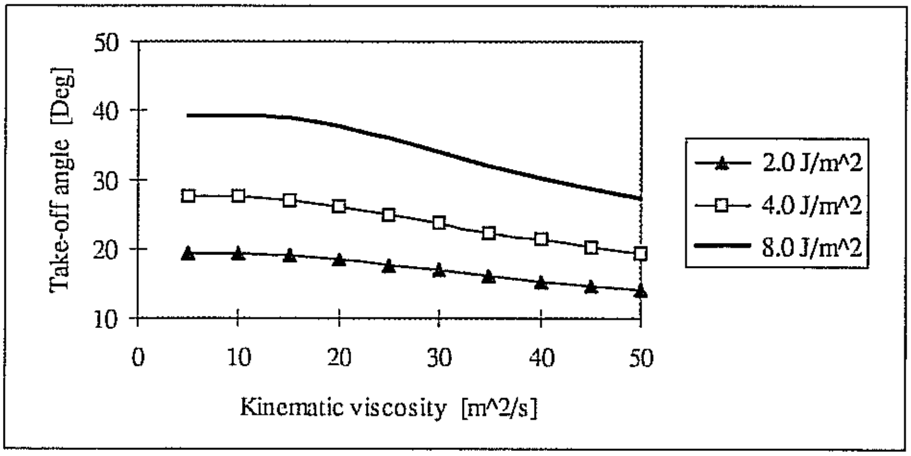

Fig. 6. Take-off angle of viscoelastic webs at constant machine velocity.

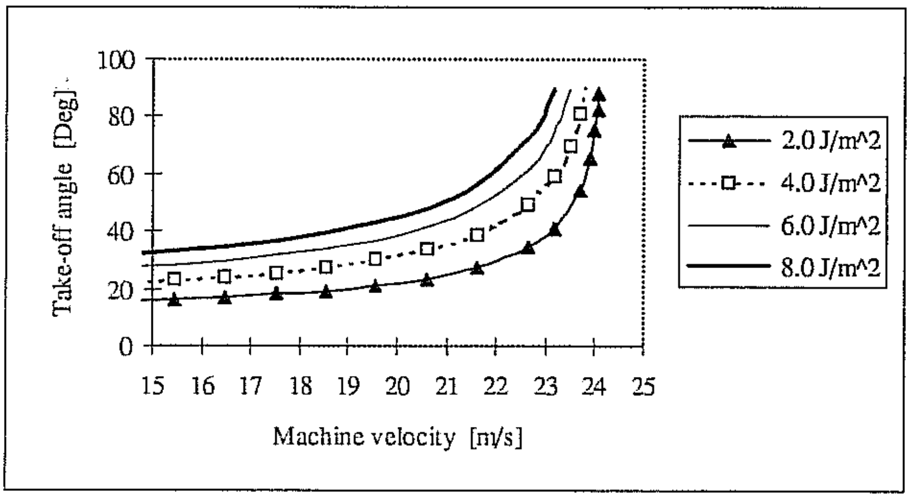

Fig. 7. Take-off angle of viscoelastic webs as function of machine velocity.

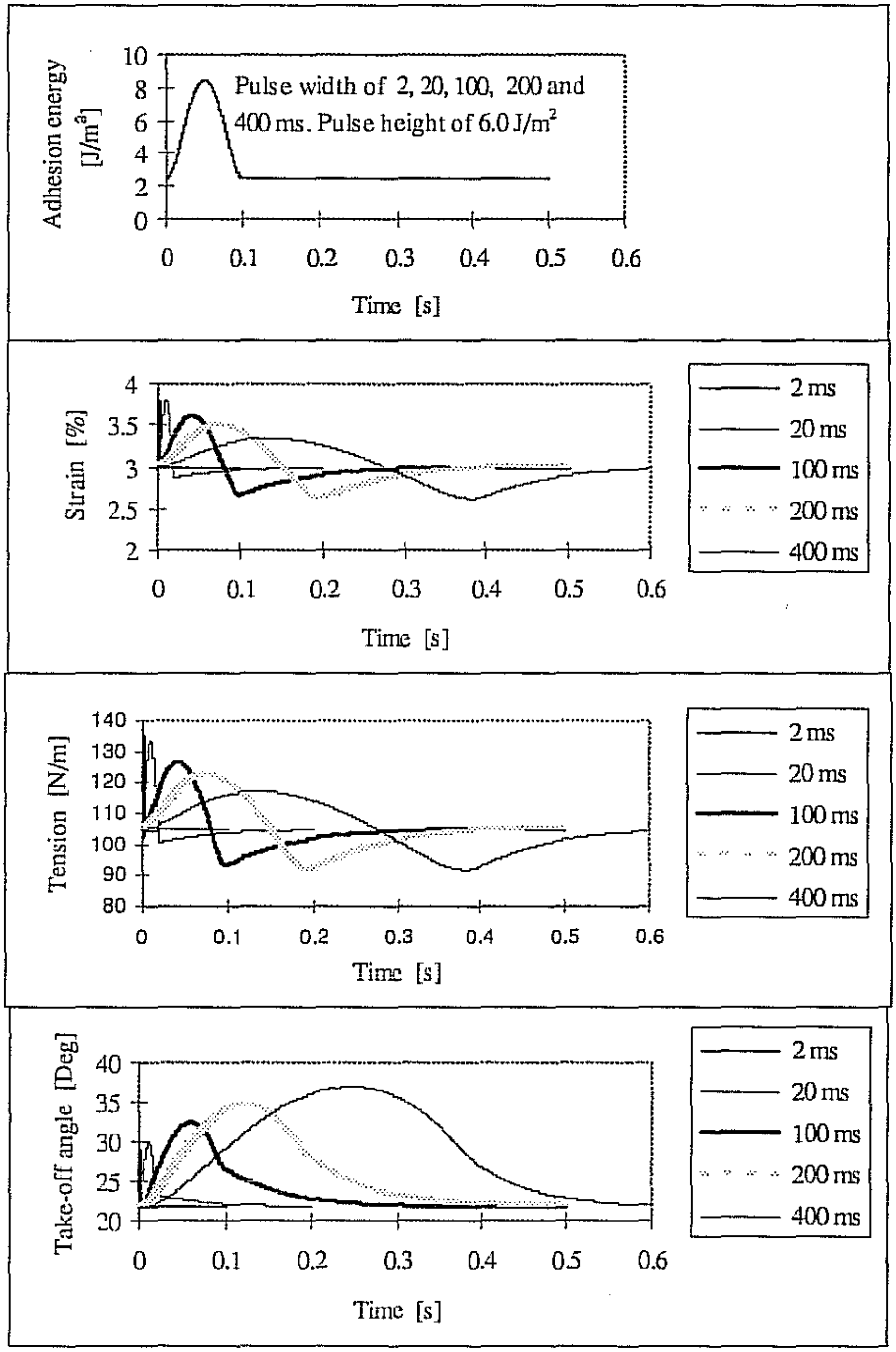

Fig. 8. System responses to adhesion energy pulses.

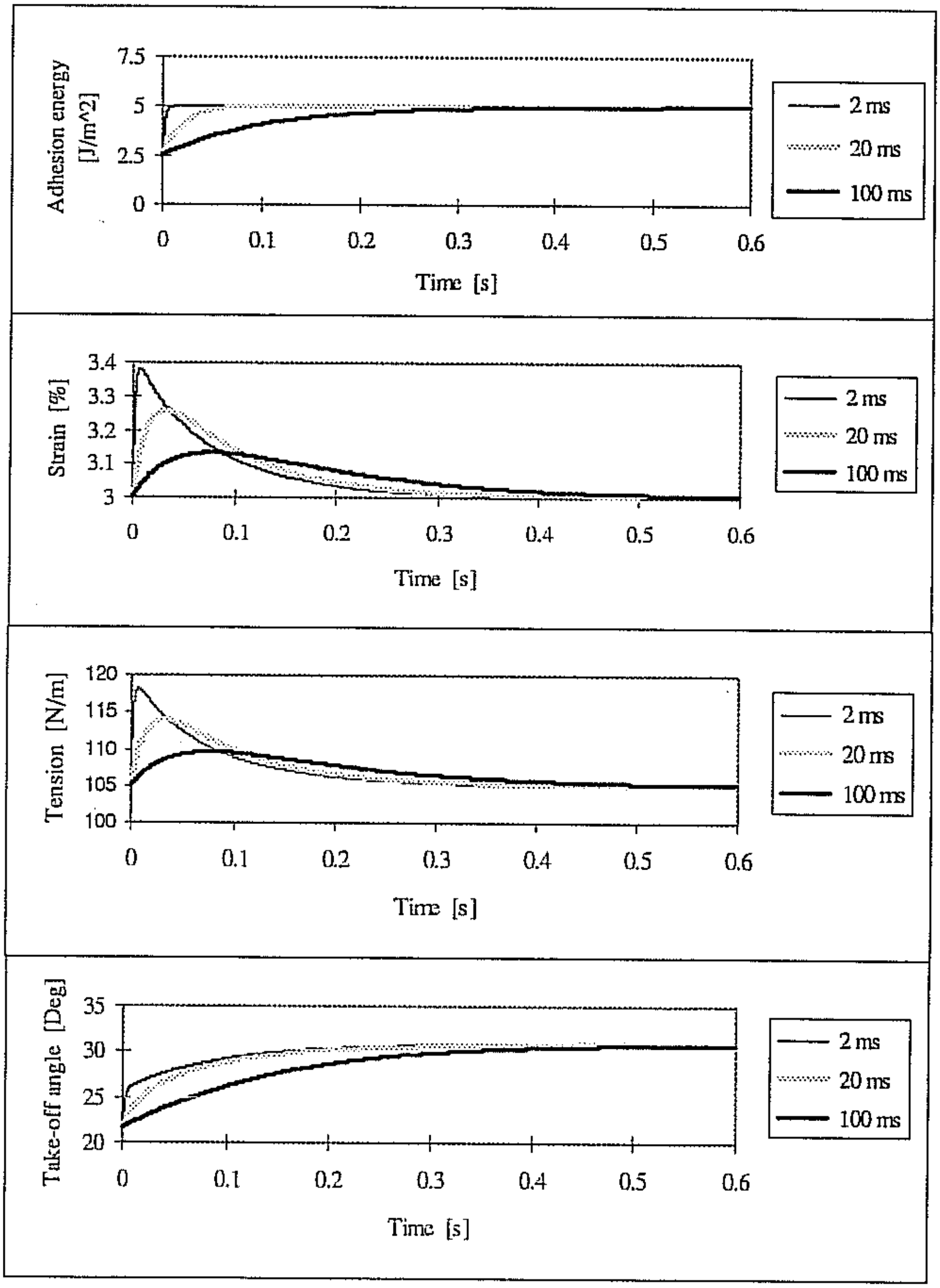

Fig. 9. Model responses to step changes with time constants in adhesion energies.

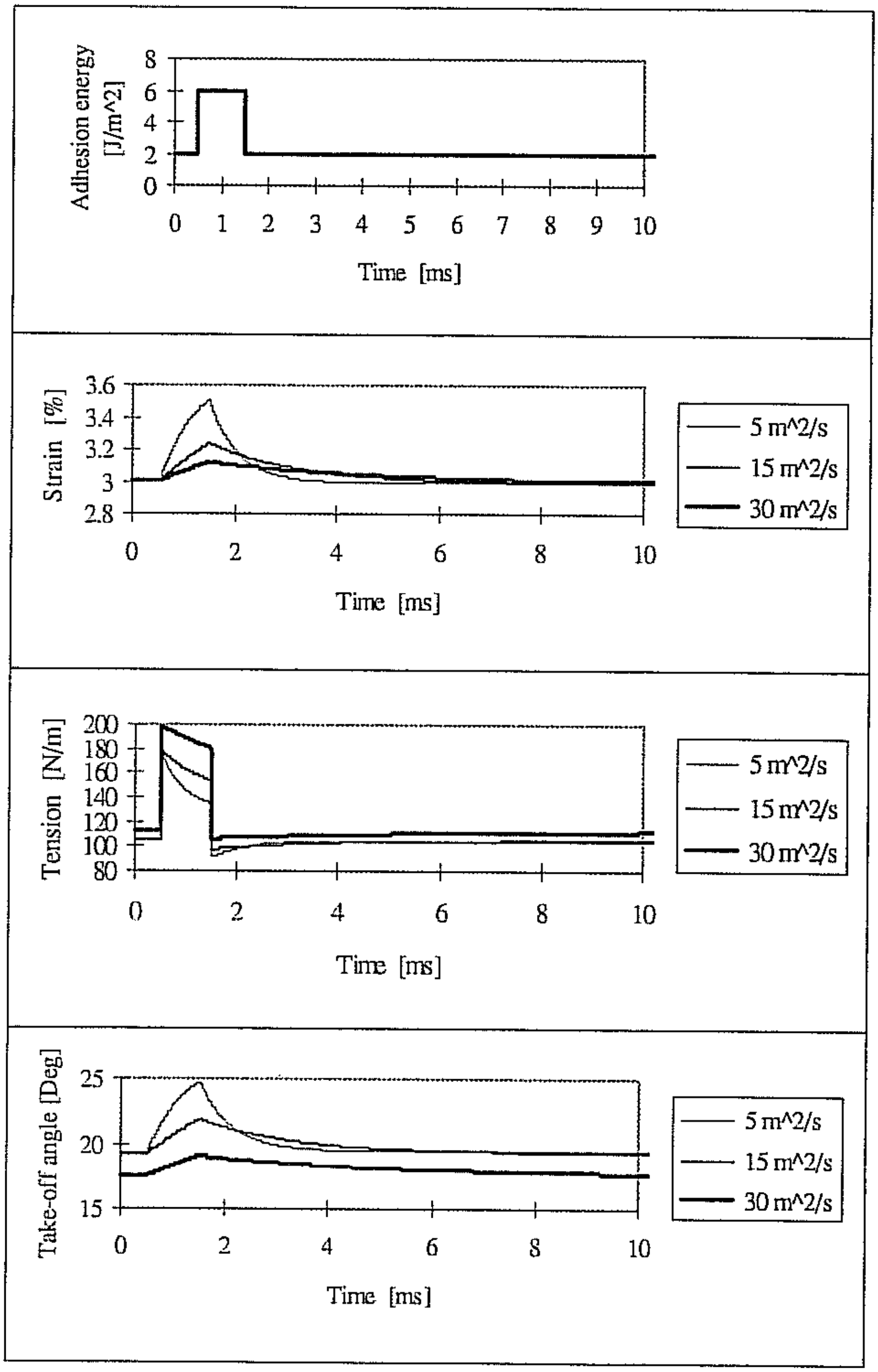

Fig. 10. Model responses to a resinous spot on web at various kinematic viscosities.

Question - Selection of your rheological model which is your Spring 2 which any strain imposed on material is totally recovered by spring 2. It seems to me that is one of the key features of the materials in that there may be a permanent deformation as a result of this strength. Can you comment on this.

Answer - It depends upon the time scale. We had a short time to produce this kind of model. So we used the AP model. The more parameters we have the more difficulty we have to determine the values. The next step would incorporate a more complex model.

Comment: Something along the lines somewhat of a Jeffrey's model.

Answer - Yes

Question - Based on your modeling work. Can you make recommendations on design or operation of the press section in order to improve runability?

Answer - We have not published on this quite a lot, but I think that this kind of considerations can lead to some success in terms and geometry and the control feed and what kind of rheology the web has in order to optimize that overall behavior.