MILL APPLICATION OF FINITE ELEMENT ANALYSIS TO SOLVE THE PROBLEM OF THE OXBOW EFFECT

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ABSTRACT

Paper uniformity is critical to the operation of large modern papermachines. The final operation in the papermaking process is calendering the paper from approximately 140 μm to 85 μm thickness. This is the last place on the papermachine to introduce non-uniformities and the last place to rectify any previous non-uniformities. The calender stack typically consists of 4 to 6 rolls up to 815 mm (32 inches) or more in diameter and 8.5 m wide. For maximum flexibility and calendering performance, the rolls are heated internally.

During the startup of a recent papermachine the paper on the reel had very hard edges, due to higher caliper paper, at the design trim and calender temperature. In the short term these were alleviated by lowering the water temperature and decreasing the trim. Careful measurements on the paper indicated that the problem originated in the calender stack. Previous experience confirmed that thermally induced distortion of the calender roll edges was a likely source. Finite element analysis of the thermally induced distortion confirmed that this was the problem and predicted the optimum amount of insulation in the calender roll to control the deformation. This solution was tried and the paper sheet ran perfectly, with no indication of hard or soft edges.

KEYWORDS: Calender Stack, Oxbow, Thermal Expansion, Temperature, Heat Transfer, Calender Rolls, Paper Machines, Cross Direction, Thickness, Caliper, Newsprint, Mathematical Model, Variability, Fluid Dynamics

INTRODUCTION

Calender rolls are used in many industries, including plastics, used as a base for magnetic media and photographic film, steel and other metal industries, used for products such as tin cans and aluminum foil, and in the paper industry, used to enhance the surface properties and printability. In this paper we will talk about its application to the paper industry.

In the newsprint industry and the lower grades of groundwood papers, most paper is finished on a hard machine calender. This typically consists of four to six heated cast iron rolls with the paper passing through the nips between the rolls. The combination of heat and pressure produces a denser paper sheet with a smoother surface finish. This decreases the caliper (thickness) of the sheet from around 140 µm down to 85 µm. The calender stack must have a uniform nip gap along its entire width to produce a sheet with a uniform cross direction (CD) caliper profile. The CD caliper profile control system can compensate for minor variations but cannot always compensate for the oxbow effect at the edges of the roll. This can result in higher or lower caliper at the edges of the sheet.

The different sources of the oxbow effect and the importance of each source are described in the literature [1,2]. These sources must be clearly understood in order to properly design new calender rolls or develop new concepts for heating calender rolls. An improperly designed roll can cause soft reel edges due to the increased roll diameter near the journal ends or hard reel edges due to smaller diameter roll ends. Understanding the oxbow effect is also important for the end user to select the optimum roll design and to gain the maximum performance from his calender stack.

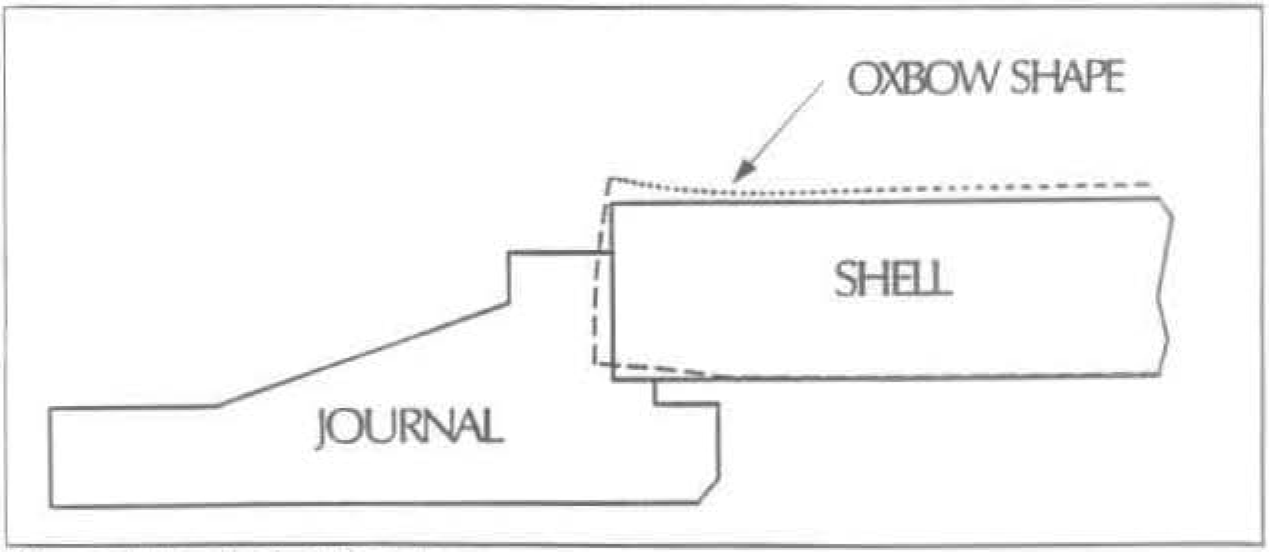

Figure 1 A typical oxbow shape.

In this report the sources of the oxbow effect are discussed in a qualitative sense. This is followed by a description of how this knowledge was used to improve calender performance on a new paper machine during the startup phase.

OXBOW EFFECT

Typically, the cast iron roll is ground to a uniform diameter at room temperature. However, under operating temperatures the roll diameter decreases toward the end of the roll and then increases as shown in Figure 1. This is referred to as the oxbow shape.

The heat flow through the cross-section of the calender roll at its lengthwise midpoint is one-dimensional in the radial direction. Near the journal ends the heat flow becomes two-dimensional. The major direction of heat flow is still in the radial direction but there is also some heat flow in the axial direction.

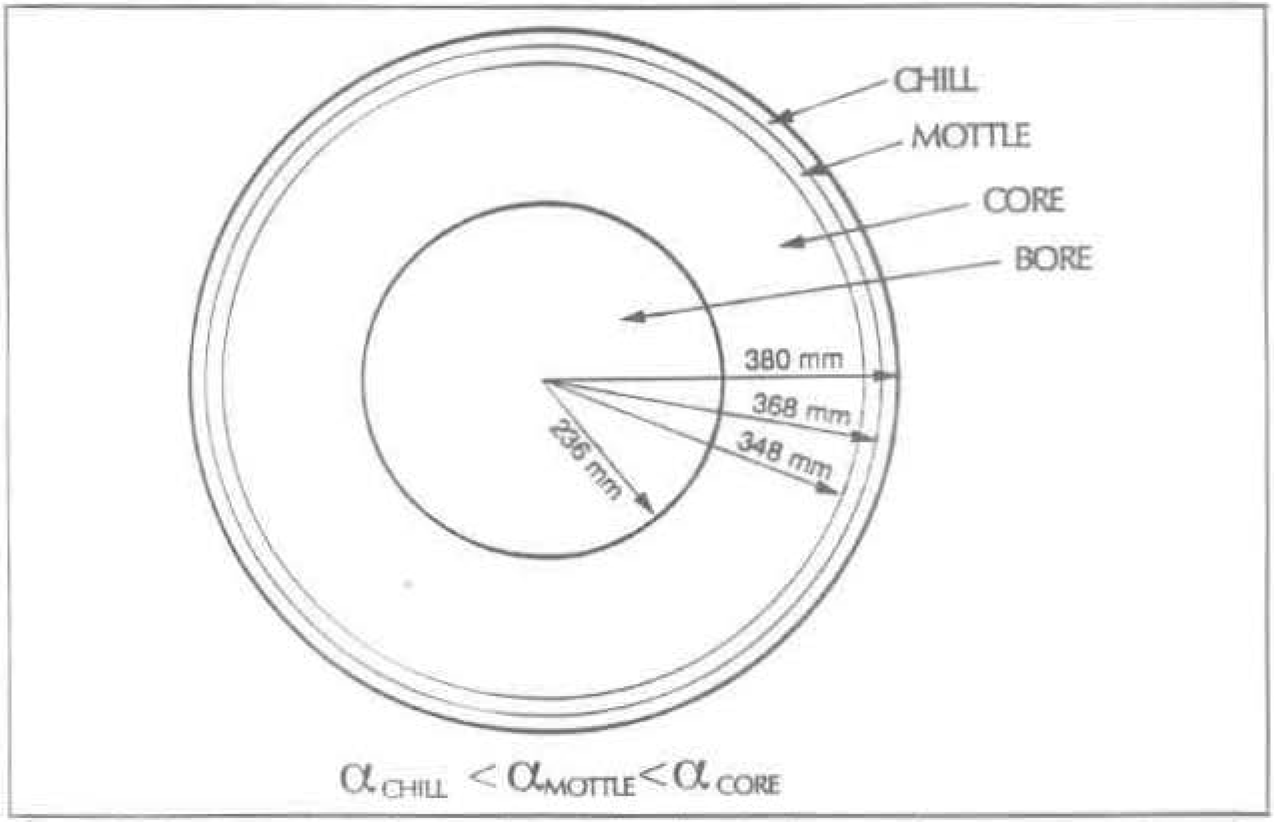

Figure 2. Cross-section of calender roll showing the layers of chill and mottle on the core iron.

The distortion causing the oxbow effect has three temperature related sources which are additive. To visualize the first two sources, ignore the end effects noted above, and assume the heat flow is in the radial direction only.

Source 1 - Uniform Temperature Effects

Figure 2 shows the construction of a typical straight bore calender roll with a 12 mm layer of chilled cast iron on the outer surface and a 20 mm layer of mottle iron between the chill and core iron. The layer of chill iron has a lower coefficient of thermal expansion than the mottle and the core iron has the highest value. When the roll is uniformly heated, the surface of the roll is under tension and the core is under compression due to the differing values of thermal expansion.

The boundary conditions on a thin cross-sectional slice at the lengthwise midpoint of the roll are such that the adjacent roll material prevents the stresses developed from causing any non-uniform axial deformation. At the end of the roll, the restraint provided by adjacent material on the outboard side is no longer present. With the stresses removed the interior material can expand axially outward to a

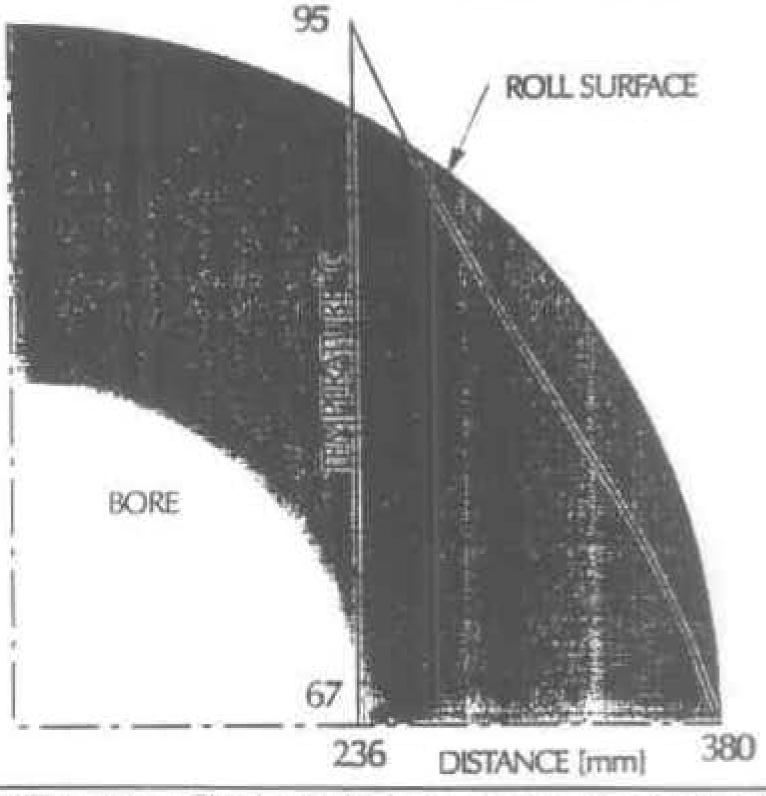

Figure 3. Temperature profile through the shell showing the hot interior and cooler surface.

much greater extent than the surface material. This is equivalent to putting a large moment on the roll end which causes the roll to grow in diameter at the very end and be reduced in diameter a short distance in from the end as shown in Figure 1.

Source 2 - Radial Temperature Gradient Effects

During normal operation, the surface of the roll is heated by the hot water flowing in the bore. Thus, the interior of the roll is hotter than the surface as shown in Figure 3. The hotter interior temperatures cause similar stresses to those described above, accentuating the distortion.

Source 3 - Actual Temperature Effects

Heat flow at the journal end of the roll is not constrained to the radial direction, but also flows in the axial direction which can result in a hotter volume average temperature at the end. Figure 4 shows such a temperature profile where the surface temperature changes rapidly at the roll edge. This is caused by the higher rate of heat flow into the paper in the wrapped portion of the roll, as compared to the heat flow into the air at the unwrapped end of the roll. Thus, the surface temperature at the roll end tends to be hotter than the surface temperature in the wrapped portion of the roll. The amount of expansion at the end is dependent upon the volume average of the temperature rise at the roll end. In a poorly designed roll the volume average temperature will be much higher at the end than at the centre causing the roll to have a larger diameter at the end.

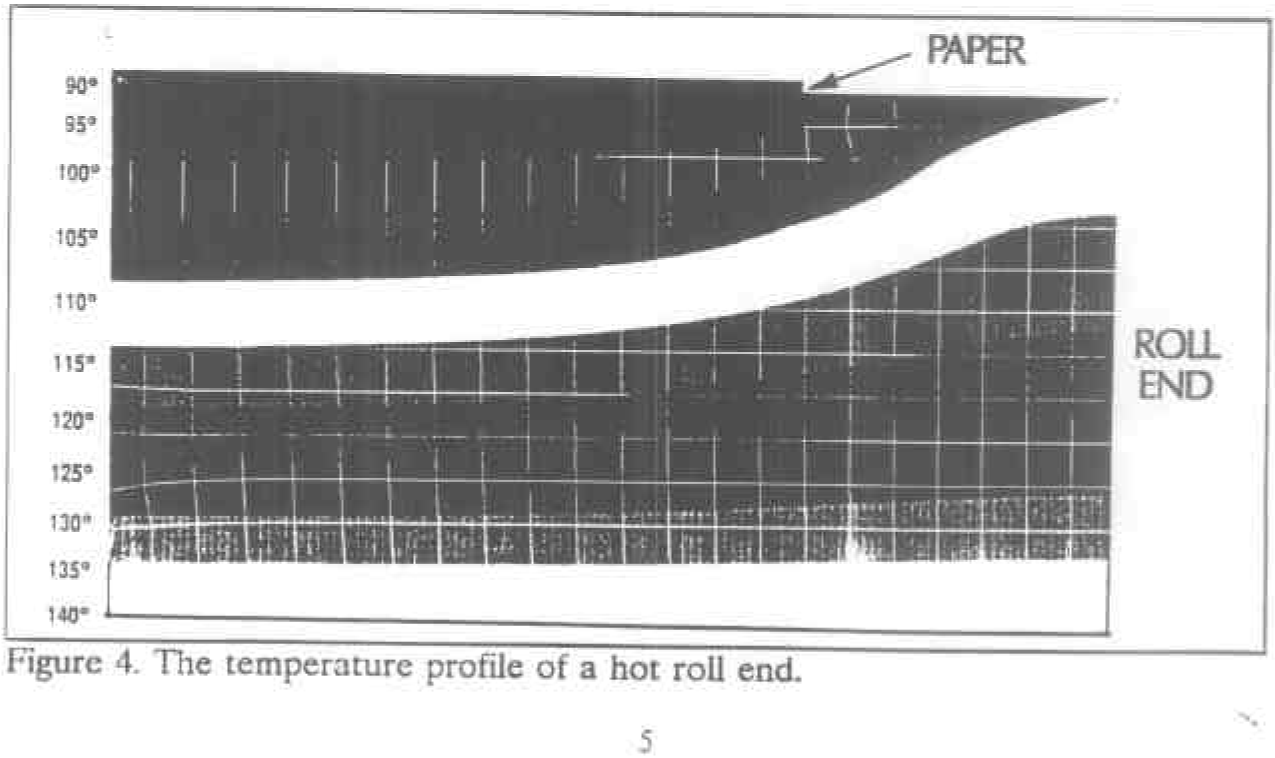

Figure 4. The temperature profile of a hot roll end.

MILL EXPERIENCE

A new mill was starting production and could not manufacture the correct width of paper at the design temperature of the calender stack. The online caliper scanner after the calender stack did not help in determining the cause of the problem. This was because this brand of scanner stopped measuring about 35 mm from the edge of the paper. Careful lab measurements of the caliper and basis weight led to the conclusion that the problem must be with the calender stack. Careful temperature measurements at the end of the rolls also indicated that the edge temperature was cooler than what it should have been for a uniform diameter.

Two ways were found to alleviate the problem. One was to reduce the calender setpoint temperature, but this had the undesirable side effect of making the paper surface finish rougher. The second method was to narrow the paper trim, meaning the paper was further from the edges, but this meant the papermachine productivity decreased. These two solutions, then were not acceptable as more than temporary measures.

SOLUTION PROCEDURE

The nip load is the most important parameter affecting the web consolidation; therefore the load, or roll diameter within the paper trim, must be as uniform as possible. Uniformity of the roll surface temperature is the second most important factor as shown in the calendering equation developed by Crotogino.[3] From the discussion above about the sources of the oxbow effect it is clear that only the end temperature can be controlled. This can be done by a careful design and implementation of insulation at the roll end to control the temperature and thus the distortion.

There are a number of variables that control the temperature and distortion of the roll ends. They are 1) the roll geometry details, 2) internal roll insulation, 3) the temperature of the heating fluid, 4) the heat transfer coefficients between the heating fluid and roll, 5) the heat transfer coefficient between the roll and air, 6) the ambient air temperature, 7) the sheet temperature, 8) the sheet basis weight and moisture, 9) the contact resistance between the sheet and roll which are functions of the sheet bulk, tension, and roughness, and 10) the sheet trim. The variable that the design engineer has control over is the amount of insulation within the roll for a retrofit of an existing roll and the geometry for a new installation. The operator also needs to be aware of these parameters so that care is taken when changing operating conditions such as the operating trim or setpoint temperature.

In practice, there cannot be a completely uniform calender diameter using conventional heating techniques because of the roll's thermal resistance and the large difference in the heat transfer between the wrapped portion of the calender roll and the unwrapped end, but the roll can be designed such that the variations are minor. Finite element analysis using SDRC I-DEAS was performed to optimize the insulation level in the rolls.

The solution procedure is interesting since the temperature field throughout the roll is the determining factor in the deformation. Thus the roll temperature first needs to be calculated based on the thermal boundary conditions and then the deformation based on the temperature field and the structural boundary conditions. Since it is an optimization problem the optimization procedure within I-DEAS was investigated to see if it could work on this type of problem. It could not because it will not vary the boundary conditions and because it will not work with problems that require the combination of heat transfer and linear static finite element analysis.

Since the rolls are axisymmetric the geometry was straight forward to model; therefore the geometry creation task of Supertab was used. The heat transfer coefficients and temperatures were based on reference 2 and temperature measurements taken on the operating calender stack. These are shown in Figure 5 for the rolls as delivered. When the shell insulation was removed the 15.8 $W/(m^2K)$ heat transfer coefficient was replaced with a linearly varying value of 1000 at the journal end to 4000 at the previous inside end of the insulation. This linear variation was estimated to model the convection coefficient in this relatively stagnant flow area. The structural boundary conditions are shown in Figure 6. The material well away from the end will only move in unison in the axial direction. Any point can arbitrarily be chosen to be fixed in the axial direction so

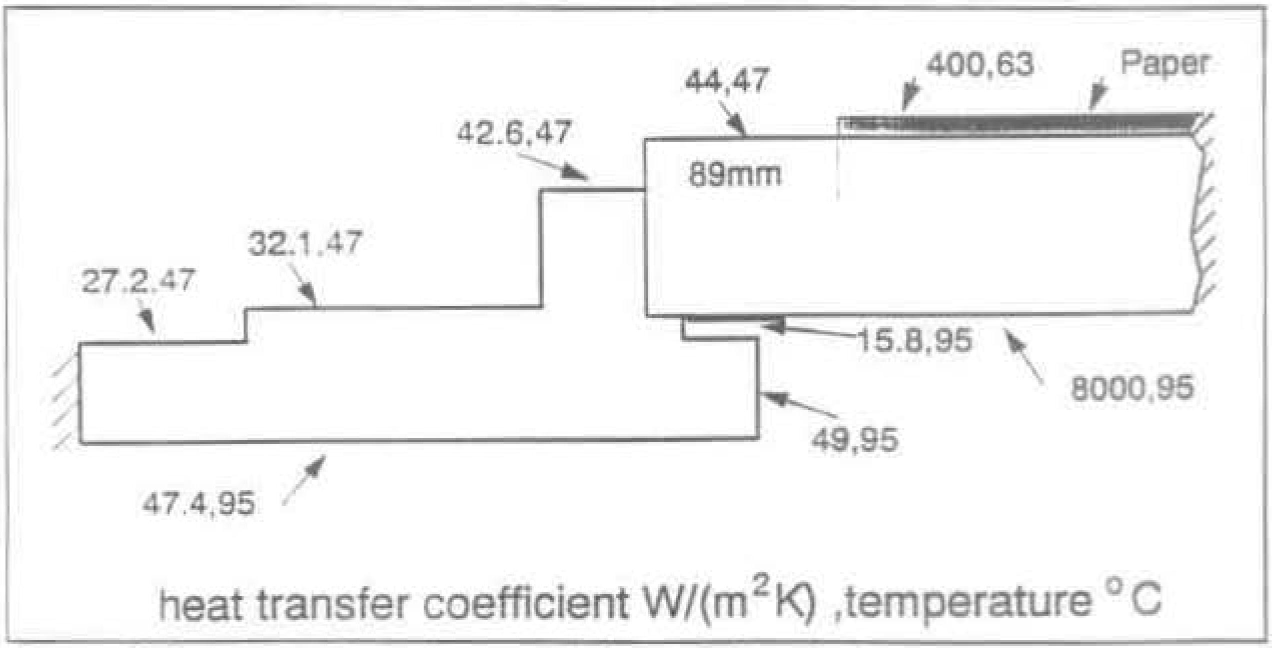

Figure 5 The thermal boundary conditions of the calender stack.

the nodes on the shell far enough from the end were chosen to be axially restrained. Since the geometry is axisymmetric, restraint is not required in the other directions. The model takes the journal end out to about the bearing location. Here the nodes will only move uniformly in the axial direction as well but the roll must be allowed to lengthen in the axial direction without restraint. This is done by constraining these nodes to move uniformly in the axial direction.

The thermal boundary conditions were optimized to match the temperature measurements taken on the operating calender stack. The major item not taken into account is the thermal contact resistance between the journal end and the shell. The manufacturer did try to minimize this by machining grooves in the journal to increase the thermal resistance which was taken into account by carefully modelling the grooves in the geometry. A very gross estimate of the contact resistance across the apparent contact area was made by slightly increasing the size of the grooves in the model. However, no attempt was made to model this accurately. To obtain a reasonably reliable estimate of the contact resistance the reader is referred to references [4,5,6]. To actually calculate the temperature distribution with such an internal boundary condition a solver such as TMG would need to be used. The next unknown variability is the convection coefficient where the flow goes around the journal end and into the annulus. The problem is not overly sensitive to this however since it is not the controlling resistance.

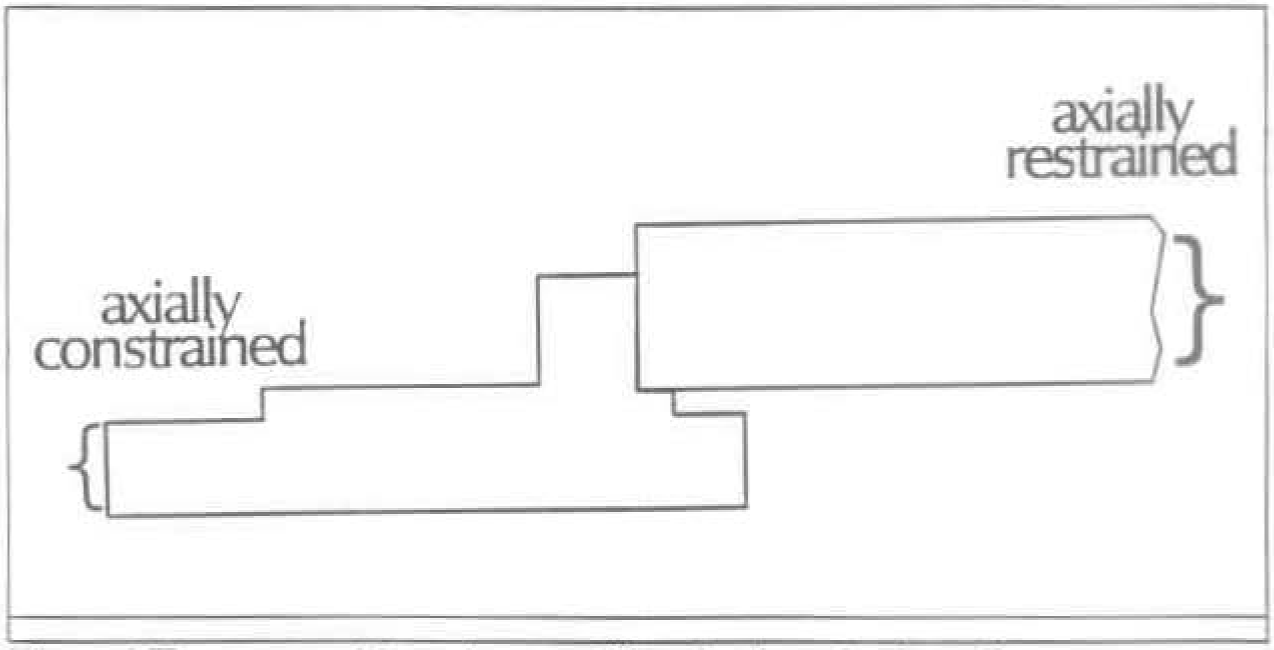

Figure 6 The structural boundary condition for the calender roll.

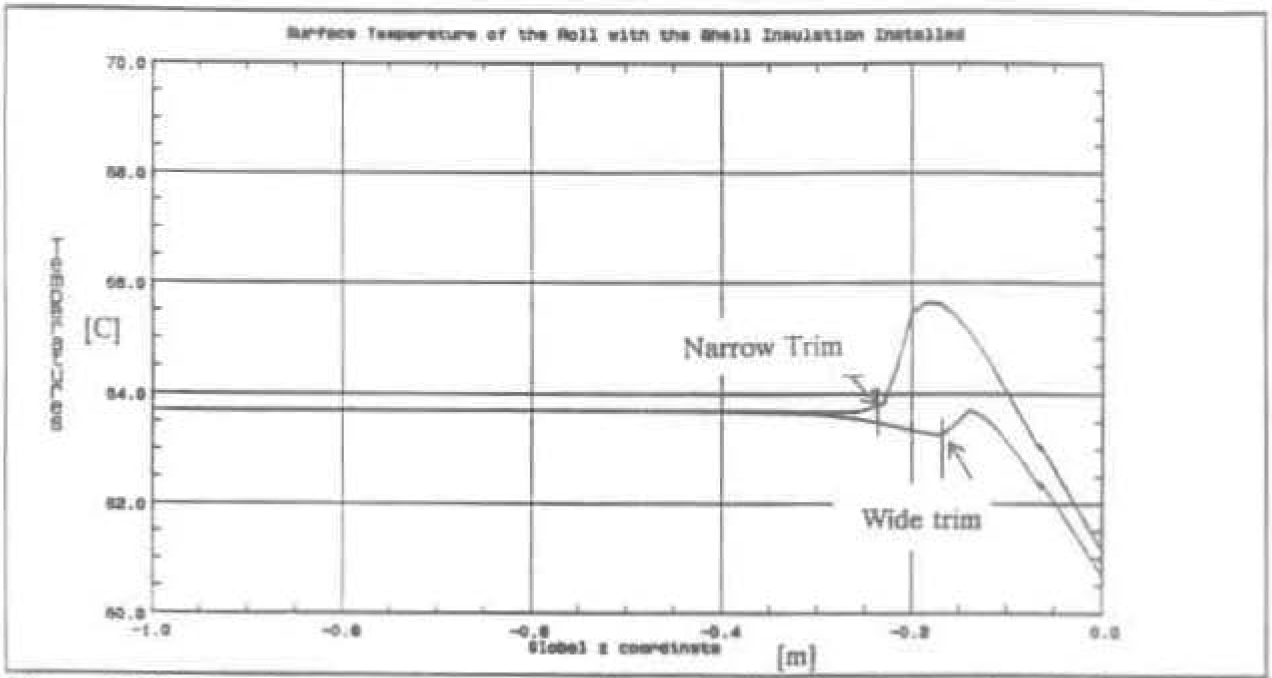

Figure 7 The surface temperature profile of the insulated calender shell with wide and narrow trim.

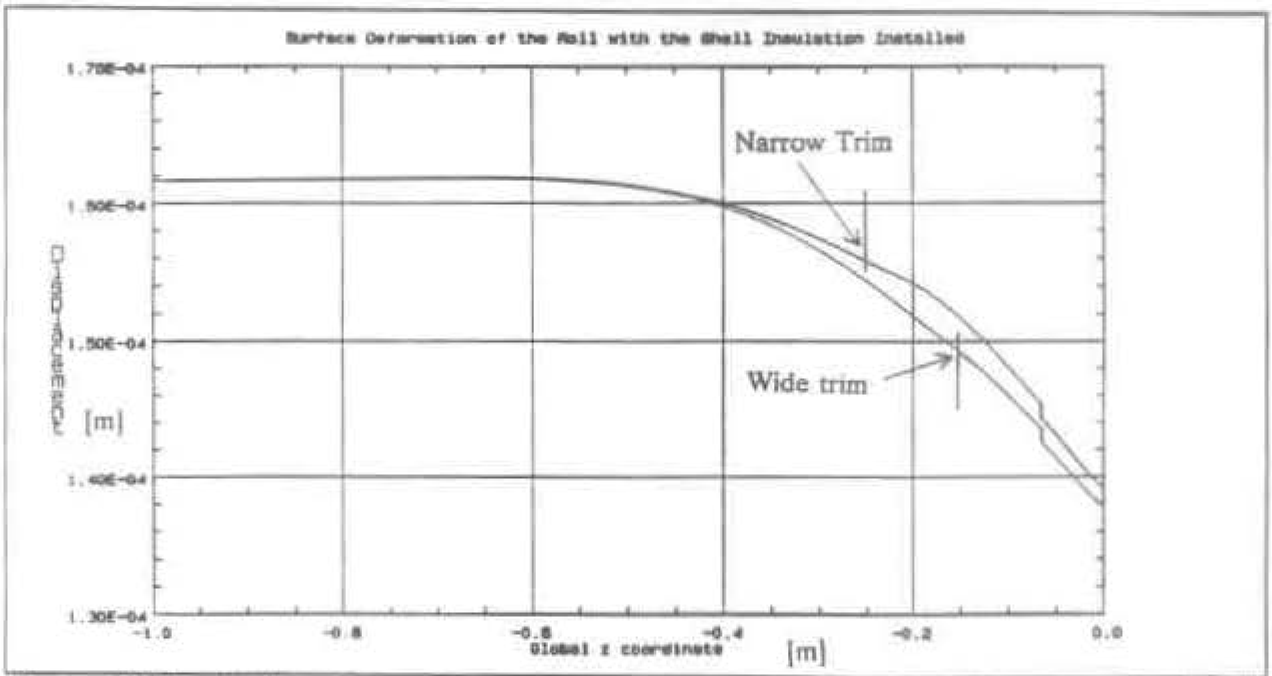

Figure 8 The shell surface deformation for the insulated shell with wide and narrow trim.

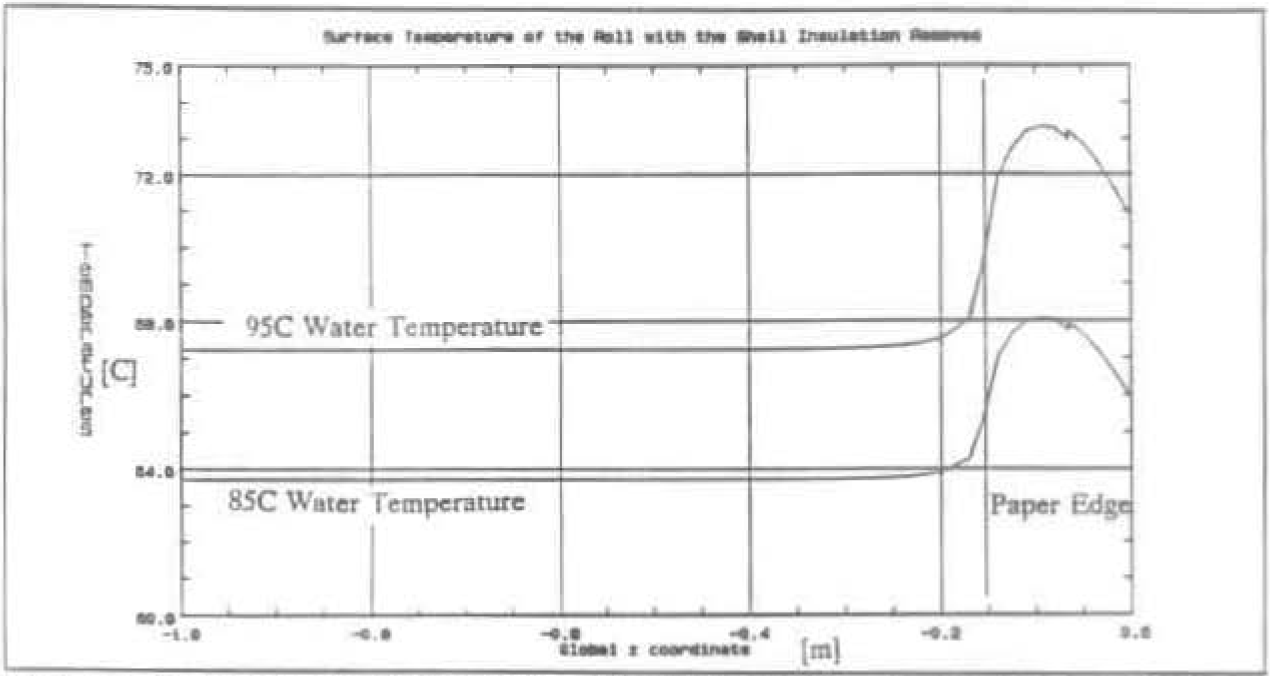

Figure 9 Surface temperature of the roll with insulation removed at two different setpoint temperatures.

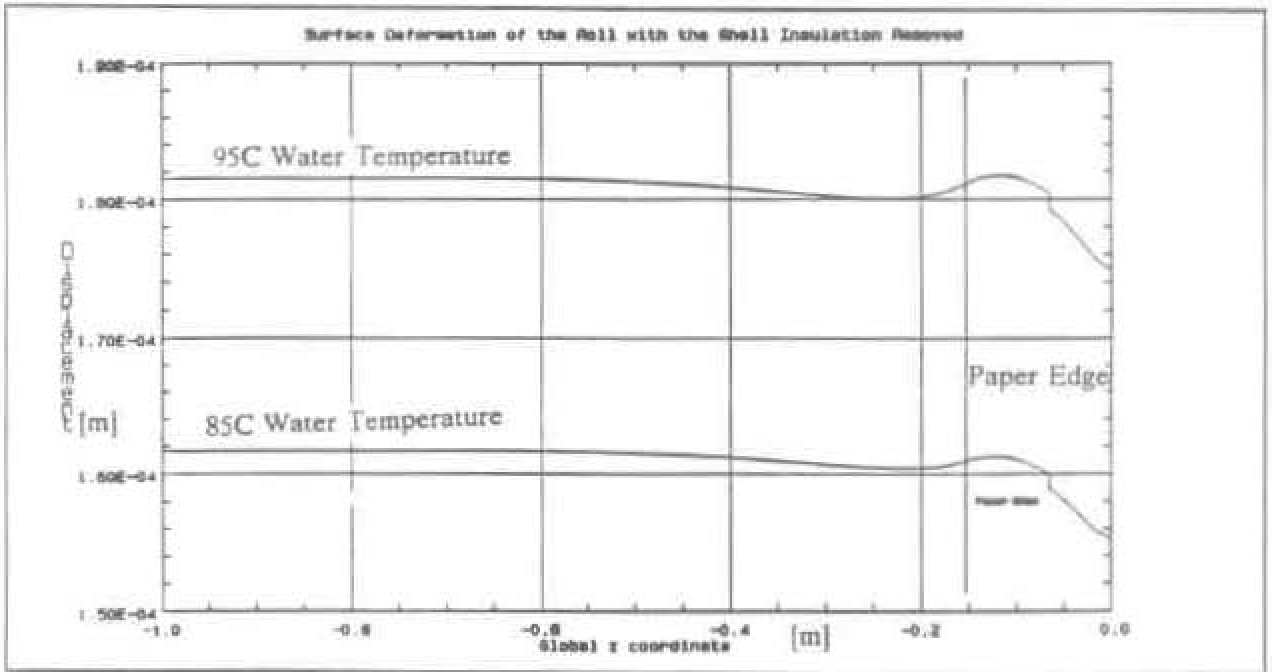

Figure 10 Surface deformation of the roll with inlsulation removed at two different setpoint temperatures.

RESULTS

The results of these calculations give the surface temperature profiles shown in Figure 7 and the deformations shown in Figure 8 for the case with the shell insulation installed. This shows that the temperature did not increase at the paper edge with wide trim and by less than 2°C with narrow trim. Figure 8 shows that the roll radius decreases by 12 µm at the paper edge for wide trim and by 6 µm for narrow trim. This confirms the mill observation of high caliper at the paper edges leading to hard roll edges with the problem somewhat alleviated when running narrower trim.

The temperature and deformation profiles for the case with the shell insulation removed are shown in Figures 9 and 10. These figures show that the temperature increases by 4°C outside the paper edge for the 85°C temperature setpoint and by 6°C for the 95°C setpoint temperature. For each case the radius varies by less than 2 µm throughout the roll length. This gives a very good profile and is the configuration that was recommended to the mill.

The insulation was removed from the shell of the roll and the rolls were reinstalled in the calender stack. With this modification the paper reel ran without hard or soft edges indicating that the calender roll was at a uniform diameter. Thus the finite element analysis was able to accurately predict the optimum insulation level for good operation of the calender stack.

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