An investigation of the limitations of the heat transfer mechanism when using a gas wedge between the web & drum.

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ABSTRACT

The heat load from any deposition source that impinges on polymer webs can be a problem. In many commonly used polymers they will heat up to a point where the web will change dimensions as it passes through the deposition zone. In many cases this dimensional change is small but in other cases it may be catastrophic to the process. Many processes are operated so near to the process limit that some rolls will pass through the process without problem whereas others will be problematic. Thus there are assumed to be variations between rolls of the same material.

In some previous work it has been shown that when using a cooled deposition drum the rate-limiting factor is the heat transfer coefficient between the back surface of the web & the drum.

This heat transfer coefficient is not only the rate-limiting factor but is also a variable & generally an unknown variable. This coefficient depends upon the surface roughness of both the deposition drum & back surface of the polymer web & also the moisture content of the polymer.

The largest uncontrolled variable is the polymer moisture content that may vary from roll to roll. The moisture can vary because of many factors including the moisture content of the feed polymer, the humidity during the film manufacturing process, the storage time & humidity of the storage atmosphere. When the roll is put under vacuum the moisture will migrate to the surface & then evaporate into the vacuum. Once the moisture has been stripped off the surface the evaporation rate will be limited by the diffusion rate of the moisture form the bulk of the polymer to the web surface. This moisture content determines the amount of gas trapped between the web & drum enabling additional transfer of heat between them.

Hugh Clow developed & patented a process for injecting gas between the web & drum to improve the heat transfer coefficient. This gas was aimed at raising the gas content between the web & drum above a minimum such that the deposition rate would not be limited by having to assume the polymer with the lowest moisture content.

This process has been used on some high-speed metallizers to improve the deposition speed.

Other deposition processes also have a problem of removing the heat but the deposition rate and hence the winding speed is much lower.

Since the publication of the patent the perception has been that the gas injection process would not work for slow speeds & narrow webs. However quite what constituted a slow speed or a narrow width and what combination of speed & width would be advantageous & which would not has never been specified. A clear case of ‘suck it & see’.

This resulted in putting the question, where is the boundary of speed & width where injecting gas is a benefit and can it be modelled?

This also led to other questions such as, if the gas leaks out of the edge between the polymer & drum does this allow the edge to collapse on to the drum & seal the rest of the gas in? Alternatively does the tension applied to the web squeeze the gas out from the centre of the web to the edge progressively & hence all the gas is lost within a finite time? The first scenario would suggest that the gas could still be a benefit at slow speed whereas the second scenario would suggest that it would not.

After modelling the process we can now show what is happening & some of the limitations to the process.

INTRODUCTION

In the following paper it is not intended to show in detail all the steps taken in developing the model. We will present an outline of the assumptions made, the components used in the model & the results produced by the model.

The starting point for this work was to collate whatever information we could find relating to the process, sift through & use what we could (Refs 10-22). The next was to look elsewhere for expertise in other areas of science (Refs 1-9).

The next step was to make some assumptions

1. Taking account of the drum surface finish, the web roughness & the pressure exerted by the applied tension, the gap between the web & drum was taken to be 1 micron but irregular in shape.

2. The gas within the gap is in the free molecular flow mode.

3. The gas pressure within the gap is less than will lift the web off the drum against the applied tension.

4. The incoming gas entrapment/capture is almost uniform across the web.

5. The gas can leak out at the edges.

The analysis looks at the dissipation of the heat load by radiation, conduction & convection between the web & drum. In particular looking at the benefits of using a gas injected between the web & drum and the possible limitations of using such a process at low speed or on narrow web systems.

For polymeric films on steel coating drums the web to drum heat transfer is significantly affected by the conduction through the small amount of gas trapped between web and drum where the mean free path of the molecules is much bigger than the gap. Radiation is a small component and direct conduction is limited and is related to the surface roughness of the two surfaces. Previous work has made estimates of heat transfer but based on gas conductivity where intermolecular collisions dominate. Our (theoretical) analysis, based on free molecular transport of heat (kinetic energy) confirms the size of the coefficients and dependence on gas density (pressure) but not gap size and suggests that higher values might occur.

We have an estimate of the molecular flux due to density-gradients also based on free molecular flow (like Knudsen flow) in a small gap. Using this, we have an analytic model (solution of partial differential equations) of the gas density distribution in the gap as a function of position along and across the moving web, which then defines the spatial variation in heat transfer.

The model shows the potential effects of molecular properties, web width, web speed and injected gas density on heat transfer and friction.

PROCESS

Methods used.

The Gombosi model (Ref 3) for free molecular flow between parallel sheets.

A model was devised that is similar to Knusden flow for the movement of gas.

A model combining linear flow & diffusion was used and developed to include the outgassing from the web.

Using partial differential equations that are assumed to have separable solutions or linear transform method an analytic model was developed. The solution was a combination of decaying exponentials and cosine series for mode shapes. The inlet series was matched as a cosine series. This model could then be extended to include the web outgassing by use of a forcing function.

Heat transfer results.

The heat transfer was found not to be related to the mean free path (mfp) because the mfp is so much larger in magnitude than the gap between the web & drum.
The heat transfer is proportional to the gas density which is a reflection on the number of molecules available to transfer the heat from one surface to the other. The molecules depend on the temperature for the kinetic energy that defines the average velocity.

$$\mathrm{hk2}(\gamma,P,T,\mathrm{mass}) := \alpha\cdot\frac{1}{4}\cdot\frac{\gamma+1}{\gamma-1}\cdot\mathrm{Nmol}(P)\cdot\sqrt{\frac{8\cdot K\cdot T}{\pi\cdot\mathrm{mass}}}\cdot K\cdot\frac{1}{2}$$

Figure 1. Gombosi gives us the above equation with the following parameters. W/sqM/sec.DegK = factor x NumberDensityMolecules x avgVel x BoltzmannsK

Gas movement results

There is Knusden flow of the gas in the gap between the web & drum. This is similar to the case of flow in a porous media rather than flow in a tube.
The movement of the gas is driven by the density gradient. With the gap size acting as a scaling parameter. The rate depends on the mean velocity of molecules.
The web edge effect acts as an open gap with molecular effusion.

$$\frac{-\mathrm{dia}}{3}\cdot \mathrm{Vavg}\cdot\left(\frac{d}{dx}n\right)$$

Figure 2. The above formula is for the Knusden flux per unit Xsec area in a tube.

$$\frac{-\mathrm{gap}}{4}\cdot \mathrm{Vavg}\cdot\left(\frac{d}{dx}n\right)$$

Figure 3. In this work the above formula is for the flux per unit Xsec area in the gap.

Analytic solutions for flow & diffusion.

Partial differential equation (PDE) for flow (machine direction, MD) and diffusion (MD and TD) is soluble analytically (separable solution).

The result (below) is a cosine series set of mode shapes that propagate in MD and decay exponentially at rates defined by web velocity and gas diffusivity.

$$-V\cdot\frac{d}{dx}U + D\cdot\frac{d^2}{dx^2}U + D\cdot\frac{d^2}{dy^2}U + F = 0$$

Since the objective is to assess the thermal conductivity which depends on molecular mass, and since the molecules don't interact with each other, we can use a weighted value for F to allow for it being a different gas from the injected or entrained species.

Figure 4.

The edge conditions and symmetry select the cosine form (for half web) mode shapes with the initial conditions for gas density distribution across web at lay-down defining the initial mode magnitudes.
An extension in the model to inject gas everywhere uniformly gives modified analytic solution.

WEB-DRUM SYSTEM RESULTS

It is clear from the results that the distribution of gas density shows drop-off near edges in all cases.

Winding the web at slow speeds lets gas leak out, reduces heat transfer and effect reaches further in to centre of web whereas fast movement makes leakage less significant. Narrower web also makes things worse.

These results are in agreement with the perceived wisdom that we started with. The great advantage of the model is that any speed & web width can be used to give an indication if any improvement in performance can be expected or not.

If out-gassing is significant, slow system equilibrates to its natural high-in-centre shape.

In the following diagrams we show graphically some results of the model.

As we wanted to look at the effect on running narrow webs & slow speeds we have taken this to be the starting set of conditions with a web width of 0.3m and a slow winding speed of 0.1m/min. The schematic then shows the series of steps taken by widening the web & by speeding up the process. The figures that follow show the how the gas density distribution is affected.

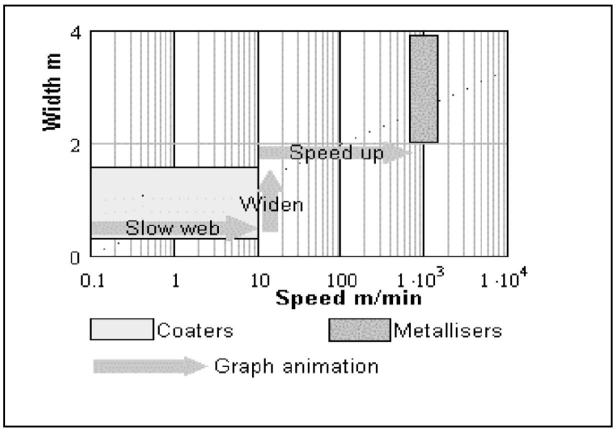

Figure 5. Schematic of the web width & speed changes made for the following series of figures.

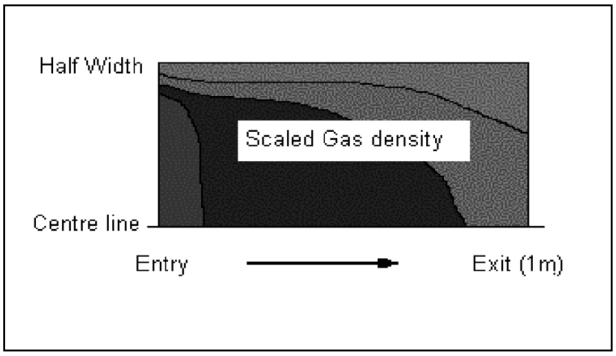

Figure 6. The figures below of configured as shown above.

In Figure 6 the entry is where the web meets the cooling drum & exit where it leaves the drum, which in this case is given a length of 1m. As the output is symmetric about the machine direction centreline of the web only half the web width is shown.

In the following figures there are two graphs shown in each figure. The upper graph is for the distribution of gas density that is present from the injection of gas as the web & drum are brought together referred to as the gas wedge. The lower graph also has the effects of outgassing from the web included.

This allows, in effect, for different polymers as some will not outgas anything & others will outgas considerably. Also within the model it is possible to look at the effect of changing the gas type injected to form the gas wedge.

The spacing of the gas injection remains constant and hence for narrow web widths there will be the same number of injection points as in wider webs.

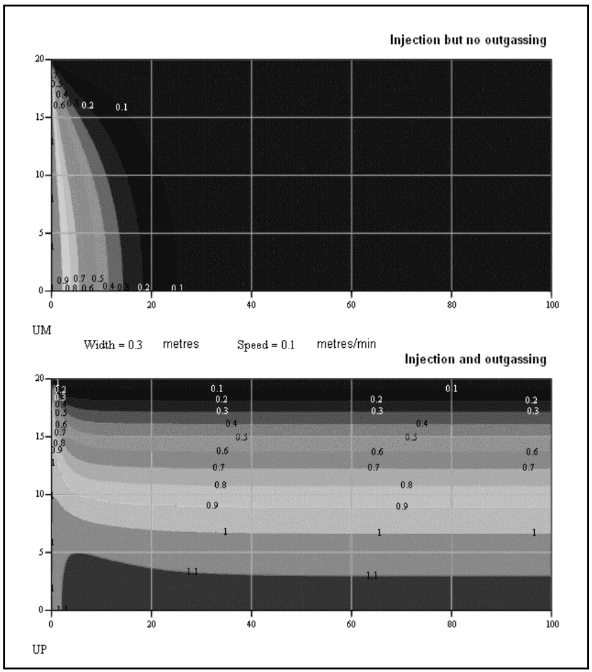

Figure 7. Graph of slow speed & narrow web width conditions.

The leakage of gas from the edge is large and there is only a single source of gas injection and so the gas density falls off very quickly. When the outgassing is included the situation improves a little but there is still a large gradient between the centre & edge of the web.

Compare this to the next figures where the width and speed has been increased.

With the increased web but still slow speed there is still a drop off of gas density towards the edge and this is more noticeable as the web progresses around the drum. Again the addition of outgassing improves things further.

Increasing the speed reduces the time the gas has to leak out of the side & thus the edge effect is further minimised.

Thus with this model any combination of web width & speed can be explored and so the benefits of the gas wedge system can be checked out on the slower sputtering machines as well as the more widely used & better known aluminium metallizers.

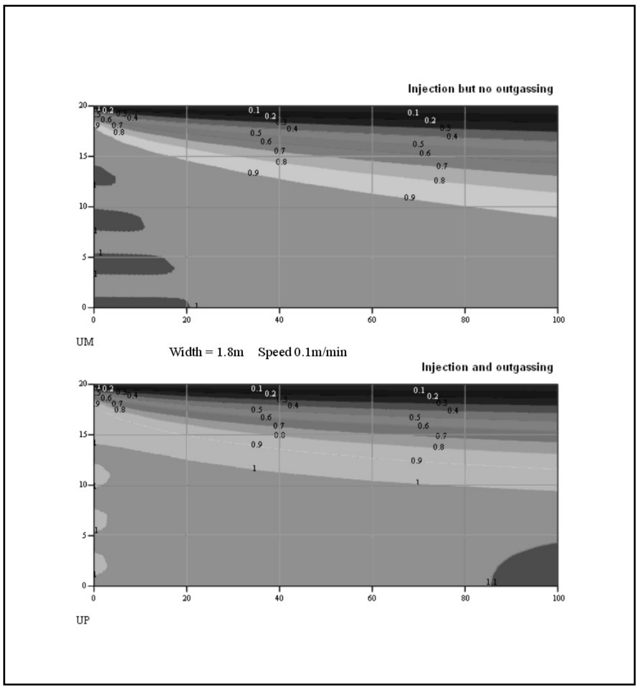

Figure 8. Showing the effect of increasing the width of the web to 1.8m with the speed remaining at 0.1m/min.

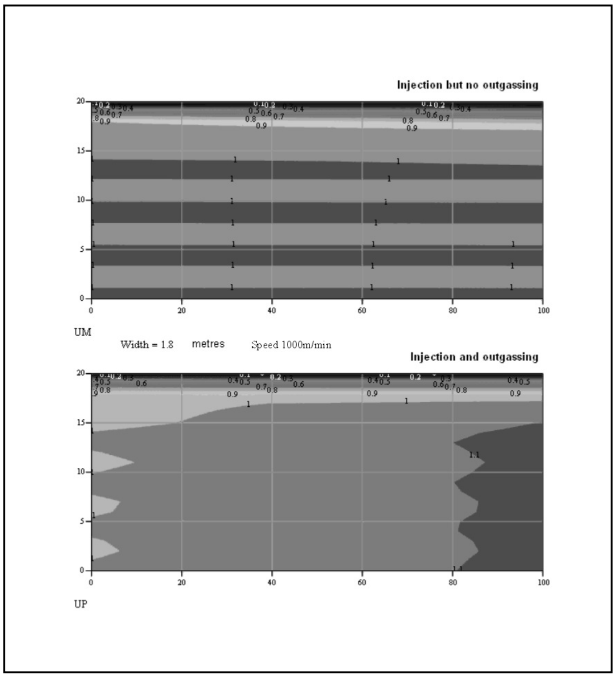

Figure 9. Showing the effect on the wide web of increasing the speed up to 1000m/min.

The results shown in Figure 9 are largely already to be had at a speed of 100m/min.

CONCLUSION

The model developed gives a good estimate of the heat transfer dependence on gap size and gas molecular properties. There are also good estimates of gas mobility in the gap.

Combining with a PDE description of the web on drum system we have predictor for heat transfer distribution as a function of web speed, tension, width, gas type etc.

The model not only confirms the expectations that processes with a slow winding speed & narrow width web do not benefit from using the gas injection method but can put numbers on what combination of speed & width will start to benefit from the method.

Although we are confident that these theoretical results are a good reflection of the process & look as if they could be useful, we would like to get a discussion going to see if we can match them up with actual measurable values, refine the analysis and generally be helpful. To this end the authors would welcome any positive input that would help refine the model.
As a first point of contact those interested should go to http://www.mccannscience.com

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