Dynamic Simulation of Yankee Drying of Paper

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Introduction:

Drying of paper using Yankee dryers is a complex process. The fundamental factors effecting paper drying in a Yankee are heat transfer through the condensate layer, heat transfer through the yankee shell, heat transfer from the yankee surface to the paper through any other intervening layers like crepe promoter etc., affinity of water to the fiber because of fiber-water isotherm, heat transfer from the hot air in the yankee hood and humidity effects of the moisture present in the hot air. As is evident, this is a highly interrelated process even during steady state operation. In addition, yankee systems exhibit a high degree of dynamic behavior during start-ups, shut downs and grade or production rate changes. A large part of the dynamics is also seen due to the dynamic behavior associated with the equipment around the Yankee such as thermo-compressors, condensate tanks etc. A dynamic model of a Yankee drying system will help in the analysis of these interactions.

Model Development:

The main objective of this effort was to develop a dynamic model for the Yankee dryer. The yankee model is represented by the following four major parts. The description in the paper for the underlying processes will substantiate the proposed structure.

1. Steam system inside the shell - comprises steam chamber calculations inside the drum and the siphons.
2. Yankee shell, yankee sides - this is the calculations for the heat transfer and accumulation in the shell and on the sides of the yankee.
3. Paper sheet and crepe promoter streams - models heating and water evaporation as the paper passes through.
4. Hot Air side - calculations for the stream of hot air impinged through the array of the nozzles under the yankee hood and leaving the yankee with the water picked up from the paper sheet.

All parts interact with each other primarily by heat exchange through the common boundaries. There are also significant mass transfer interactions between parts 3 & 4 due to the moisture being evaporated from the wet tissue into the hot air system. The steam inside the shell supplies heat to the yankee. The shell transfers the heat to the crepe promoter and paper layers. The paper is also heated by the hot air. This heat is utilized in the evaporation of water in the wet sheet thus making it dry as the tissue moves around the yankee. Effects of the heat exchange to the paper, can be attributed to following sequence. As the paper travels along the periphery it absorbs heat for drying from the yankee shell and the hot air. This leads to cooling the shell from the time the sheet contacts the shell to the time it departs the shell. After the sheet leaves the shell, the shell gets heated up before it contacts the paper again.

There are significant dynamic changes in the operation of the yankee. These arise mainly due to the fact that the yankee cylinder has a large heat holding capacity and is particularly important to take into account during startup, grade changes and shut down. The steam inside the yankee shell interacts dynamically with the piping and hot air duct networks. The transients in the steam

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system and hot air systems are fairly fast with time constants in the order of seconds. The yankee shell itself accumulates heat as it gets heated up. Conventional operating floor experience suggests that the time constant for the temperature of the shell is of the order of several minutes.

The pressure drops around the yankee determine the steam and hot air flows to the yankee which in turn accounts for drying performance. The blow through from the yankee is determined by the pressure drop across the yankee cylinder and steam separation tanks. The amount of water carried over with the blow through is determined by entrainment of water with the steam and is a function of the condensate layer thickness, the exiting steam velocity and the centrifugal forces involved.

Model Assumptions:
The mathematical model built to capture the above mentioned physical processes is based on the following assumptions:

a. The dynamics of heat accumulation in the paper, crepe promoter and hot air can be ignored.
b. The conditions of steam and condensate layer inside the yankee and the hot air can be considered constant and uniform for one simulation time step Δt.
c. The yankee shell is divided into several sections. Each section of the yankee shell, the crepe promoter, and the paper tissue can be assumed to have their own constant temperature for a small internally selected sub-step time dt.
d. The yankee sides exchange heat only with the steam chamber and the ambient as a uniformly distributed two dimensional mass.
e. The condensate layer is considered to be uniformly distributed among the water removal channels of the part of the inner yankee drum surface, the rest are plateaus covered with a small film of condensate.

Mathematical Model:
In this section we outline the main equations numerically representing behavior of the process.

Schematically, the heat interaction between the parts of the yankee is shown below. The explanation of symbols may be found in the Nomenclature section.
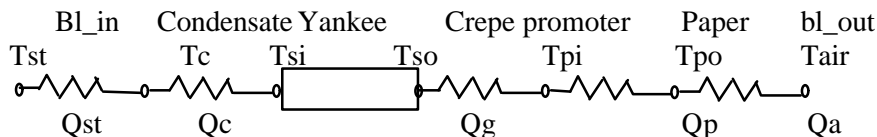
For a small time dt the following model will be assumed to hold good for the wrap portion of the yankee.

Heat convection from the steam to the condensate or the shell (during startup) is defined by:

$$q_{st} = h_{bl}\left(T_{st} - T_c\right) \qquad [1]$$

Heat conduction through the condensate gives

$$q_c = h_c\left(T_c - T_{si}\right) \qquad [2]$$

where $h_c = k_c/L_c$.

Heat conduction through the crepe promoter layer gives

$$q_g = h_g\left(T_{so} - T_p\right) \qquad [3]$$

where $h_g = k_g/L_g$.

Here hg is a combination heat transfer coefficients of fresh crepe promoter and stuck crepe promoter.

Heat is absorbed by the paper from yankee & air giving

$$q_p = h_p\left(T_{so} - T_p\right) + q_a \qquad [4]$$

where $h_p = k_p/L_p$ and L_p is the effective boundary thickness of paper.

Heat convection to the hot air is defined by

$$q_a = h_{conv}\left(T_{air} - T_p\right) \qquad [5]$$

where h_{conv} is defined by Martin's equations {1}.

The mass transfer driving force available for moisture in paper is defined by

$$\Delta p = p_{sat}(f) - pp_{air}$$

where p_{sat} is the saturation pressure of water at the temperature T_p, pp_{air} is the partial pressure of water vapor in the hot air and f, the isotherm factor, is a function of moisture content in the paper. As the paper dries the value of f will reduce, signifying the falling rate period where it becomes more difficult to dry the paper further.

Water evaporation rate is given by

$$m_{ev} = \boldsymbol{b}M\,\frac{\Delta p}{RT_p};\, q_{ev} = m_{ev}\boldsymbol{l}_{ev} \qquad [6]$$

The rate of change in paper and crepe promoter temperature for given time dt is described by

$$\frac{dT_p}{dt} = \left(\frac{q_p - q_{ev} - q_{des}}{m_p C_p}\right) \qquad [7]$$

where m_p is the mass of paper in a particular sector and C_p is the average specific heat of paper in a particular sector and q_{des} is the heat needed for desorption of water from paper.

Since we assumed that the condensate is at steady state for time dt , we have

$$q_{st} = q_c$$

One dimensional heat transfer through the yankee can be represented by Fourier Equation

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\boldsymbol{a}\,\frac{\partial T}{\partial x}\right) \qquad [8]$$

further the heat flux into the yankee shell is balanced by the gradient at the inner shell surface giving the following boundary condition

$$q_c = -k_{shell}\left.\frac{\partial T}{\partial x}\right|_{x=0} \qquad [9]$$

and the heat flux out of the yankee shell is balanced by the gradient at the shell outer surface giving the following boundary condition

$$q_g = -k_{shell} \frac{\partial T}{\partial x}\bigg|_{x=L} \qquad [10]$$

Using equations [9] and [10] as boundary conditions and solving numerically the heat conductance equation [8] through the yankee divided into a number of elements in radial direction, we can obtain a new temperature distribution inside the yankee. This process is initialized by a uniform temperature distribution.

The unwrap portion of the yankee shell sees the ambient air. The paper and crepe promoter layers have been removed by the doctor blades. For a small time dt heat transfer behavior of the unwrap portion of the yankee can also be modeled by a similar set of equations. The following resistance model can be applied where Tenv and Qenv are the temperature and heat lost to the environment respectively.
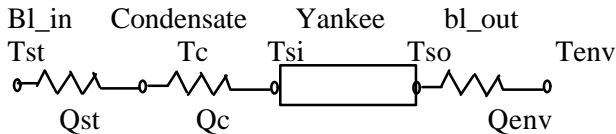
Heat convection from the steam to the condensate or the shell is defined by:

$$q_{st} = h_{bl}\left(T_{st} - T_c\right) \qquad [11]$$

where h_{bl} is the heat transfer rate between saturated steam and the yankee shell calculated from standard boundary layer models.

Heat conduction through the condensate gives

$$q_c = h_c\left(T_c - T_{si}\right) \qquad [12]$$

where $h_c = \dfrac{k_c}{L_c}$.

Heat convection to the environment gives

$$q_{env} = h_{env}\left(T_{env} - T_{so}\right) \qquad [13]$$

where h_{env} is calculated using heat transfer correlations {3} describing heat transfer rates between a stationary plate and moving air boundary.

Since we assumed that the condensate layer is at steady state for time dt, we have

$$q_{st} = q_c;$$

further the heat flux into the yankee shell is balanced by the gradient at the surface giving

$$q_c = -k_{shell} \frac{\partial T}{\partial x}\bigg|_{x=0} \qquad [14]$$

and the heat flux out of the yankee shell is balanced by the gradient at the surface giving

$$q_{env} = -k_{shell} \left. \frac{\partial T}{\partial x} \right|_{x=L} \qquad [15]$$

The sides of the yankee have a considerable amount of mass and there is significant heat loss through the sides also. This could effect the dynamics of heat build up in the yankee. If we assume the heat transfer from the yankee sides to the main face the yankee to be negligible we can use the following resistance model.

Bl_in   Yankee   bl_out

Tst   Tsi   Tso   Tenv

Qst   Qenv
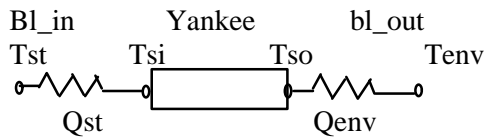
Heat convection from the steam to the condensate or the shell is similar to that defined by Eqn [11]. Heat convection to the environment shell is similar to that defined by Eqn [13].

Implementation:

The system was implemented on the platform of IDEAS – a dynamic simulation tool of general purpose. The implementation of the underlying algorithms involves numerical and analytical solutions of the model system of algebraic and differential equations. A number of numerical experiments have been conducted to establish discretization structure being used to reach the adequate accuracy. The yankee in radial direction has been divided in a number (5) of uniform layers. Circumferentially, the yankee is split into 18 uniform sectors, each of which is characterized by its relative order on yankee, and by the absolute position relative to unmoving yankee parts (or the environment) at any given small time discretization period dt. This interval dt is chosen to be the time for the yankee to sweep one sector with the current angular speed. The paper segments are associated with the corresponding yankee sectors they are attached to. All calculations for heat and mass exchange of the paper with the yankee and the hot air are performed by the integration for each sector. The heat exchange with the hot air is executed only for the paper positions that are currently located under the hood. Heat transfer coefficients for paper sectors are computed as the composite of paper, fresh crepe promoter, and build up crepe promoter coefficients. Hot air flow rate is calculated, using standard equations for air flow through the nozzles.

One step solution for the system is found in the following order.

a. Yankee is rotated in accordance with the speed imposed.
b. Temperature distribution in the yankee shell is recalculated based on the current distribution, the rates of heat exchange with the steam system, the paper, and the heat loss to the environment.
c. The steam conditions are recomputed to account for the heat transfer to the shell. The blow through and condensate removal rates are calculated.
d. Paper and crepe promoter drying equations are integrated along the sectors of the yankee, and the exiting paper conditions are computed.
e. The hot air flow and heat exchange rates are computed.

Simulation Experiments:

The experiments were designed to reflect the yankee behavior in different stages of the process and with the various conditions. The simulation "equipment" set up was as it is shown on the

Fig.1. Equipment present other than the yankee are thermocompressors, flash tanks, steam valves and pipes, condensate pumps. All these equipment provide the necessary functionality and is modeled, using standard dynamic IDEAS objects.

First the system was brought to steady state to examine the temperature and moisture profiles in the paper and temperature profile in the yankee cylinder. It was suspected that the yankee shell may loose a significant amount of stored heat as it travels with the paper and heats the paper and causes the outside surface temperature of the yankee to drop significantly. After the paper leaves the yankee, the shell will have a chance to reheat before contacting the paper again. To test this hypothesis two simulation conditions were explored, one with the yankee specific heat kept at 0.78 kW/mC and the second with the yankee shell specific heat kept at 0.01 kW/mC (very low heat holding capacity)

The results of this case study are shown in Figure 2. As can be seen the case with normal Cp (0.78 kW/mC) shows practically no change in yankee temperature relative to position and the case with artificially low Cp (0.01 kW/mC) shows a temperature difference of 4 deg C. This happens because the heat capacity of the yankee is so large that the dynamics of heat loss to the paper or environment within one rotation (about 0.25 seconds) does not affect the shell temperature significantly. There is though significant temperature gradient in the shell across the thickness direction due to heat transfer.

Figure 3 shows the heat transfer rate from the yankee cylinder at different positions at steady state. As can be seen, a large amount of heat is transferred from the yankee to the paper when the paper is wet. This is because at this point the paper temperature is low thus allowing a large heat transfer driving force. As the paper travels along with the yankee, its temperature rises thus reducing the heat transfer driving force. Towards the middle of the travel the paper temperature almost equals that of the yankee surface making the heat removal from the yankee to near zero. At this point all of the heat picked up by the paper is received from the hot air which usually much warmer. When the paper leaves the yankee, the hot air cap is lost and the yankee changes heat with the environment. After this fresh crepe promoter is sprayed on the yankee surface which is wet and cold and hence we see a large heat transfer rate that evaporates most of the water from the crepe promoter.

Figure 4 shows the paper temperature profile as it moves along the yankee surface. The paper enters at a low temperature (40 deg C). The paper initially gets heated as at low paper temperature evaporation from the paper is relatively low. As the paper gets heated, the evaporation rate increases and hence the rate of rise in paper temperature drops. Around a position of 1.3 meters from reference, the paper temperature has a flat profile. This is because the paper has reached wet bulb temperature where all the heat transferred from the yankee is used for evaporation. This temperature is a function of the effective heat and mass transfer rates. At a position of 1.61 meters the yankee air cap comes effective. The air temperature is much higher resulting in further heating of the paper and eventually attaining a new wet bulb temperature that is a function of the new heat transfer rate. At a position of 2.6 meters the paper temperature begins to rise again. This is due to the drying of paper at the start of the falling rate period. The temperature of paper after this point is a function of the isotherm curve in addition to the balance between heat and mass transfer rates. Figure 5 shows the paper moisture profile. The paper enters the yankee at 40 % moisture. There is an initial increase in moisture as the paper picks up moisture from the wet crepe promoter. The paper moisture starts dropping at a steady pace until it reaches the falling rate period. Eventually a base line moisture of about 4 % is maintained due to isotherm related issues. It becomes increasingly difficult to evaporate the last few percent moisture in the sheet. It is interesting to see that the sharp profiles seen in the paper temperature is not seen in the

moisture profile. This is due to the fact when the paper reaches wet bulb temperature, there still is the same of amount of energy consumed for evaporation.

The model was also tested for the dynamic startup behavior of the yankee dryer. The startup response depends on the response of the systems around the yankee also. A dynamic model was built as shown in Figure 1 with dynamic objects for fans, dampers, tanks and thermo-compressors. More over a realistic start-up procedure that is used to start up a real plant was also simulated.

The results of the dynamic start up response is shown in Figure 6. Initially steam is brought into the yankee at a low flow rate (2000 kg/h). The yankee starts heating up gradually and the pressure in the yankee also builds up gradually. The yankee shell starts from 25 deg C and gradually rises as the shell gets heated up. During this phase the air inside the yankee drum is being purged by the incoming steam. After about 30 minutes the thermo-compressor is turned over to pressure control and the pressure set point starts ramping at a predetermined rate to meet a target pressure. This has the effect of opening the thermo-compressors spike to modulate the required amount of steam to maintain a set point pressure. The rate of heating of the shell is also trended during this phase. It is important that this heating rate is controlled as rapid heating of the yankee shell could cause undue thermal stresses and possible damage to the yankee. At the end of the start up procedure which lasts over 2.5 hours, the yankee reaches its target pressure and the shell temperature reaches its normal operating values.

The yankee will be held at this condition until other systems are prepared for start-up at which hot air will be brought on to the hood followed by wet paper. The dynamics associated with bringing hot air on and paper on are relatively quick and the yankee will reach steady state operating conditions shown in Figures 2 to 5 shortly.

Conclusions::

A dynamic model of a Yankee dryer has been built. Heat transfer through the shell is computed using finite difference methods. The heat transfer through the condensate layer, yankee surface to paper, hot air to paper and heat loss from the yankee sides are modeled using first principles. The drying of paper itself through the constant and falling rate periods is also modeled using first principles. The associated systems like thermo-compressors and condensate tanks etc., are also modeled with the Yankee dryer to capture their contribution to the system dynamics.

The model has been used to study process response characteristics to the start-up, shut-down and upset conditions like production rate changes, change in hot air temperature & flow rates, change in steam pressure, change in blow-through ratio etc. The results of the model experiments can be used to formulate and test control strategies and help in the design and sizing of various pieces of equipment.

References::
1. Advances in Heat Tansfer, Vol: 13, Holger Martin, Academic Press (1977).
2. Conduction of Heat in Solids, Carlslaw & Jaeger, Oxford Science Publications
3. Handbook of Chemical Engineering, Perry, J.H.
4. A study of the drying process of pigment coated paper webs – Ph.D. Thesis, Perti Heikkila – Abo Akademi
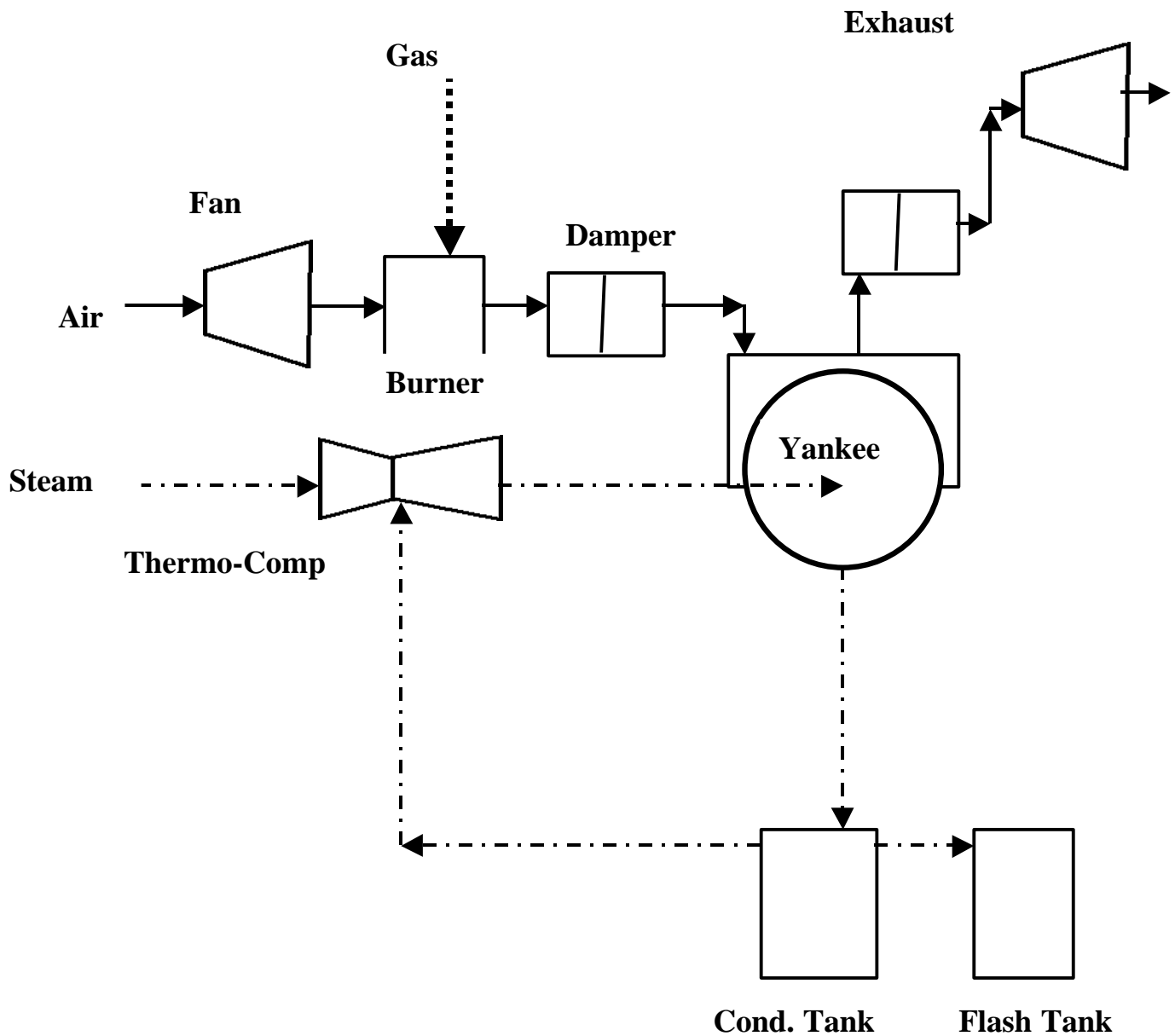
Gas

Exhaust

Fan

Damper

Air

Burner

Steam

Yankee

Thermo-Comp

Cond. Tank

Flash Tank

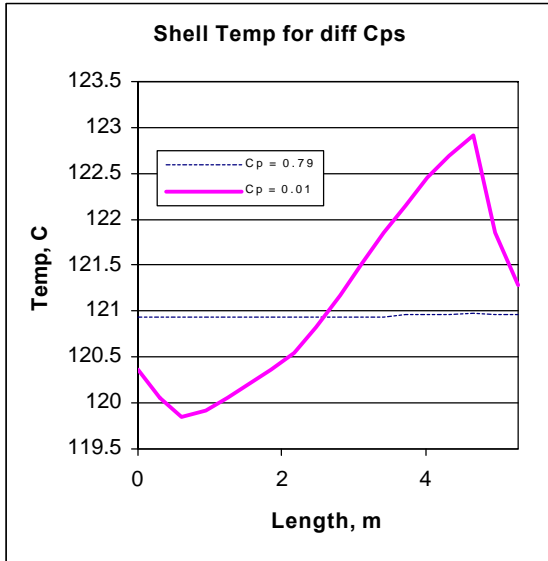**Fig 1: Schematic Arrangement of Yankee dryer**

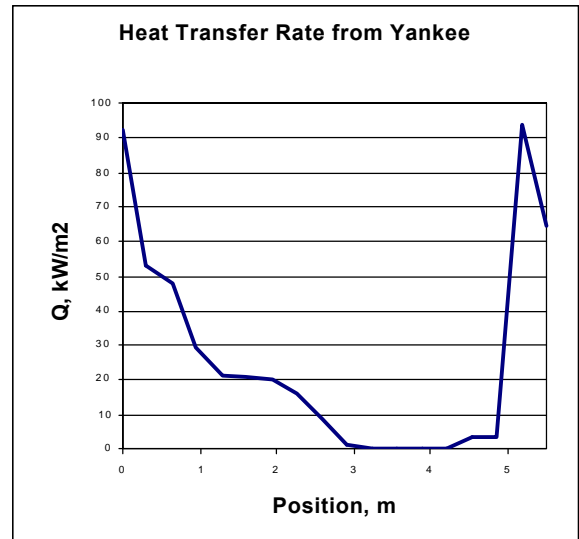Fig 2: Shell temperature profiles for diff Cps.

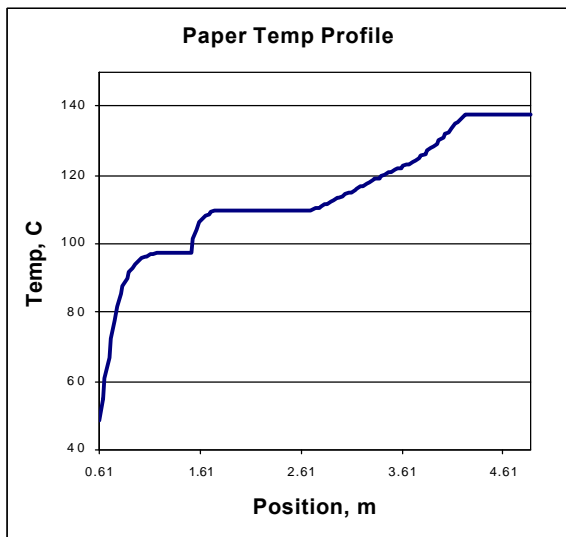Fig 3: Shell heat transfer rate profile.
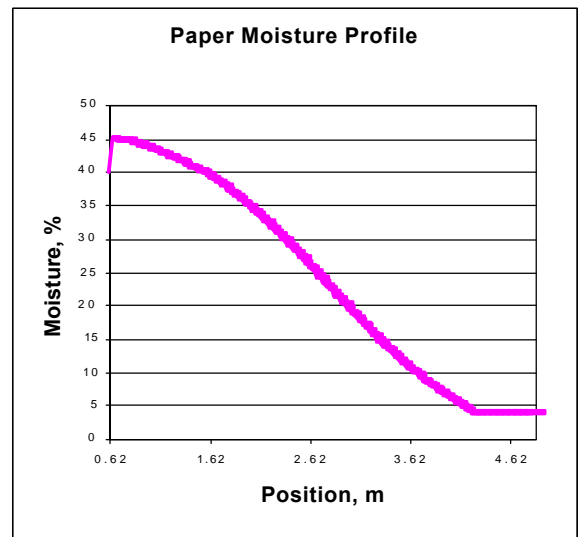

Fig 4: Paper temperature profile at steady-state.
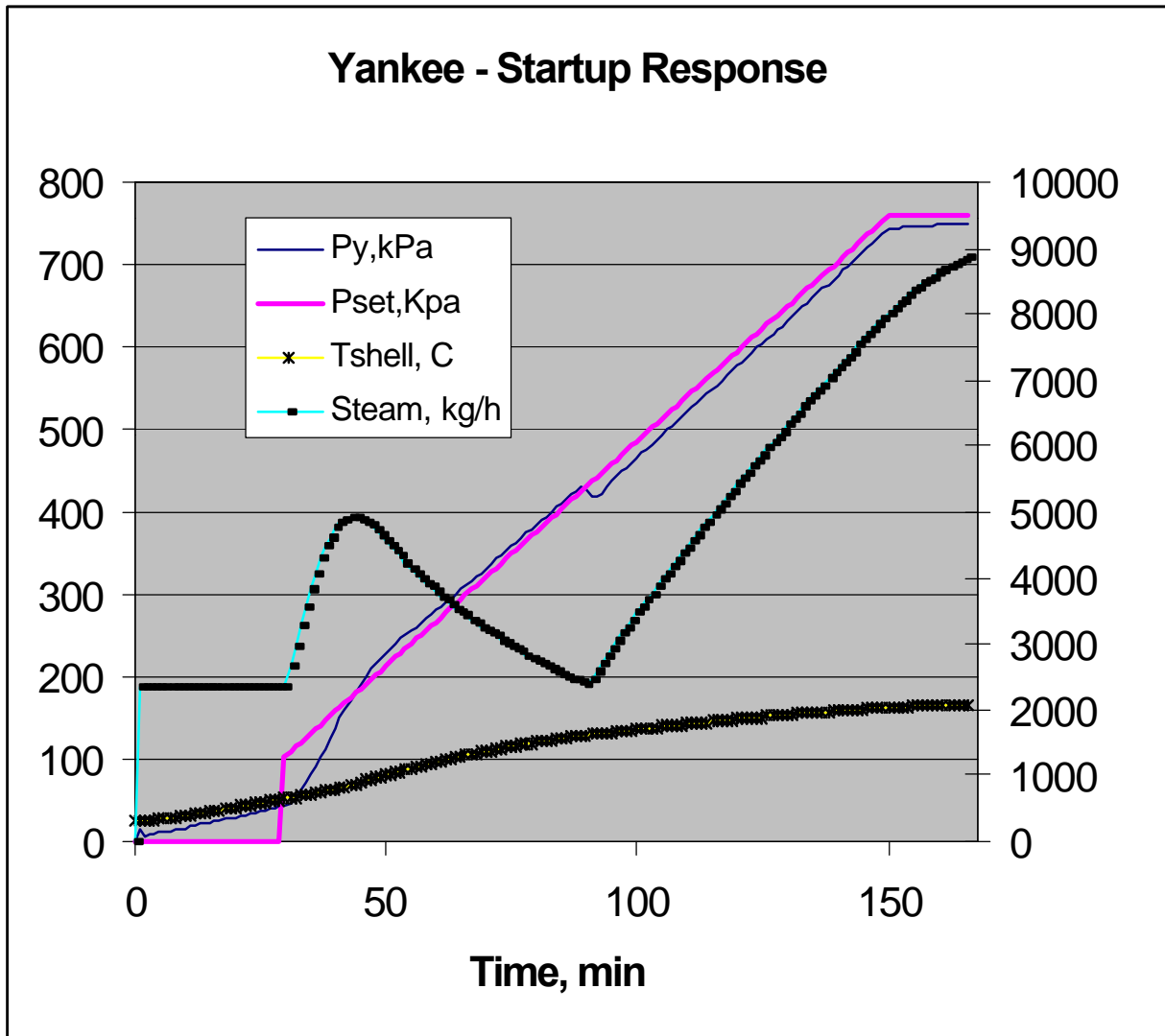

Fig 5: Paper Moisture profile at steady-state.

Figure 6: Yankee Startup Response

Nomenclature:

Table 1: Subscripts

Name	Description
st	steam
c	condensate
si	inside shell
so	outside shell
air	Hot air
env	environment
p	paper
shell	yankee shell
bl	boundary layer

Table 2: Nomenclature

Name	Description	Units
k	Thermal conductivity	kW/m.K
h	Heat Tr.Coeff.	$kW/m^2.K$
L	Thickness	m
q	Heat transfer	kJ/s
M	Mass	Kg
Cp	Specific heat	kJ/kg.K
dt	internal time step	s
Δt	simulation time step	s
Δp	Vapor pr. driving force	Pa
β	Mass Tr. Coeff.	m^3/s
λ	Heat of evaporation	kJ/kg
α	Thermal diffusivity	m^2/s
T	Temperature	K
m_{ev}	Water Evap. Rate	$Kg/m^2.s$